*Transactions of the Korean Nuclear Society Autumn Meeting*
*Goyang, Korea, October 23-24, 2019*

# Evaluation of 0.01%-offset Yield Strength by Ultrasonic Reconstruction of Quadratic Nonlinear Stress–Strain Curve within Elastic Range

Jongbeom Kim [a], Kyung-Mo Kim [a*], Kyung-Cho Kim[b] and Kyung-Young Jhang[c*]

[a]*Korea Atomic Energy Research Institute, Daejeon 34057, Republic of Korea*
[b]*Korea Institute of Nuclear Safety, Daejeon, 34142, Republic of Korea*
[c]*School of Mechanical Engineering, Hanyang University, Seoul 04763, Republic of Korea*

[*]*Corresponding author: kmkkim@kaeri.re.kr, kyjhang@hanyang.ac.kr*

## 1. Introduction

The nonlinear ultrasonic technique has been considered as a potential nondestructive evaluation method for assessing the early damage in a material. This technique is based on the nonlinear elastic interaction between a material and propagating ultrasonic wave. The ultrasonic nonlinearity parameter β is used to quantify the second-order nonlinearity, which is defined by the ratio of the second-order harmonic amplitude to the square of fundamental frequency amplitude. The nonlinearity parameter β is measured from the amplitude of the second-order harmonic frequency component [1]. It is well known that β is closely related to the microstructure of a material [2, 3]. Therefore, this nonlinearity parameter β can be used for evaluating the material degradation [2, 3] caused by microstructural changes induced by degradation. However, it is difficult to compare the parameter β with the yield strength quantitatively, because those two measurands are obtained under different stress-strain condition. That is, β is defined under conditions of one-dimensional propagation of a longitudinal wave through an isotropic material in which the lateral strain is restrained, whereas, the tensile test to measure the yield strength is carried out under the uniaxial stress condition in which the lateral deformation is free. Furthermore, the parameter β does not tell quantitatively about the degree of material degradation.

Therefore, this study proposes a nondestructive evaluation method to evaluate the yield strength directly from the ultrasonic measurements by reconstructing the tensile stress-strain curve represented in the form of a quadratic nonlinear stress–strain equation within the elastic range. The tensile stress–strain curve is represented in the form of a quadratic nonlinear stress–strain equation within the elastic range, which includes Young's modulus and the second-order nonlinearity parameter $\beta_t$ derived under the uniaxial stress condition. The Young's modulus is obtained by measuring the propagation velocities of longitudinal and transverse waves using a traditional ultrasonic pulse-echo method, and the second-order nonlinearity parameter $\beta_t$ is obtained by using acoustoelastic effects. Then, the tensile stress–strain curve is reconstructed to estimate the 0.01% offset yield strength.

To demonstrate the application of the proposed algorithm, experiments were performed for heat-treated SA508 specimens. The results indicate that the 0.01% offset yield strength obtained using the proposed algorithm exhibit a good agreement with that obtained via destructive tensile testing.

## 2. Yield Strength Estimation Algorithm

The proposed 0.01% offset yield strength algorithm mainly consists of three steps: 1) Measurement of Young's modulus (E). 2) Measurement nonlinearity parameter $\beta_t$ and reconstruction of the tensile stress-strain curve using Eq. (1) to estimate the 0.01% offset yield strength [4].

$$\sigma_{11} = E\varepsilon_{11}\left(1 - \frac{1}{2!}\beta_t\varepsilon_{11}\right) \quad (1)$$

where $\sigma_{11}$ is the uniaxial stress, $E$ is the linear elastic modulus (Young's modulus), $\varepsilon_{11}$ is the strain in the stress direction, and $\beta_t$ is the second-order nonlinearity parameter under the uniaxial stress condition.

In the first step, propagation velocities of longitudinal and transverse waves were obtained by the using a traditional ultrasonic pulse-echo method, and then Young's modulus is calculated. In the second step, the nonlinearity parameter $\beta_t$ were obtained by using acoustoelastic effects by measuring the change of longitudinal and transverse wave velocities as a function of the stress applied to the specimen.

Then, the 0.01% offset method was adopted to determine the yield strength. In general, the 0.2% offset method is used to determine yield strength; however, the 0.2% offset yield strength includes not only elastic deformation but also plastic deformation while the ultrasonic measurement can evaluate the elastic properties only. Thus, in this study, yield strength is determined using the 0.01% offset method which is considered to be a good approximation of the elastic limit of a material [5,6].

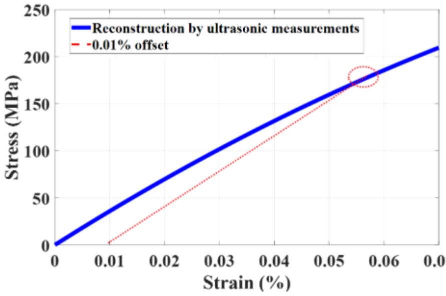

Fig.1. Example of the stress-strain curve reconstructed by the ultrasonic measurements and the 0.01% offset method.

## 3. Specimens and Experiments

### *3.1 Specimens*

To demonstrate the proposed method, SA508 specimens were prepared. SA508 alloy is widely used in commercial applications of nuclear power plants such as reactor pressure vessel and steam generator. The specimens were heat-treated at a constant temperature of 700 ℃ with different aging times (0, 100, 1000, 5000, and 10000 hours). Then, ultrasonic measurements and the destructive tensile tests were conducted.

### *3.2 Ultrasonic Measurements*

To measure Young's modulus, the 5 MHz longitudinal and shear waves PZT transducers with diameter of 0.375 inch were attached to the top of the specimen, respectively, and a pulse signal was input by a pulser-receiver (Panamertric, PR5072). The generated longitudinal and shear waves were transmitted through the material, and the reflected signal from the back-wall was received by the transducer. Then, $\beta_t$ is obtained by measuring the Lamé constants $(\lambda, \mu)$ and Murnaghan constants (l ,m, n) [7] using pulse-echo method and acoustoelastic effect.

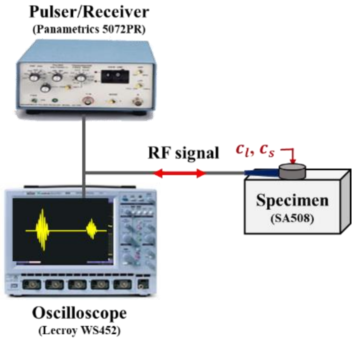

Fig. 2. Experimental setups to measure Young's modulus.

## 4. Experimental Results and Conclusions

The experimental results showed that the variations of both yield strengths are in good agreement with each other as a function of aging time. Therefore, the proposed method can access the material degradation intuitively and quantitatively by estimating the variation of 0.01% offset yield strength.

Consequently, this method can replace the destructive tensile test for quantitative evaluating material degradation. However, this algorithm is limited to the 0.01% offset yield strength. In general, the 0.2% offset yield strength is more popular than the 0.01% offset yield strength in the field. Therefore, further study is needed to evaluate the 0.2% offset yield strength to commercialize the proposed method in the field.

## Acknowledgement

Funding: this research was supported by the Nuclear Power Research and Development Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (NRF-2017M2A8A4015158.

## References

[1] K.-Y. Jhang, Application of nonlinear ultrasonics to the NDE of material degradation, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 47, pp. 540-548, 2000.

[2] K. Balasubramaniam, J. S. Valluri, and R. V. Prakash, Creep damage characterization using a low amplitude nonlinear ultrasonic technique, Materials Characterization, vol. 62, pp. 275-286, 2011.

[3] J. Kim and K.-Y. Jhang, Evaluation of ultrasonic conlinear characteristics in heat-treated aluminum alloy (Al-Mg-Si-Cu), Advances in Materials Science and Engineering, vol. 407846, pp. 1-6, 2013.

[4] J. Kim, K.-Y. Jhang, D.-G. Song, and C.-S. Kim," Quantitative Evaluation of Yield Strength Degradation by using Nonlinear Ultrasonic Techniques," Proceeding of SPIE, vol. 10600, pp. 106001C, 2018.

[5] G. F. Weissmann, "Where is the elastic limit?," *Experimental Mechanics*, vol. 15, no. 3, pp. 96-101, 1975.

[6] B. Wonsiewicz and R. Hart, "Finite Strain and the 0.01 Percent Offset Yield Strength," Journal of Testing and Evaluation, vol. 1, no. 5, pp. 412-415, 1973.

[7] S. Takahashi and R. Motegi, "Measurement of third-order elastic constants and applications to loaded structural materials," Springerplus, vol. 4, no. 325, pp. 1-20, 2015.