THE FEASIBILITY EVALUATION USING THE AUTOMATED BALL INDENTATION TECHNIQUE TO OBTAIN MECHANICAL PROPERTIES OF THE STEELS IN THE NUCLEAR VESSELS

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ABSTRACT

The amount of nuclear vessels has grown rapidly all over the word, however, the conventional destructive test methods can't be used to measure the performance of nuclear vessels in service, so that we cannot make an accurate assessment of the remaining life of the nuclear vessels. As the substitution of destructive test, the Automated Ball Indentation (ABI) technique is a relatively simple, rapid, and nearly non-destructive technique to evaluate mechanical properties of metallic materials. In this study, a series of ABI tests was performed on SA508Gr3, SA516Gr70, and SA533B, which are three kinds of steels used in nuclear vessels, some mechanical properties, such as true stress-true plastic strain curve, strain-hardening exponent, yield strength, and tensile strength were obtained from these experimental results. At the same time, the traditional standard tensile tests were used to obtain the same properties. The measured results were analysed in detail in this paper, and the results of ABI tests were in fairly agreement with those from conventional destructive tests. All these results proved that the ABI technique can be available to measure the mechanical properties of the steels used in nuclear vessels.

INTRODUCTION

With the extensive application of nuclear energy and the serious consequence of nuclear accident, concerns about the safety of in-service nuclear vessels have risen to unprecedented level. So it is necessary to detect a large number of nuclear vessels and pipelines in service by non-destructive means. The conventional non-destructive testing methods, such as RT (Radiographic testing), UT (Ultrasonic testing), MT (Magnetic particle testing), PT (Penetrant flaw testing), can only detect those macro defects, and find the dangerous part of the equipment in service. They aren't able to evaluate the mechanical properties of current materials. But the mechanical properties, such as yield strength, and tensile strength et al, are very important aspects of structural integrity, which is a key point for experts and scholars to study. Tensile properties can be measured using standardized test methods, for example, those developed by ASTM (ASTM A370-14, 2014) and BSI (EN 10002-1, 2001). However, it can be difficult to measure tensile properties of in-service equipment with these methods because they require specific specimen dimensions and complex test procedures. In addition, standard measurements can't be applied to small-volume regions (e.g. weld zones, thin films) or in-service industrial structures because of the requirements of the test procedures and the destructive nature of the tests. Among the alternative test methods available, the ABI (Automated Ball Indentation) technique is widely used to evaluate mechanical properties of metallic materials because of the simplicity of the test procedure and specimen preparation. In addition, ABI technique can be applied to small-volume regions and in-service structures because it is localized and nearly non-destructive in nature.

The ABI technique can be traced back to 1881. Hertz first proposed that using indentation method to obtain the material hardness. With the improvement of the indentation method by Taber (1951) and Meyer et al (1908), the indentation method began to be used for the detection of mechanical properties of the material. Until the early 1980s, Haggag et al proposed that the ABI technique can be used for testing a variety of mechanical properties. At the same time, they developed the ABI testing machine and commercial promotion (Haggag and Nanstad et al, 1989; Haggag, 2006). On the basis of ABI technique, more researchers have joined the ranks how to use non-destructive testing technique which don't require sampling and can be used both in the fields and laboratories.

In this paper, authors describe the derivation of the true stress-true plastic strain curve and other mechanical parameters from the indentation load-depth curve measured by the ABI tests. To consider SA508Gr3, SA516Gr70, and SA533B as the representative for the steels used in nuclear vessels, by comparing the true stress-true plastic strain curve derived from ABI tests with those measured directly by the uniaxial tensile tests, the author verified the feasibility of using the ABI Technique to obtain mechanical properties of the steels used in nuclear vessels.

THE PRINCIPLE OF ABI TECHNIQUE

ABI technique is, in fact, a kind of progressive multiple loading and partial-unloading continuous indentation experiment in the same point. A spherical indenter is pressed into the polished sample surface at a constant speed in the normal direction, and load and displacement are measured simultaneously in real-time using load and displacement sensors. Then a continuous curve of the indentation test process (load-indentation depth curve) is obtained. Finally the load-indentation depth curve can be changed into the true stress and true plastic strain curve of material to gain various material properties, including the yield strength, tensile strength, strain hardening exponent and strain-hardening coefficient, and so on (Kim and Baik et al, 2012; Jia and Xuan, 2012; Lee and Kim et al, 2008).

True Stress-True Plastic Strain Curve

Assuming the material to obey the familiar power law equation (Holloman), as shown in Eq. (1), and measuring the true stress and true plastic strain curve in material uniform deformation stage, we shall determine the material strain-hardening coefficient K and the strain-hardening exponent n.

$$\sigma_{\mathrm{t}} = K\varepsilon_{\mathrm{p}}^{n} \tag{1}$$

Where: σ_{t} means true stress; ε_{p} means true plastic strain.

Tabor (1951) determined the empirical equation of true plastic strain of ball indenter contact edge by traditional optical technique, as shown in Eqs. (2)-(4).

$$\varepsilon_{\mathrm{p}} = \frac{0.2 d_{\mathrm{p}}}{D} \tag{2}$$

$$d_{\mathrm{p}} = \sqrt[3]{\frac{0.5CD\left[h_{\mathrm{p}}^{2} + \left(d_{\mathrm{p}}/2\right)^{2}\right]}{h_{\mathrm{p}}^{2} + \left(d_{\mathrm{p}}/2\right)^{2} - h_{\mathrm{p}}D}} \tag{3}$$

$$C = 5.47P\left(\frac{1}{E_1} + \frac{1}{E_2}\right) \tag{4}$$

Where: d_{p} is the diameter of plastic indentation; h_{p} is the depth of plastic indentation; D is the diameter of the spherical indenter; P is applied indentation force; E_1 and E_2 are the elastic module of indenter and material respectively.

There are three regimes in the process of material deformation: the elastic regime, the elastic-plastic regime and the fully plastic regime. If the effect of constraint state is considered, the true stress can be obtained from the applied indentation force P and constraint factor δ, as shown in Eq. (5).

$$\sigma_{\mathrm{t}} = 4P / \left(\pi d_{\mathrm{p}}^{2} \delta\right) \tag{5}$$

Where: δ is the constraint factor which describes the material deformation state. The solution of δ is described by Jia and Xuan (2012). This stress is smaller than the mean indentation pressure because the plastic deformation of materials is constrained by the surrounding elastic material.

The simultaneous solution of Eqs.(2)-(5), a series of data points of $\sigma_{\mathrm{t}} - \varepsilon_{\mathrm{p}}$ being measured. According to Eq. (1), the data points including the yield stress-yield strain point are fitted to obtain a uniform plastic flow curve, the true stress-true plastic strain curve. The solution of yield stress will be described in detail in the following.

Yield strength and Tensile strength

If the spherical indenter be assumed stiffness enough, according to the law of Meyer (1908), the relationship between the applied load and the diameter of plastic indentation can be written as Eq. (6):

$$P / d_{\mathrm{t}}^{2} = A\left(d_{\mathrm{t}} / D\right)^{m-2} \tag{6}$$

Where: A is the indentation parameter, which associated with the yield strength and strain hardening of measured materials; m is the Meyer exponent. For ABI tests, every loading-partial unloading cycle will measure the depth of indentation h_{t}, and according to the geometric structure of spherical indenter, the depth of indention h_{t} can be converted to the diameter of indention d_{t} through Eq.(7).

$$d_{\mathrm{t}} = 2\left(h_{\mathrm{t}} D - h_{\mathrm{t}}^{2}\right)^{1/2} \tag{7}$$

When $d_t / D \le 1.0$, the P and d_{t} acquired from each loading-partial unloading cycle in ABI tests meet to the Eq.(7). Based on the relationship between yield strength and indentation parameter A obtained by previous experiments, the yield strength R_{eL} can be characterized by Eq.(8) (Haggag and Nanstad, 1989):

$$R_{\mathrm{eL}} = \beta_{\mathrm{m}} A \tag{8}$$

Where: β_{m} is yield coefficient, which can be obtained through the yield strength of the conventional tensile tests divided by A value. George and Dinda et al (1976) concluded $\beta_{\mathrm{m}} = 0.325$ through a lot of experiments of the cold-rolled and hot-rolled carbon steels whose yield strength is 193-655MPa. In the study, if the yield strength offset parameter B under different working state is taken into consideration, the empirical formula Eq.(8) is revised to the Eq.(9) (Murty and Haggag, 1996):

$$R_{\mathrm{eL}} = \beta_{\mathrm{m}} A + B \tag{9}$$

The researchers showed that the strain hardening exponent n and true uniform strain is approximately equivalent when material bears tension load and reaches its tensile strength (Haggag and Murty, 1997). Thus according to the transformation of the relationship between true stress and engineering stress, the tensile strength value R_{m} can be expressed as Eq.(10) when the relationship between the true stress and true strain is coincident with the power law equation.

$$R_{\mathrm{m}} = K\left(\frac{n}{e}\right)^{n} \tag{10}$$

EXPERIMENTAL PROCEDURES

The specimens used in this study were sampled from SA508Gr3, SA516Gr70, and SA533B steels, which are the most used steel in nuclear vessels. And the steels are accepted state. The analysed chemical compositions and the ASME code specifications of the steels were summarized in Tab.1. By contract, it is found that all kinds of steels are accord with the standard.

Table 1 The analysed chemical compositions and AMSE code specifications of the steels (wt%)

Steels		C	Si	Mn	Cr	Mo	Ni	P	S
SA508Gr3	Analysed	0.226	0.194	1.475	0.227	0.469	0.956	0.0066	0.0012
	ASME code	≤0.25	≤0.40	1.20-1.50	≤0.25	0.45-0.60	0.40-1.00	≤0.025	≤0.025
SA516Gr70	Analysed	0.206	0.302	1.294	0.052	<0.001	0.00[13]	0.020	0.0014
	ASME code	≤0.26	0.13-0.45	0.79-1.30	-	-	-	≤0.035	≤0.035
SA533B	Analysed	0.195	0.282	1.409	0.203	0.524	0.684	0.013	0.0021
	ASME code	≤0.25	0.13-0.45	1.07-1.62	-	0.41-0.64	0.37-0.73	≤0.035	≤0.035

Specimen dimension for indentation tests is 10×10×50mm. The upper surface and the lower surface were polished with 320, 400, 600, and 800-mesh silicon carbide abrasive papers in turn. In addition, the specimens for the tensile tests were fabricated as a round bar type with 50mm gauge length and 10mm diameter. The specimens of indentation tests and tensile tests are along the rolling direction of the steel plate.

A series of ABI tests was carried out to measure the indentation load-depth curves. SSM-B4000™ System produced by Advanced Technology Corporation in American is chosen as the experimental equipment. It consists of a 4450N load sensor with resolution of 0.01% and a Liner Variable Displacement Transducer (LVDT) with resolution of 0.0025%. The indenter is a tungsten carbide ball of 0.76mm diameter and the indentation speed is 0.00533mm/s. 8 times load-unload cycle are set in each test. Every unloading down to 60% of the maximum load at each point were applied and the last time completely unloading. More than five indentations per specimen were performed to examine reproducibility. In addition, in order to verification our analysis, stress-strain curves for various steels were directly measured by tensile tests at cross-head speed of 1 mm/min. Two times tensile tests were carried out in each material.

RESULTS AND ANALYSIS

Flow Properties

In indentation tests, more than 5 curves were measured for each specimen, and reproducibility was excellent at every depth. The measured indentation load-depth curves of SA508Gr3, SA516Gr70, and SA533B are showed in Fig.1. The plastic flow properties derived from indentation load-depth curves and those measured by tensile tests are shown together in Fig.2. The agreement between the true stress-true plastic strain data converted from indentation and those measured by tensile tests is good. The strain-hardening exponent (n) and strain-hardening coefficient (K) which were obtained by indentation tests and tensile tests are showed in Fig.3. In the figure, each point marked in abscissa is the average of the repeated tensile test results of the same steel, while the point marked in ordinate are the ABI test results of the same steel. The relative error of strain-hardening coefficient (K) is less than 10%, so it is meet the acceptable range in engineering. The strain-hardening exponent (n_{ind}) derived from indentation load-depth curve is, however, somewhat different from that measured by tensile test (n_{ten}). This is similar with the previous observation (Ahn and Kwon, 2001). The difference is that the value of n_{ind} is available in strain range more than 0.05 in our study while n_{ten} is obtained using true stress-true strain data from the yield point. Another is that the phenomenon of pile-up or sink-in has some influences on the calculation of true stress and true plastic strain (Kim and Baik, 2005), and this study ignored the impact.

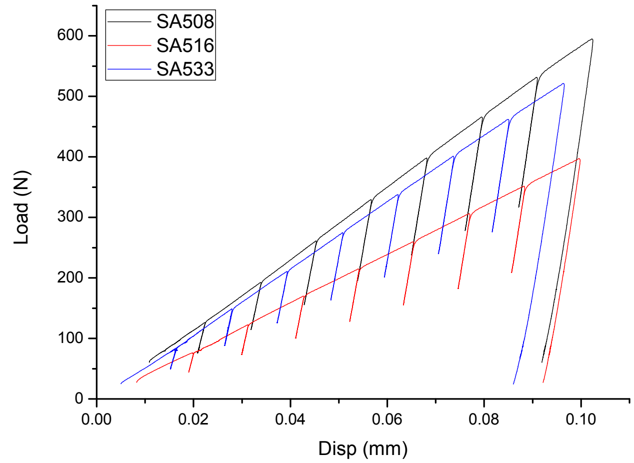

Figure 1 The indentation load-depth curves of steels adopted in this study

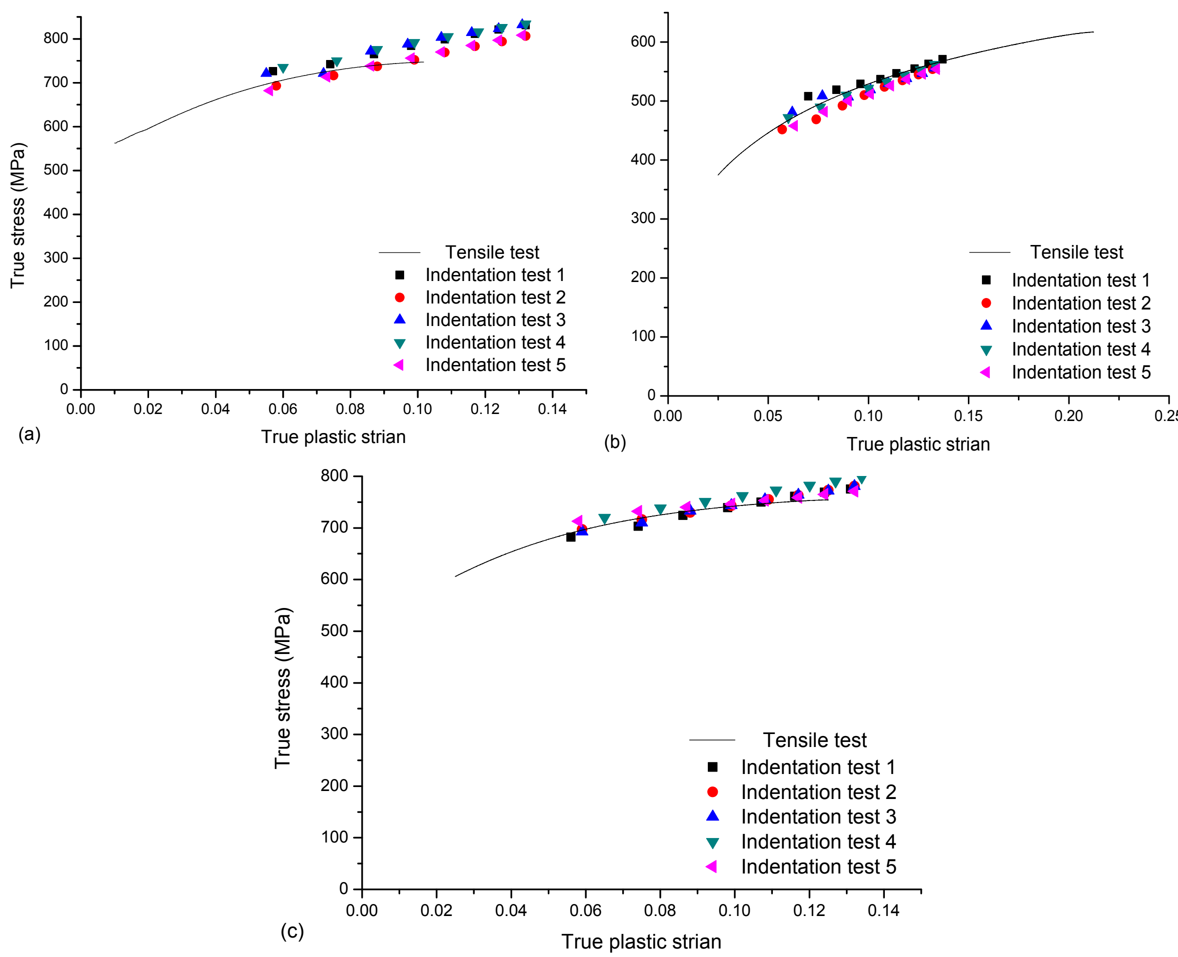

Figure 2 The comparisons of plastic flow properties calculated from the ABI tests with those from the tensile tests for (a) SA508Gr3, (b) SA516Gr70, and (c) SA533B

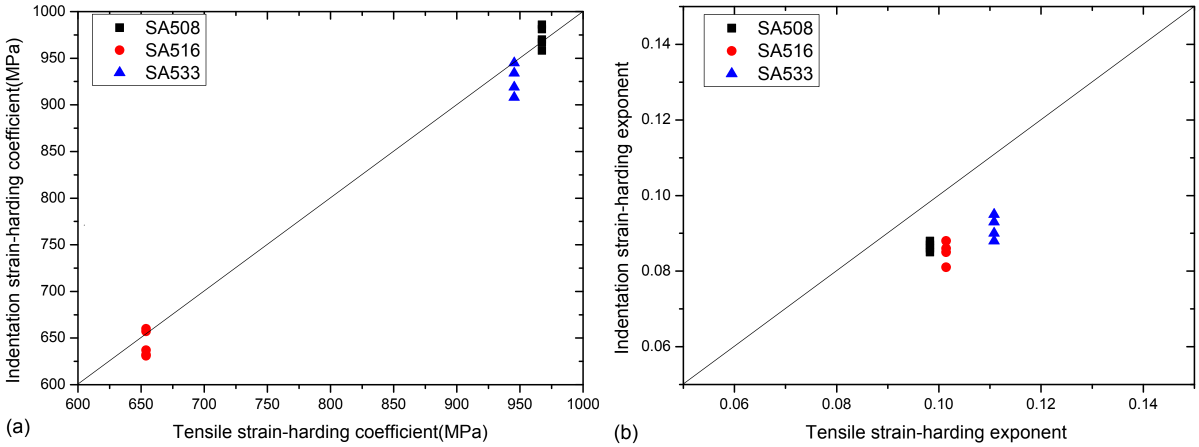

Figure 3 Comparisons of *K* and *n* derived from ABI tests with those measured from tensile tests for (a) strain-hardening coefficient *K*, (b) strain-hardening exponent *n*

Table 2 Comparisons of tensile strength derived from the ABI tests with those from the tensile tests

Test steels	Tensile strength by Tensile tests/MPa		Tensile strength by indentation tests/MPa		Relative deviation （%）
	experimental	average	experimental	average	
SA508Gr3	706	723.5	726	714.6	1.23
			728		
			713		
	741		688		
			718		
SA516Gr70	501	501	489	480.6	-4.07
			488		
			475		
	501		475		
			476		
SA533B	670	668	671	675	1.05
			661		
			676		
	666		676		
			691		

Tensile Strength

The tensile strength values, R_m, of SA508Gr3, SA516Gr70, and SA533B evaluated by ABI tests and those measured by conventional tensile tests are listed in Tab. 2. It shows that the relative deviation between tensile strength values by two methods is less than 10%. The reason of the deviation may be due to the following two points: (1) errors exist in conventional tensile test and indentation tests themselves; (2) the test point or position may also affect the measured and evaluated results as the heterogeneity of steels. Anyway the deviation is fairly small. So estimating the tensile strength of the steels used in nuclear vessels by the ABI technique is feasible and reliable.

Yield Strength

First of all, the yield strength R_{eL} of steels was estimated from Eq.(8) in which $\beta_m = 0.2285$ and B=0 proposed by Haggag based on his previous works and experiments. The relative deviation between the yield strength tested by tensile tests and estimated by ABI tests is quite large. The errors are mainly caused by: (1) Errors of ABI tests and errors of conventional tensile tests will be superimposed when comparing the data by two test methods. (2) Errors in the yield coefficient β_m and yield strength offset parameter B for different steels when simply using their default values, that is $\beta_m = 0.2285$ and B=0. Therefore we need to adjust the yield coefficient β_m and yield strength offset parameter B appropriately.

We take the conventional tensile test results as benchmark for SA508Gr3, SA516Gr70, and SA533B in this paper, and regress the relation between indentation parameter A and yield strength linearly by the least squares method in the form of Eq.(9). The correction equation of yield strength is given by Eq.(11), as shown in Fig.(4):

$$R_{eL} = 0.3313A - 200.1279 \tag{11}$$

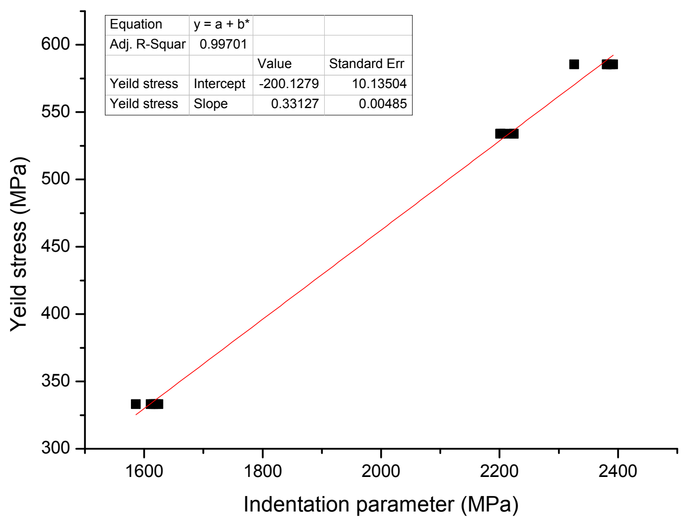

Figure 4 Correlation of yield strength with indentation parameter A

The correlation coefficient of the regression is 0.9970, which shows that the indentation parameter A determined by ABI tests is closely related with the yield strength of steels. The yield strength measured by conventional tensile tests and estimated by corrected ABI tests is showed in Fig.5. In the figure, the points marked in abscissa are the average of the repeated tensile test results in the same steel, while the points marked in ordinate are the corrected results of ABI test in the same material. As is shown in Fig.5, the results between conventional tensile tests and corrected ABI tests are in good consistency. Therefore, Eq. (11) can be used to estimate the yield strength of SA508Gr3, SA516Gr70, and SA533B.

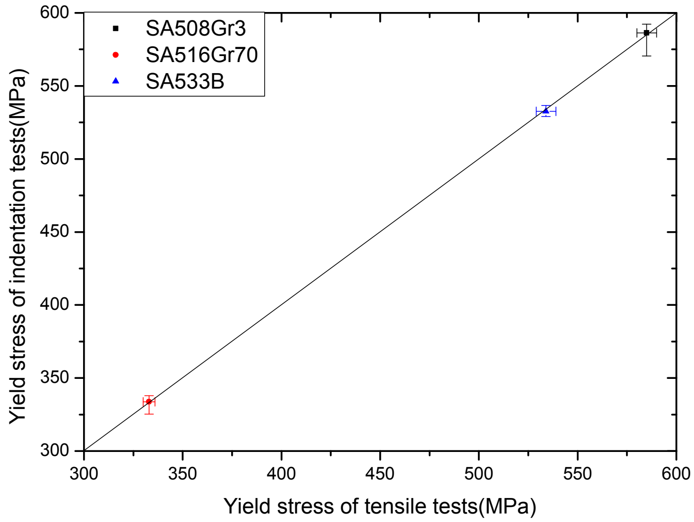

Figure 5 The yield strength measured by conventional tensile tests and converted by ABI tests

CONCLUSIONS

In this study, the ABI tests and traditional tensile tests were carried out in SA508Gr3, SA516Gr70, and SA533B. The mechanical properties were acquired respectively. The following remarks can be drawn from the above investigations:

(1) ABI technique can clearly distinguish the true stress-true plastic strain curves of different steels used in nuclear vessels and reflect the differences in steel mechanical properties.

(2) Mechanical properties of the steels used in nuclear vessels, including plastic flow properties and tensile strength, were evaluated from the load-depth curves measured by ABI technique. And the results were in good agreement with those measured by tensile tests.

(3) The agreement between the yield strength evaluated by ABI tests and measured by conventional tensile test is not good enough. By modifying the yield coefficient and yield strength parameter offset, we improved the accuracy of correlation very much. The yield strength of SA508Gr3, SA516Gr70, and SA533B can be evaluated by $R_{\mathrm{eL}} = 0.3313A - 200.1279$.

(4) Our research work reveals that it is feasibility to acquire mechanical properties of the steels used in nuclear vessels by ABI technique. This technique was proved to be excellent substitute by the standard tensile test. And it has the potential to be applied non-destructively to evaluation the mechanical properties of small volumes such as welds and heat-affected zones in nuclear vessels.

ACKNOWLEDGEMENT

Thanks to National Natural Science Foundation of China, 'The investigation of the mechanism and universality of material mechanical properties tested by automated ball indentation method' (Project No.: 51475269), and National Key Research and Development Project, 'micro damage testing of material properties and development of testing instrument' (Project No.: 2016YFF0203005), for financial support.

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