Analysis of the mechanical properties of Q345R steel in deep-regulating units by the spherical indentation method

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Abstract. The principles of testing the mechanical properties of metallic materials through the use of the spherical indentation test have been analysed and studied in this paper. The error between the representative indentation stress from spherical indentation and the theoretical stress of the power exponential equation was taken as the convergence condition using the optimization function in Matlab. The yield strength, strain hardening index and elastic modulus were optimized between the stress-strain curve from spherical indentation and the theoretical stress-strain curve of the power exponential equation. The smallest error that could be achieved between them was obtained and from this the mechanical properties of the material could then be calculated and analysed. Q345R steel, which is used for pressure vessels, was taken as an example and the mechanical properties were tested using the spherical indentation test, and the results were compared with the conventional tensile test. Comparative analysis of the mechanical properties of the steel between the results from the spherical indentation test and the conventional tensile test showed that the difference was small. The accuracy of the spherical indentation method when testing the mechanical properties of metallic materials is high. The results have shown that the spherical indentation test can be used as a replacement for the conventional tensile test and can be applied in the field of testing the mechanical properties of Q345R steel for pressure vessels.

1. Introduction

The safety of industrial equipment during its operation is very important, but there has always been a bottleneck in ascertaining the material properties that affect the safety assessment of industrial equipment. Usually, it is only after pressure vessel equipment is in service that it can be regularly checked for defects. Samples of the material are required for conventional testing of the mechanical properties and it is difficult to test its mechanical properties by conventional methods while in situ.

Instrumented indentation testing technology is a new technology to test the mechanical properties of materials, which was developed on the basis of the traditional Brinell hardness test. The indentation method obtains the mechanical properties of materials, such as the elastic modulus, the yield strength, the tensile strength and the Brinell hardness, by simultaneously measuring and recording the load and displacement curves during the indentation process. This technology is known as a material’s mechanical properties probe [1].

The indentation method has many advantages, such as utilizing compact and portable equipment, which can be used in the field to directly test a material’s mechanical properties; it can be used to test in-service equipment; the test site is small, which can be used to determine the local characteristics of...
the materials; the indentation method determines the mechanical properties of materials using a load-depth curve, and does not require the use of optical microscopy to measure the indentation.

Tabor first proposed the formulas for calculating stress and strain based on the indentation method in 1951, and also used the indentation method to test the tensile properties of metals [2]. In the 1980s, Haggag et al established a method of calculating the tensile properties of a material without the need to measure the indentation diameter, based on automatic collection of the load and displacement. Many studies have been conducted to calculate the tensile properties of materials by automatically collecting data from displacement and load sensors [1-3]; to this end, various formulas can be used to calculate stress and strain. In this paper, automatic spherical indentation tests were carried out on Q345R steel and then the results were compared with the conventional tensile test; the method of obtaining the mechanical properties of Q345R steel using spherical indentation was also studied.

2. Experimental principles of the spherical indentation method

2.1. The spherical indentation test
The spherical indentation tester is driven by a motor which is loaded onto the spherical indentation head and then pressed vertically into the surface of the material. Load and displacement sensors are used to measure the load and displacement throughout the entire process, and from this the continuous indentation curve (load-displacement curve) for the indentation test process can be obtained. The load-displacement curve is then transformed into the stress-strain curve of the material, and the mechanical properties of the material, including the yield strength, tensile strength, elastic modulus, strain hardening index and strength coefficient can be obtained.

2.2. Load-displacement curve for spherical indentation
The deformation of the material that is caused during the indentation process includes both elastic deformation and plastic deformation. The extent of the elastic deformation can be calculated using the Oliver-Pharr method [4]:

\[ h_d = \omega \frac{F_{\text{max}}}{S} \]  
\[ h_d = \omega (h_{\text{max}} - h_r) \]  
\[ h^*_c = h_{\text{max}} - h_d \]  
\[ a^2 = 2Rh^*_c - h^*_c \]

where, \( F_{\text{max}} \) is the maximum load; \( h_d \) is the depth of the elastic deformation; \( \omega \) is the shape coefficient of the indenter; \( h^*_c \) is the depth when the pile-up or sink-in effect are not considered; \( h_{\text{max}} \) is the maximum depth; \( h_r \) is the intersection point of the tangent line of the unloading curve and the depth axis; \( h_p \) is the permanent indentation depth after the load has been removed; \( R \) is the radius of the spherical indenter.

Figure 1 has shown an illustration of a spherical indenter being pressed into a metal surface. The plastic deformation at the indentation is characterized by the pile-up or sink-in that occurs around the indentation. The extent of the pile-up or sink-in depends on the strain hardening index. The influence of the material’s pile-up or sink-in near the indenter should also be considered when calculating the contact radius, and various correction methods have been proposed that take the material pile-up or sink-in into consideration. Hill introduced dimensionless parameters in the literature in order to
consider the effect of the material’s pile-up or sink-in [5], which can be written as follows:

\[ c^2 = \frac{a^2}{a*^2} = \frac{5}{2} \left(\frac{2-n}{4+n}\right) \]  

(5)

\[ a^2 = \frac{5}{2} \left(\frac{2-n}{4+n}\right) \left(2Rh_c^* - h_c^*\right)^2 \]  

(6)

where, \( c \) is a dimensionless parameter; \( a^* \) is the contact radius without taking the pile-up or sink-in effect into consideration; \( a \) is the contact radius after taking the pile-up or sink-in effect into consideration; \( n \) is the strain hardening index.

Figure 1. Schematic representation of a ball indentation into a metal surface.

2.3. Stress in the spherical indentation method
In the case of complete plastic deformation, Tabor proposed that the equivalent stress of the indentation can be replaced by the average stress \( \sigma_r \), expressed by the load \( F \) and the contact area \( A \) [2], which can be written as:

\[ \sigma_r = \frac{1}{\Psi} \frac{F}{A} = \frac{1}{\Psi} \frac{F}{\pi a^2} \]  

(7)

where, \( \Psi \) is the plastic constraint factor, which is related to the extension of the plastic zone, i.e. the yield strain and strain hardening index of the materials. From the results of many studies, the plastic constraint factor was recommended to be \( \Psi=3 \) in the Dutch indentation guide in the literature [6].

2.4. Strain in the spherical indentation method
The earliest representative strain \( \varepsilon_r \) was obtained by Tabor using traditional optical techniques based on experience, as shown in equation (8), where the contact angle between the indenter and the specimen was \( \gamma \) and \( K = 0.2 \). The maximum strain value obtained by the strain expression is 0.2:

\[ \varepsilon_r = K \frac{a}{R} = K \sin \gamma \]  

(8)

Ahn and Kwon proposed the concept of shear strain at the contact edge of the indenter in the literature [7], which expanded the scope of the representative strain; the representative strain \( \varepsilon_r \) is defined as:
\[ \varepsilon_r = \alpha \frac{1}{\sqrt{1-(a/R)^2}} \frac{a}{R} = \alpha \tan \gamma \]  

(9)

where, \( \alpha \) is a material constant. The expression of the shear strain at the contact edge of the indenter has been demonstrated to be in good agreement with the experimental results.

2.5. Elastic modulus of the spherical indentation method

According to Sneddon's early research into the elastic contact system, the relationship between the elastic modulus and the elastic contact stiffness of metallic materials can be written as follows [8]:

\[ S = \frac{dF}{dh} = \frac{2}{\sqrt{\pi}} E_r \sqrt{A} \]  

(10)

\[ \frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i} \]  

(11)

where, \( S \) is the elastic contact stiffness; \( E_r \) is the reduced elastic modulus; \( A \) is the contact area of the indenter; \( E \) and \( \nu \) are the elastic modulus and the Poisson’s ratio of the materials being tested; \( E_i \) and \( \nu_i \) are the elastic modulus and the Poisson’s ratio of the indenters.

2.6. Stress-strain curve of the power exponential equation

In the uniform deformation stage, the plastic behavior of metals can be approximately described by the power exponential law. At present, a two-parameter power exponential equation is commonly used to describe the elastic-plastic properties of materials when testing them using the spherical indentation method. The yield strength of the materials \( \sigma_y \) is obtained from the point where the line of 0.2% strain intersects with the true stress-strain curve.

Dao et al. used a three-parameter modified elastic-plastic model to describe the true stress-strain curve [9], the specific formula of which can be written as follows:

\[ \sigma_r = \sigma_y \left(1 + \frac{E}{\sigma_y} \varepsilon_r\right)^n \]  

(12)

This equation is a three-parameter elastic-plastic equation for use with the spherical indentation method.

2.7. Tensile strength

The tensile strength \( \sigma_u \) is the maximum value that is reached in a stress-strain curve. Therefore, when the value of the true strain \( \varepsilon = n \), the stress that corresponds to the true stress is the tensile strength [10], which can be written as:

\[ \sigma_u = K \left( \frac{n}{e} \right)^n \]  

(13)

3. Computational method and flow chart

3.1. Analytical method

In this paper, the indentation test was carried out fifteen times and the cyclic curves of the stress and strain from the tests were obtained, including fifteen unloading points. Fifteen stress and strain points
from the spherical indentation were obtained, and then these points were fitted as stress-strain curves for the spherical indentation process. The theoretical stress-strain curve could be obtained using the theoretical power exponential equation.

The elastic modulus, the yield strength and the strain hardening index of the materials are unknown variables that must be solved. The trial and error method were used to optimize the selection, that is, to select a group of different parameters, and then compare the errors between the stress-strain curve of the spherical indentation test and the stress-strain curve of the theoretical power exponential equation [11]; theoretically the two curves should coincide. The combination of the parameters of the material that gives the smallest error is the actual performance parameters of the materials that need to be determined.

3.2. Optimization conditions
The three material parameters of the improved elastic-plastic model, namely the elastic modulus, the yield strength and the strain hardening index, are taken as unknown variables and can be solved using the optimization method [12]. The optimum condition that was adopted is where the sum of the square of the error between the stress from the indentation test and the stress from the theoretical power exponential equation has the smallest value, that is:

$$error = \min \sum_{i} [\sigma_i - \sigma_y (1 + \frac{E}{\sigma_y} \epsilon_i)^n]^2$$

(14)

4. Experimental results

4.1. Indentation curve test results
The load-displacement curve from the indentation test was acquired using an instrument indentation instrument. The maximum load of the instrument is 2000 N and the displacement precision is 0.2 µm. The indenter was a tungsten carbide ball with a diameter of 1mm, and the test material was Q345R steel.

Figure 2 has shown the multi-cycle load-displacement curve obtained from the test; there were 15 loading and unloading cycles.

![Figure 2. Multiple load-depth curve from the ball indentation test and the calculated curve.](image)

The optimized results of the stress-strain curve and the theoretical power exponential stress-strain curve for the spherical indentation have been shown in figure 3. The red line denotes the stress-strain
curve for the spherical indentation test and the blue line denotes the stress-strain curve of the theoretical power exponential law. The error between the spherical indentation stress and the theoretical stress was the smallest when the yield strength of the material was 381 MPa, the strain hardening index was 0.1421 and the elastic modulus was 210120 MPa which had been optimized using Matlab.

4.2. Comparison of the two methods

According to standard GB/T 228.1-2010 Tensile Tests of Metal Materials Part 1: Room Temperature Testing Method; uniaxial tensile tests were carried out using an electronic universal testing machine CMT5205. The material tested was Q345R steel for pressure vessels, which had been processed into standard specimens with dimensions of 10 mm × 50 mm.

Table 1 has shown the comparison of the results of the stress-strain method for spherical indentation and the uniaxial tensile test. The errors of the yield strength, the strain hardening index, the elastic modulus and the tensile strength between the two methods were small, and the accuracy of the measurement of the mechanical properties of the metallic materials using the spherical indentation method was high.

|                          | Uniaxial tensile test | Indentation test | Error   |
|--------------------------|-----------------------|-----------------|---------|
| Yield strength /MPa      | 380                   | 381             | +0.26%  |
| Tensile strength /MPa    | 549                   | 520             | -5.28%  |
| Strain hardening index   | 0.1335                | 0.1421          | +6.44%  |
| Elastic modulus /MPa     | 206420                | 210120          | +1.79%  |

5. Conclusion

- In this paper, three parameters, the elastic modulus, the yield strength and the strain hardening index, were automatically optimized using the optimization function in Matlab. The error between the stress from the spherical indentation test and the stress from the theoretical power exponential law was taken as the convergence condition. The mechanical properties of Q345R steel, such as the yield strength $\sigma_y$, 381 MPa, the strain hardening index $n$, 0.1421, the elastic modulus...
modulus $E = 210120$ MPa and the tensile strength $\sigma_u = 520$ MPa, were then obtained.

- The errors between the results from the spherical indentation method and the uniaxial tensile test were small and they were all less than 10% for all of the values investigated. The results showed that the accuracy of the spherical indentation method is high and meets the requirements of the field. Therefore, the spherical indentation method can be used to analyse the mechanical properties of Q345R steel for field testing in engineering.

Acknowledgments
This work is supported by the National Key Research and Development Program of China (No. 2017YFB0902100).

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