Calculating the Mechanical Properties of DX56 Steel by the Spherical Indentation Method

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Abstract. The mechanical properties of metal materials are studied by indentation method in this paper. The elastic-plastic curve of indentation experiment is obtained by fitting the representative stress and strain points, and the theoretical elastic-plastic curve is described by the power index equation of three parameters. After optimal coincidence of two curves, the yield strength, strain hardening index and elastic modulus of the material are obtained. Taking DX56 steel as an example, which has good deep drawing property for automobile, the mechanical properties of the steel are tested by indentation method and compared with the results of uniaxial tensile test. The error of tensile properties is small, so the indentation method can be used to detect the mechanical properties of metal materials.

1. Introduction
The conventional mechanical property test needs to destroy the materials and process them into standard samples. Testing the mechanical characteristics of materials using conventional methods in the field is difficult.

Test the load and displacement curve of the indenter during pressing into the sample by indentation method. The indentation method provides much more information than the traditional hardness test and can accurately and reliably evaluate the tensile properties of materials.

Indentation method has many advantages, which can directly evaluate the mechanical characteristics of materials in the field. It can also be applied for testing in-service equipment. This methods requires small areas for conducting tests and can be employed for the determination of the local properties of materials.

In 1951, Tabor applied indentation method to develop stress-strain calculation formula and tested the tensile properties of metal by indentation method [1]. Haggag and Kwon et al. developed a method to calculate the tensile characteristics of materials without measuring indentation diameter via automatic detection of displacement and load. Several research works have been carried out for the calculation of material tensile characteristics of through automatic collection of load and displacement data from relevant sensors [1-3]. Here, the indentation test of DX56 steel is carried out and the obtained data compared with those obtained from conventional tensile tests. The collection method of the mechanical characteristics of DX56 steel by spherical indentation is also investigated.
2. Experimental Principles of Spherical Indentation Method

2.1. Spherical Indentation Test
A motor drove the indentation test machine which was loaded onto spherical indentation head and vertically pressed onto material surface. Displacement and load were measured using relevant sensors and load-displacement curves were obtained for indentation test process. Through mechanical analysis method, the experimental load displacement curves were transformed into material stress-strain curves. Then, the mechanical properties of material, including elastic modulus, tensile strength, yield strength, and strain hardening index were achieved.

2.2. Load-displacement Curves for Spherical Indentation
Both plastic and elastic deformations occurred during the indentation process in materials. Oliver-Pharr method could be used for the calculation of elastic deformation [4]:

\[ h_d = \omega \frac{F_{\text{max}}}{S} \]  

\[ h_d = \omega (h_{\text{max}} - h_x) \]  

\[ h^*_c = h_{\text{max}} - h_d \]  

\[ a^2 = 2Rh^*_c - h^*_c \]  

where \( F_{\text{max}} \) is the maximum load; \( h_x \) is the depth of the elastic deformation; \( \omega \) is indenter shape coefficient; \( h_i \) is intersection point of depth axis and unloading curve tangent line; \( h_{\text{max}} \) is maximum depth; \( h^*_c \) is depth without taking into account sink-in or pile-up effects; \( h_x \) is the permanent indentation depth after removing load; and \( R \) is spherical indenter radius.

Indentation plastic deformations can be classified into sink-in or pile-up types which occur around the indentation. The amount of sink-in or pile-up depends on the index of strain hardening. When calculating contact radius, the effects of material sink-in or pile-up around indenter have to be taken into account and a variety of correction methods have been developed to consider these effects. Hill developed dimensionless parameters to take into account material sink-in or pile-up effects [5], which can be expressed as:

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

\[ a^2 = \frac{5}{2} \frac{2 - n}{4 + n} (2Rh^*_c - h^*_c) \]  

where \( n \) is strain hardening index; \( c \) is a dimensionless parameter; \( a \) and \( a^* \) are contact radii with and without taking into account sink-in or pile-up effects, respectively.

2.3. Stress in Spherical Indentation Method
Tabor suggested that, when there is a complete plastic deformation, average stress \( \sigma_t \) can replace equivalent indentation stress which is stated by contact area \( A \) and load \( F \) as:

\[ \sigma_t = \frac{1}{\Psi} \frac{F}{A} = \frac{1}{\Psi} \frac{F}{\pi a^2} \]
where Ψ is plastic constraint factor, which depends on plastic zone extension, i.e. material strain hardening index and yield strain. Based on several research findings, Dutch indentation guide suggested plastic constraint factor to be Ψ=3 [6].

2.4. Strain in Spherical Indentation Method
Tabor applied experience-based traditional optical techniques to obtain the first representative strain εr, as shown in equation (8), where K = 0.2 and γ is specimen-indenter contact angle. The maximum value of strain achieved by strain expression was 0.2:

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

(8)

Ahn and Kwon introduced the concept of indenter contact edge shear strain [7], expanding the scope of representative strain εr which is defined as:

\[ \varepsilon_r = \alpha \frac{1}{\sqrt{1-(a/R)^2}} \frac{a}{R} = \alpha \tan \gamma \]  

(9)

where α is a material constant. The equation of indenter contact edge shear strain complied well with experimental findings.

2.5. Elastic Modulus of Spherical Indentation Method
Based on Sneddon’s early studies on elastic contact systems, the relationship between elastic contact stiffness and elastic modulus in metallic materials could be stated as [8]:

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

(10)

\[ \frac{1}{E_r} = \frac{1}{E} + \frac{1}{E_i} - v^2 - v_i^2 \]  

(11)

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

2.6. Stress-strain Curve of Power Exponential Equation
Power exponential law can provide an approximate description on the plastic behavior of metals during uniform deformation stage. Currently, a two-parameter power exponential equation is generally applied to describe the elastic-plastic characteristics of materials when being tested by spherical indentation method. Material yield strength \( \sigma_y \) is calculated from the point at which the line of 0.2% strain intersects with true stress-strain curve.

Dao et al. employed a three-parameter modified elastic-plastic model to draw true stress-strain curve [9], using the following equation:

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

(12)

This is a three-parameter elastic-plastic equation and was employed by spherical indentation method.
2.7. Tensile Strength

Tensile strength $\sigma_u$ is the peak value of stress-strain curve. Hence, when true strain value was $\varepsilon = n$, the value of stress corresponding to true stress was equal to tensile strength [10] and was stated as:

$$\sigma_u = K \left(\frac{n}{\varepsilon}\right)^n$$

(13)

3. Analytical and Optimization Method

3.1. Analytical Method

Here, 15 cyclic indentation tests were conducted and strain and stress cyclic curves were drawn using test results obtained from 15 unloading points. There were 15 unloading points in stress-strain curve and 15 stress-strain points were obtained. Theoretical stress-strain curves were drawn based on the theoretical power exponential equation.

The values of strain hardening index, yield strength and elastic modulus of materials were unknown and had to be calculated. Trial and error method was employed for the optimization of selection process; i.e. for the selection of a group of various parameters and comparison of the deviations between the stress-strain curves obtained from theoretical power exponential equation and spherical indentation tests [11] which, theoretically, have to coincide. The combination of material parameters with the smallest error was considered as the actual material performance parameters that needed to be determined.

3.2. Optimization Conditions

Elastic-plastic curves of indentation experiments were obtained by fitting the representative stress and strain points. The theoretical elastic-plastic curves were described by the three parameter power index equation. The three material parameters of elastic-plastic model, i.e. strain hardening index, yield strength and elastic modulus, were considered as variables and the two curves were optimized [12]. The optimal condition is that the deviation between theoretical power exponent stress and indentation test stress was the smallest, that is:

$$\text{error} = \min \sum_i \left[ \sigma_i - \sigma_y \left(1 + \frac{E}{\sigma_y} \varepsilon_i\right)^n \right]^2$$

(14)

4. Experimental Results

4.1. Indentation Curve Test Results

Load-depth curves were drawn based on indentation test results obtained from an indentation instrument. Displacement precision was 0.2 $\mu$m and maximum instrument load was 2000 N. A tungsten carbide ball with diameter 1mm was used as indenter and test material was DX56 steel.

The experimentally obtained multi-cycle load-displacement with 15 loading and unloading cycles is shown in Figure 1.
Figure 1. 15-cyclic load-depth curve from the spherical indentation test.

Figure 2 shows the optimized results of spherical indentation and theoretical power exponential stress-strain curves. In the figure, blue and red lines represent stress-strain curves drawn based on theoretical power exponential law and spherical indentation test results, respectively. The deviation between theoretical and spherical indentation stress was the lowest when the values of material yield strength, strain hardening index and elastic modulus after optimization were 152 MPa, 0.2189 and 150960 MPa, respectively.

![Stress-strain curve at Evals = 290](image)

Figure 2. Fitting curve for representative stress-strain points and the theoretical power exponential stress-strain curve values.

4.2. Comparison of Spherical and Uniaxial Tests

Based on standard GB/T 228.1-2010 Tensile Tests of Metal Materials Part 1: Room Temperature Testing Method, uniaxial tensile tests were conducted by an electronic universal testing machine CMT5205. Test material was DX56 steel with thickness 2.3 mm, which is processed into a plate-like
tensile sample.

Table 1 compares the results obtained from uniaxial tensile tests and stress-strain method for spherical indentation. There were small deviations in the values of tensile strength, elastic modulus, strain hardening index and yield strength between the two methods and high measurement accuracy was obtained by spherical indentation method for the mechanical characteristics of metallic materials.

|                        | Uniaxial tensile test | Indentation test | Error  |
|------------------------|-----------------------|------------------|--------|
| Yield strength /MPa    | 149                   | 152              | +2.01% |
| Tensile strength /MPa  | 285                   | 302              | +5.96% |
| Strain hardening index | 0.246                 | 0.2189           | -10.59%|
| Elastic modulus /MPa   | 150000                | 150960           | +0.64% |

5. Conclusion
In this paper, three parameters of elastic modulus, strain hardening index and yield strength were optimized using the optimization function. The convergence condition was the deviation between theoretical power law stress and spherical indentation stress. The obtained mechanical characteristics of DX56 steel, included strain hardening index $n=0.2189$, tensile strength $\sigma_u=520$ MPa, yield strength $\sigma_y=152$ MPa, and elastic modulus $E=150960$ MPa.

The deviation between the results obtained from uniaxial tensile and spherical indentation tests was relatively small, especially tensile and yield strength values. Spherical indentation method has high precision and can be applied to analyse the tensile characteristics of DX56 steel.

6. References
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