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Influence factors in small punch test to estimate the yield strength by energy method

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Abstract. In this study, an elastic deformation energy method based on small punch test (SPT) for the yield stress estimation is presented. The area beneath the load-displacement (L-D) curve in the elastic deformation domain is measured for examining the yield strength. The elastic deformation domain included at elastic deformation initiation is defined as elastic reverse displacement during an unloading stage. A finite element model (FEM) for SPT specimen ductile damage numerical analysis is established. SPT is carried out on SUS304 with small disks, 10 mm in diameter and 0.5 mm in thickness, in room temperature. The correlation between the yield strength of SUS304 and the elastic deformation energy is verified, and the effects of geometrical factors (ball diameter, diameter of lower die and sample thickness) on SPT are analyzed by finite element analysis. The research shows that the geometrical factors dominate the elastic deformation energy, and an optimal geometrical relation among the three factors is proposed. The yield stress attained from simulation result has a good agreement with the true one. The acquired results will conduct the future development of SPT energy method to predict the yield strength.

Key words. Elastic deformation energy, small punch test, finite element model, influence factor; energy method.

1. Introduction

Plenty of damage of metallic materials such as creep deformation, eroding and thermal aging would induce the failure of steam power plants. The mechanical properties degradation of materials will cause unpredictable disasters, which requires careful attention and monitoring overtime. But the conventional tensile test would cause damages to in-service components because of the big samples size needed. Compared with tensile test, SPT is a new method to measure the performance of

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steels, which use small scale specimens extracted from components in-service [1].

As a novel testing technique, SPT was first proposed by Okada et al. [2]. For the past two decades, the small punch test has been used successfully to characterize the mechanical strength, impact toughness, fracture property and creep property of materials with specimens measured only $0.1 - 0.5$ mm in thickness [3], [4]. Small punch test has been adopted successfully in the fields of nuclear power, aviation, space flight and petrol-chemical industries. The test materials included metal, mineral [5], composite [6], coating [7], weld zone [8], etc.

Mechanical properties are analyzed by the SPT L-D curve gained from the initiation deformation to the final rupture. SPT possesses the merits of sample testing on almost nondestructive and economical, preserves the advantages and get rid of the disadvantages of the conventional examining method. Yield strength and tensile strength have been confirmed by the SPT in recent research. The estimated value of tensile strength is close to the true value of the plants, but the examining yield strength is not accurate comparing with that in the tensile strength testing. The main reason causing the inaccuracy of yield strength examining in SPT is the large deviation of the yield load confirming in the conventional method (two tangents method [9] and offset method [10]). Determining the yield load by the two tangents method and the offset method mostly depends on the experience of handlers plotting lines [11]. It is unrealistic to think that every engineer can get the same yield load [12]. The yield load is a crucial parameter to determine the yield strength, so the inaccurate yield load will cause the inaccuracy yield strength. As a new way to evaluate the yield strength, the elastic deformation energy method is proposed in order to improve the precision of yield stress and get a good agreement with the true value. In this paper, the energy method was employed to estimate the yield strength of metallic materials. The influence factors in SPT have been investigated and the Finite Element Modeling was used as the simulation tests to assist the analysis.

2. Experimental part

2.1. Experimental part

This test focuses on SUS304 under Chinese standard, which is commonly used in the steam power plants and pressure vessels. The chemical composition of the material examined here is showed in Table 1, and the mechanical properties are showed in Table 2. The specimens are prepared by metal wire-electrode cutting to obtain rough discs of 10 mm in diameter and 0.65 mm in thickness in the first procedure. Secondly, the two sides of the sample have been polished by 1000 papers grade up to the final thickness of $0.5\,\text{mm} \pm 0.2\,\mu\text{m}$. It is recognized that using small specimen to examine the mechanical behavior can induce a scattering in the result owing to a large size of micro structural constituents relative to the size of the specimen.

Table 1. Chemical compositions of S30403 (wt%)

Composition	C	S	Mn	P	Cr	Ni	Si
Content	0.05	0.019	0.81	0.025	17.81	8.50	0.47

Table 2. The mechanical properties of SUS304

Young's Modulus E, GPa	Poisson's Ratio ν	Yield Stress σ_{s}, MPa	Ultimate Stress σ_{b}, MPa
199	0.285	286	668

2.2. Experimental details

The SPT is carried out with a constant low speed (0.5 mm/min) on INSTRON-5869 at room temperature (20 °C). Figure 1 is the schematic diagram of the SPT device. The procedure of SPT is described as follows: firstly, put a polished disc specimen into the concave whose dimension is $\oslash 10\,\mathrm{mm} \times 0.5\,\mathrm{mm}$ and depth is $2\,\mathrm{mm} \pm 0.1\,\mathrm{mm}$ in the center of the lower die; Secondly, the upper die and the lower die are joined together with the screw-thread on the interface between the upper die and lower die. The upper die is designed as a hexnut. It is easy to determine the pressure on the specimen by examining the arm of force on the upper die when assemble the two dies together. Finally, place a small steel ball 2.4 mm in diameter into the 2.5 mm diameter hole through the upper die and put the punch insert the same hole, until constrain the ball in the hole. During the test a constant velocity was applied to the punch (the same to the ball) by the INSTRON test machine, the L-D curve is obtained in the end of the test.

2.3. Energy method

By the deformation of specimen, the process of SPT can be divided into four distinct stages as follows [13], [14] elastic bending deformation, plastic bending deformation, membrane stretching and plastic instability. From the beginning of SPT to the end of the elastic bending stage, the elastic deformation increases with the accumulated elastic energy which can be taken as the area under the L-D curve in the elastic bending stage. From the SPT elastic deformation and the SPT plastic deformation points of view, the elastic deformation energy (EDE) increases with the punch displacement during the elastic stage, and remain constant when the test completely enter the plastic bending stage. The accumulated energy value is involved in the elastic behaviors of the materials and stored in the specimen until unloading in the plastic bending domain. When the test experiences an unloading process during the plastic bending stage, the elastic energy will release with the specimen rebounding, and it is effective to calculate EDE by the rebounding displacement integral of the load in the elastic bending stage. The procedure can be expressed as Fig. 2. Thus the correlation can be established between the yield strength and the EDE generating during the elastic bending deformation stage. The analytical relation has been proposed by Isselin et al. as follows [15]

$$\text{energy} = \sigma_{\mathrm{s}}^2 \times \frac{2\left(1-\nu^2\right)a^2 t_0}{3E\pi\left(1+\nu\right)^2}, \tag{1}$$

where a (mm) is aperture of the lower die, t_0 (mm) is thickness of specimen, E (MPa) is Young's modulus, ν is Poisson coefficient. According to the former information, energy method is used to evaluate the yield strength of SUS304 in present paper. This evaluation is based on the measurement of the energy plastically deformed completely.

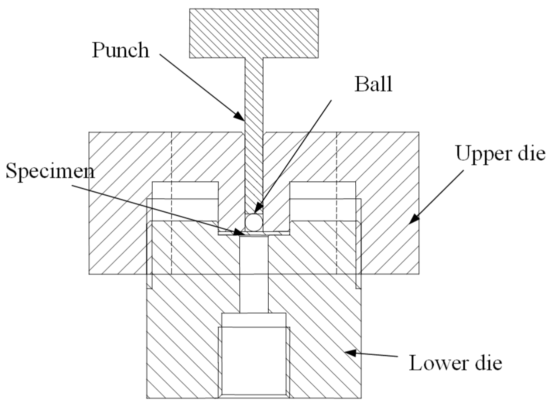

Fig. 1. Schematic diagram of the SPT device

2.4. Finite element modeling

In this simulation, the ball has been considered as rigid body and the sample as elastic-plastic material. Because of the symmetry of the problem, a two dimensional FEM model is adequate to duplicate the process of the test, so the specimen, ball and other boundary conditions are axisymmetry. The information of the true stress and true plastic strain needed in the FEM is obtained from the tensile test. According to the actual experimental condition, the upper die and the lower die are simplified as the supported constraints which applied to the both surfaces of the sample restricting the degree of freedom in thickness direction. The friction coefficient between the sample and the tools has been fixed at value which equals 0.3. The element type is bilinear axisymmetric quadrilateral, reduced integration, hourglass control (CAX4R). FEM software ABAQUS-Explicit with progressive damage and failure modeling method is used to simulate the SPT process. Figure 3 is the illustration of the finite element model.

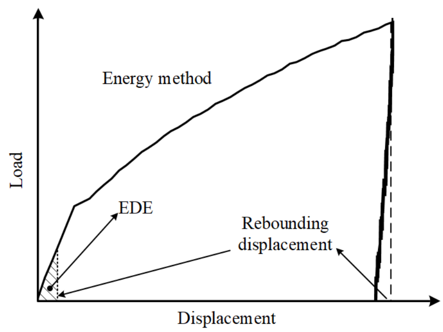

Fig. 2. Energy method

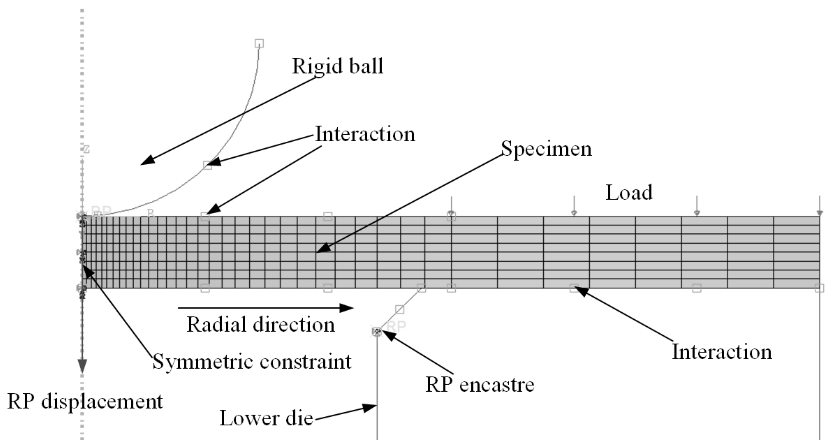

Fig. 3. Finite Element Model

3. Result and discussion

3.1. L-D curves comparison between the experiment and simulation

The L-D curves of SPT and simulation are drawn in Fig. 4. It is obviously that the curves from experiment and simulation have a good agreement in the elastic bending stage and the plastic bending stage. Because of the undifferentiated curves, it strongly proves the validity of the former FEM reproducing the condition of elastic deformation and elastic energy. In membrane stretching and plastic instability stages, the difference between experimental curve and simulation one is attributed to the initial slight misalignment of the whole experimental set-up and isotropic assumption in FEM, respectively.

3.2. Difference factors influence

Zhou and Ling [1] claim that small differences in ball diameter, lower die diameter and specimen thickness will cause the deviation of L-D curves. But, how about the three factors influences the Energy-Displacement curve and EDE are not clear.

3.2.1. Influence of ball diameter

In order to inspect the effect of ball diameter, lower die diameter 4 mm, specimen thickness 0.5 mm and ball diameter ⌀ 2.0 mm, ⌀ 2.2 mm, ⌀ 2.4 mm, ⌀ 2.6 mm are carried out in the FEM, and the result is showed in Fig. 4. The illustration shows that the energy increase with the raise of punch displacement during the elastic bending stage, and stand as a constant in the plastic bending stage. When the test go into the membrane stretching stage, the energy increase rapidly owing to more parts of the specimen start to elastic deformation, and more new elastic energy is storing in the disc. Because the elastic deformation energy we pay attention to only generate in the initial stage of SPT, the new incremental energy cannot be recognized as the EDE. Figure 5 shows that different ball diameters in the SPT don't affect the EDE (from the start of elastic bending stage to the end of plastic bending stage) obviously. In the whole process of the SPT, due to the complicated stress and strain distribution, it is difficult to indicate the explicit boundary between elastic bending stage and plastic bending stage in the L-D curve, and the same as the plastic bending stage and membrane stretching stage. For this reason, none specific point in the Energy-Displacement curve can be taken as the final of EDE. Fortunately, we can get the EDE by calculating the mean value from the horizontal curve (e.g. Fig. 5, displacement from 0.6 mm to 1.2 mm). Using the EDE obtained from Energy-Displacement of different ball diameter, the yield strength of the SUS304 has been calculated by formula (1), showed in Table 3. We can see that the estimated yield strength in small ball is closer to the true value compared with the big ball.

3.2.2. Influence of lower die diameter

The lower die diameter is a significant parameter in SPT. Compared with the small die diameter the large die diameter will induce the L-D curve to shift to the left. Then, the Energy-Displacement curve will change with the die diameter change. In order to find out the influence on the energy, ball diameter ⌀ 2.4 mm, specimen thickness 0.5 mm and die diameter ⌀ 4 mm, ⌀ 5 mm, ⌀ 6 mm, ⌀ 7 mm are applied in the FEM. Figure 6 describes that the Energy-Displacement curve shifts upwardly with the lower die diameter increasing, and the horizontal curve stage increases with the die diameter growing. The length of the horizontal curve is important to the evaluation of EDE: At first, it is unreliable to obtain the EDE from a short mild curve, because the indefinite boundary of elastic bending and plastic bending stage is expressed as the mild curve. If the mild curve is too short, the curve will be

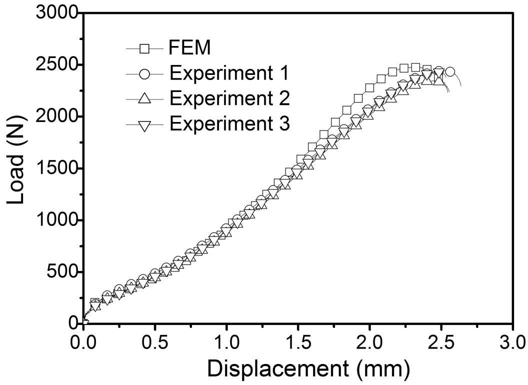

Fig. 4. L-D curves from experiment and FEM simulation

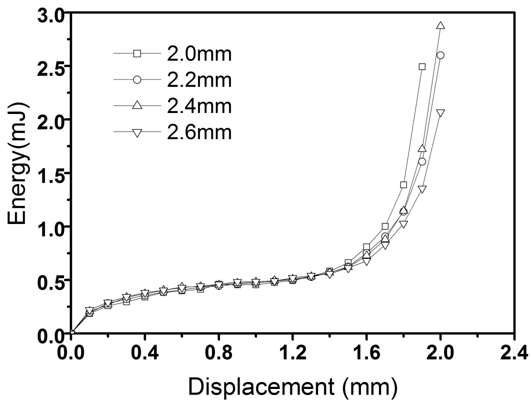

Fig. 5. Energy-Displacement curve with different ball diameter

not level enough (e.g. Fig. 6, die diameter in 4 mm). The EDE identified as the mean value of the energy in the mild curve will be suspicious. For second, longer horizontal curve means longer time of SPT. It is not necessary to obtain a too long horizontal curve by adding the test time. In conclusion, the elastic deformation or EDE is increased with the growth of die diameter. Using the EDE calculated from different die diameters, we obtain the yield strength of the SUS304 by formula (1). Table 3 indicates that the evaluated yield strength of large low die is closer to the true value compared with the small die.

3.2.3. Influence of the specimen thickness

The thickness of disk is a main geometrical parameter to describe the specimen. In previous research, the L-D curve shifts upwardly with the specimen thickness

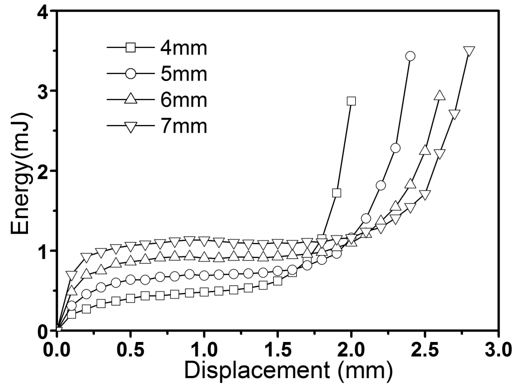

Fig. 6. Energy-Displacement with different lower die diameter

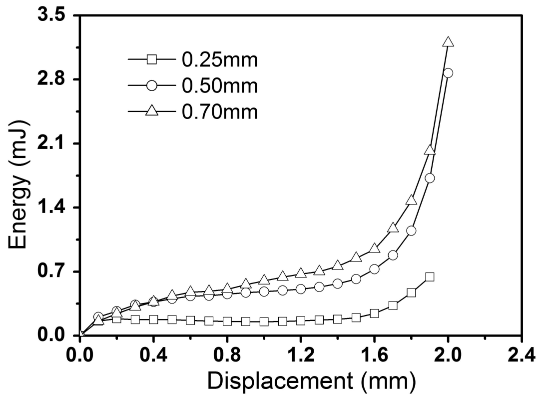

Fig. 7. Energy-displacement with different thickness of specimen

increasing. For the purpose of inspecting the influence of the specimen thickness, ball diameter $\varnothing$ 2.4 mm, specimen die diameter $\varnothing$ 4 mm and disk thickness 0.25 mm, 0.5 mm, 0.7 mm are applied in the FEM. From Fig. 6 we can see that the Energy-Displacement curve shifts upwardly with the specimen thickness increasing, that is to say, EDE increase with the growth of specimen thickness. However, Fig. 7 also indicates that the slope of the mild curve increases with the incrassation of specimen (e.g. thickness 0.7 mm). Using the EDE obtained from Energy-Displacement of different ball diameter, the yield strength of the material has been calculated by formula (1), the result is figured out in Table 3, and the mild curve of specimen thickness 0.7 mm is not level enough to calculate the mean value of energy, so there is no value about thickness 0.7 mm in Table 3. We can find that the calculated yield strength by thin specimen is closer to the true value than that by the thick specimen.

Table 3. The estimated yield strength of different factors (true yield strength is 286 MPa)

Factor	Ball diameter (mm)				Die diameter (mm)				Specimen thickness (mm)		
Level	2.0	2.2	2.4	2.6	4	5	6	7	0.25	0.5	0.7
Energy (mJ)	0.4548	0.4708	0.4816	0.4908	0.4816	0.7043	0.9262	1.1357	0.1852	0.4816	/
Yield strength (MPa)	309.5	314.9	318.5	321.6	318.5	308.2	294.5	278.1	279.4	318.5	/

4. Conclusions

In this study, SPT on SUS304 with small disk is performed. Meanwhile, in order to reproduce the process of SPT, a FEM is established and has a good agreement with the actual SPT. The influences of three factors (ball diameter, diameter of lower die and sample thickness) on estimating the yield strength by elastic deformation energy method is discussed by FEM. The results are summarized as follows:

1. Different ball diameters in the SPT don't affect the Energy-Displacement curve and EDE (from the start of elastic bending stage to the end of plastic bending stage) obviously. The estimated yield strength in small ball is closer to the true value compared with the big ball.

2. The elastic deformation or EDE is increasing with the growth of die diameter. The estimated yield strength of large die diameter is closer to the true value compared with the small die diameter.

3. The Energy-Displacement curve shifts upwardly with the specimen thickness increasing, that is to say, EDE increases with the growth of specimen thickness. The calculated yield strength by thin specimen is closer to the true value than that by the thick specimen.

4. To sum up, we can get more accurate yield strength from small ball, large die diameter and thin specimen. In other words, increasing the space between the under surface of specimen and the lower die could improve the precision of the evaluated yield strength. In this paper, the proposed geometric relationship among the three factors could be expressed as follows:

$$a \approx 2d + 4t\,, \tag{2}$$

where a (mm) is the lower die diameter, d (mm) is the ball diameter, and t (mm) is the specimen thickness.

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