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Yield Strength Analysis by Small Punch Test Using Inverse Finite Element Method

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Abstract

Considering the change of material behavior in in-service component due to temperature, loading and irradiation, several micro-specimen techniques have been proposed to describe deformation and fracture behaviors of materials under different conditions. This paper investigates the mechanical characterization of materials by the experimental and numerical method of small punch test. A two-dimensional finite element model was established to simulate the deformation behavior of X80. The resulting Load-Displacement curve contains key information about the mechanical properties of the tested materials. Thus, an application of inverse finite element method was used in the investigation of mechanical properties of materials which have been tested by small punch test. The difference between experiment and simulation curves was defined as objective function based upon the calculation model established by ABAQUS and MATLAB procedure. Finally, the estimated results suggested confidence in the analysis of the inverse finite element method for material's yield strength.

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Keywords: Small punch test; Yield strength; Inverse finite element method

1. Introduction

The reasonable description of mechanical behavior of critical components under severe conditions, such as elevated temperature, high pressure and irradiation, constitutes a prerequisite for avoiding material failure in many industries. However, it is formidable to evaluate the degraded properties of components under extreme conditions by standard method because this requires large volume of materials and means destruction of components. Compared to

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the traditional test, miniature specimen test allows extracting specimens from in-service structure, welding and treated surface to obtain information on the impact of the loading, oxidation and irradiation conditions. The use of small punch test (SPT), which is economical and nearly non-destructively, is a novel way to describe the key parameters of in-service component.

Over the last decade, numerical studies have been carried out for evaluating mechanical properties and creep life of materials [1-3]. Giddings et al. [4] applied small punch test in the investigation of elastic modulus and fracture behaviors of Polymethylmethacrylate. Based on the fracture energy calculated by Load–Deflection curves, Dobes et al. [5] showed that small punch test could be a validity method to assess the ductile-to-brittle transition temperature. Due to this diversity, investigation on the evaluation methodology of small punch test is extremely important. These empirical formulas provide an appropriate way to describe the macroscopic behavior of materials. Nevertheless, these and similar correlations rely on the accurate acquisition of tensile and fracture properties values which will limit the further application.

Along with the rapid development of computer science, numerical computing technologies were developed to analyze the complex deformation behavior of small punch test. Abendroth et al. [6,7] trained neural networks using Load-Displacement curves calculated by finite element simulations in order to predict the fracture and damage parameters. Feng et al. [8] described a similar approach to ensure creep properties with neural networks. The advantage of this method is that it can provide accurate performance parameters through analysis of test curves, which is convenient and rapid.

Different to neural networks which learn and recognize material parameters by a large number of data, inverse numerical model is another powerful tool to estimate parameters truly using calculated curves to approximate the experimental results. Although this method is still at its preliminary stage, it has been proved to be a significant attempt. In the present study, the mechanical properties of X80 have been investigated based on experimental investigation and numerical simulation. A finite element model was established to simulate the fracture and deformation behavior of small punch test. After the verification of rationality and veracity of model, the yield strength was determined by using inverse finite element model and Load-Displacement curves. In order to optimize the prediction model, golden section method was chose. The calculated value was in good agreement with the conventional experimental results.

2. Experimental Methods

All the experiments in this paper were carried out on the INSTRON machine with self-designed fixtures. In order to ensure the surface roughness, the specimens were machined and polished to Φ10 mm×0.5±0.02mm firstly. Then the upper and lower dies are applied to fix the location of disks as shown in Fig. 1 [9]. The dimension of receiving hole in lower die is 4mm and the diameter of ball is 2.4 mm. During the test, a constant speed was used here to press the specimen through the punch and ball. Meanwhile, the Load-Displacement curves were monitored and recorded for analyzing the material properties.

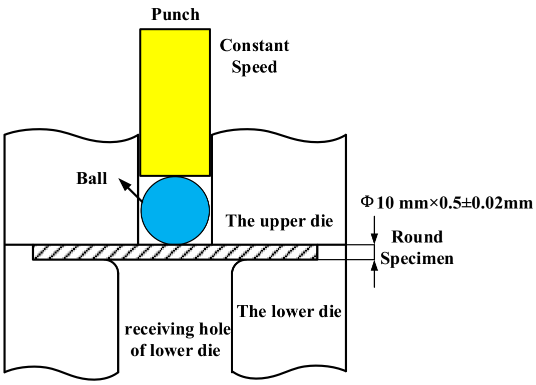

Fig. 1. Schematic diagram of small punch test.

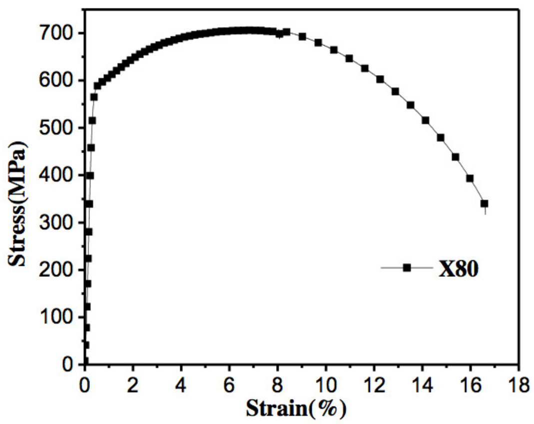

Fig. 2. Conventional tensile testing curve of X80.

In order to verify the results of small punch test, mechanical properties of X80 were also analyzed by the traditional tensile tests. The tensile curve is shown in Fig. 2 and the results are summarized in Table 1.

Table 1. Mechanical properties of X80 at room temperature.

Elastic Modulus *(MPa)*	Poisson' ration	Yield Strength *(MPa)*	Ultimate tensile Strength *(Mpa)*
206000	0.3	587	704.87

3. Modeling Study

3.1. Small punch test model

In the present work, the finite element simulation was performed to predict the deformation behavior of small punch test and used to obtain load-displacement data for inverse analysis. An important feature of small punch test is the symmetry of deformation and damage evolution process. For this reason, a two-dimensional axisymmetric finite element model was established as shown in Fig. 3 [10]. The ball, upper die and lower die were modeled as rigid bodies. The specimen was meshed uniform with a reasonable mesh size in order to save computational time. Meanwhile, fine element was defined in the thickness direction, according to preliminary investigation of large deformation process [11].

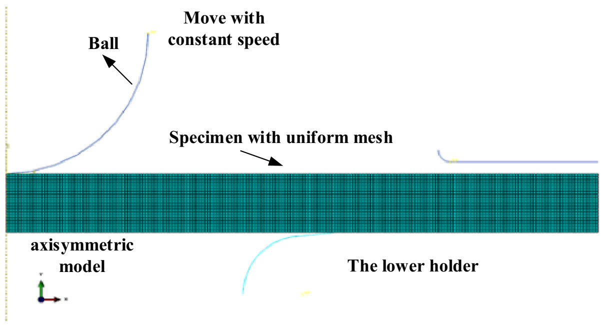

Fig. 3. Finite element model of small punch test.

3.2. Inverse finite element model

Different to the previous researches, the Load-Displacement curves predicted with different parameters here were applied to approximate experimental result. The difference between experiment and simulation curve was set as objective function:

$$f = \int_0^D \left| f^{EXP}(D) - f^{FEA}(D) \right| d(D) \tag{1}$$

Where D is the displacement, $f^{EXP}(D)$ is the Load- Displacement curve function of experiment, $f^{FEA}(D)$ is the curve function of experiment.

As an effective region elimination method [12], golden section search algorithm to be used for the determination of a signal parameter has been introduced in this study. The main idea behind this search algorithm is that a golden ratio of the major subsegment to the minor part, which has been found in a large number of structures [13]. As an effective technique for finding a minimum value of objective function by narrowing the range of calculation, the Schematic diagram of golden section is shown in Fig. 4.

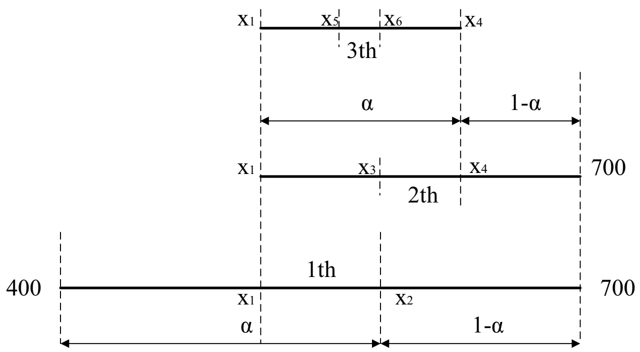

Fig. 4. Search interval[13].

Based on the search algorithm and finite element analysis, a calculated model combined MATLAB and ABAQUS was adopted as core idea in order to complete the iterative computations.

4. Results and Discussion

4.1. Load-Displacement curves

Typical examples of the Load versus Displacement curves of small punch test measured on the X80 are given in Fig. 5. It can be seen that the over shape of three curves is similar to each other, which proves the veracity and repeatability of small punch test in this paper. The similar trend can also be found in the curves of finite element simulation (Fig. 6). At high-load region, there is distinct difference between experimental and numerical curves. This is because of the stress concentration and local damage in this phase with large deformation. Meanwhile, as a multi-axial stress state, the isotropic assumption will lead to the inaccuracy in the prediction of plastic instability phase. It is worth to be noted that there are only fine difference in the elastic deformation and plastic deformation ter processed by LSP, which implies the welding tensile residual stress can be modified and changed into s can be calculated by the transition value from elastic phase to plastic phase [14-16]. Thus, this model established here is rational which can be used to analyse the yield strength of X80 accurately.

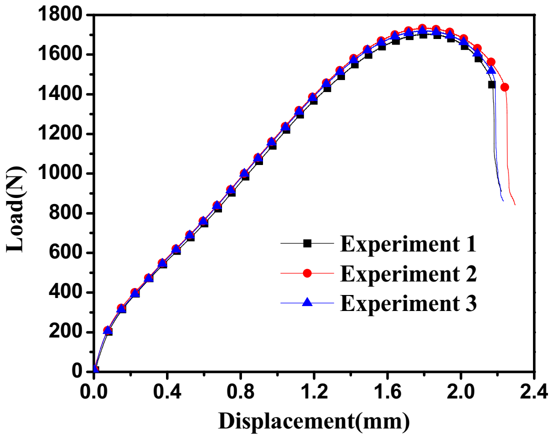

Fig. 5. Load-Displacement curves of X80.

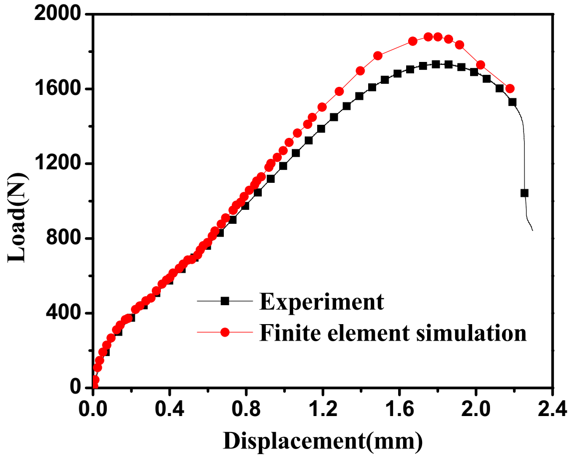

Fig. 6. The comparison of the experimental and simulation curves of X80.

4.2. Optimization of yield strength

The flow chart of optimization is shown in Fig. 7. In line-search optimization, an original range is need for searching a local minimum point [13]. Without loss of generality, the range [400,700] is set as search interval in this paper. In the golden search algorithm, the α is 0.618 [17]. Finally, the calculation terminates when the range is less than the set value (0.1).

The Optimization result of yield strength is indicated in Table 2. It is distinct that there is deviation between results of inverse finite element analysis and tensile test. This is because of the effect of complex stress state on the deformation behavior of small punch test, which is different from conventional tensile test under uniaxial stress[18,19]. Another reason is that the predicted curve of finite element simulation is not able to entirely overlapped, the slight misalignment between curves will lead to the apparent error of prediction. Overall, the predicted model created in this study is reasonable and accurate, which can be used to analyze the mechanical properties of materials based on small punch test.

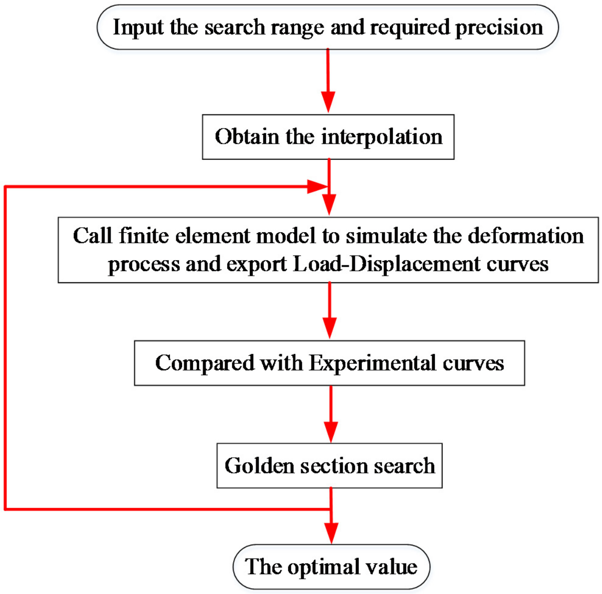

Fig. 7. Flow chart.

Table 2. Optimization value of yield strength.

Material	Optimization value *(MPa)*	Results of tensile test *(MPa)*	Erroe *(%)*
X80	520.1	587	11

5. Conclusion

In this study, an inverse finite element technique based on small punch test was used to evaluate yield strength of X80. The experiment investigation of mechanical properties of X80 was accomplished by tensile test and small punch test. Meanwhile, a two dimensional finite element model was established and the Load –Displacement curves of model was compared with the experimental results. It was proved that there was a good agreement between experimental and simulated data, especially in the elastic and plastic deformation phase. Then, a optimize procedure was used in order to obtain the exact value. Considering the computational efficiency with data as few as possible, golden section search algorithm was introduced as core idea. Ultimately, the yield strength of X80 was predicted by experimental data and inverse finite element model successfully. Compared to the results of conventional tensile test, the veracity of model was verified and the error was discussed.

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