Results in Physics 11 (2018) 440–448

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp

Construction of whole stress-strain curve by small punch test and inverse finite element

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ARTICLE INFO

Keywords:
Small punch test
Inverse finite element
Tensile model
Damage model
Whole stress-strain curve

ABSTRACT

Small punch test is applied to estimate mechanical properties and damage evolution by a miniature specimen. Combining small punch test and inverse finite element, the elastoplastic parameters in Hollomon model and damage parameters in Gurson-Tvergaard-Needleman (GTN) model were identified by the undamaged and damaged stages of the load-displacement curve. Then, the whole stress-strain curve of 316L austenitic stainless steel was constructed based on finite element simulation of a tensile specimen considering the constructed Hollomon model and GTN model. To validate the constructed whole stress-strain curve, standard tensile test was performed as a control group. The result demonstrates that the constructed stress-strain curve is in agreement with the experimental data obtained by standard tensile test. Finally, the plastic damage distribution and fracture mechanism of the miniature specimen were analyzed to understand the damage evolution of small punch test.

Introduction

Small punch test was first proposed to determine the postirradiation mechanical behavior of 316 stainless steel for in-service equipment in 1981 [1]. Due to small punch test requiring miniature specimen with a diameter of 3–10 mm and a thickness of 0.25–0.5 mm [2], the experimental technique has promising applications in some situations like in-service component and weld joint [3–5]. But small punch test is different from standard tensile test, it can obtain load-displacement curves rather than uniaxial stress-strain curves [6,7]. Therefore, researchers [8,9] studied the relationship between small punch test and standard tensile test. Rodríguez [8] found that the empirical equations obtained by small punch test could predict yield strength and ultimate tensile strength of the welded area for metal materials. García et al. [9] used the empirical equations established by small punch test to evaluate yield strength, ultimate tensile strength and fracture toughness of different steels and alloys.

With the progress of computer technology, finite element simulation is developing to evaluate the mechanical behavior of materials, especially in prediction of weld residual stresses [10] and calibration of plastic and damage parameters [11–13] from a load-displacement curve. Madia et al. [11] used small punch test and numerical analysis to evaluate the tensile and damage behavior of 1CrMoV aging steel. Yang et al. [12] investigated the mechanical characterization of X80 steel by small punch test and inverse finite element. Egan et al. [13] obtained the relationship between stress and strain of annealed steel by combining small punch test with inverse finite element. In addition, Cai et al. [14,15] constructed uniaxial stress-strain constitutive relationships based on the coupling methods of small sample test and finite element simulation. Researchers [11–13] obtained the tensile properties, damage parameters and partial stress-strain relationship of materials by small punch test and finite element simulation. However, there are few studies about obtaining the whole stress-strain curves of materials by small punch test. The whole stress-strain curve can comprehensively reflect the mechanical properties, damage evolution and failure process of materials. Thus, it is of great significance for small punch test to obtain the whole stress-strain relationship.

In this work, the elastoplastic parameters and damage parameters of 316L austenitic stainless steel are determined by small punch test and inverse finite element. Then, the whole stress-strain curve is obtained based on finite element simulation considering the constructed Hollomon model [16] and GTN damage model [17,18]. Finally, the plastic damage distribution and fracture mechanism of the miniature specimen are analyzed to understand the damage evolution of small punch test.

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https://doi.org/10.1016/j.rinp.2018.09.024
Received 7 August 2018; Received in revised form 10 September 2018; Accepted 11 September 2018
Available online 25 September 2018

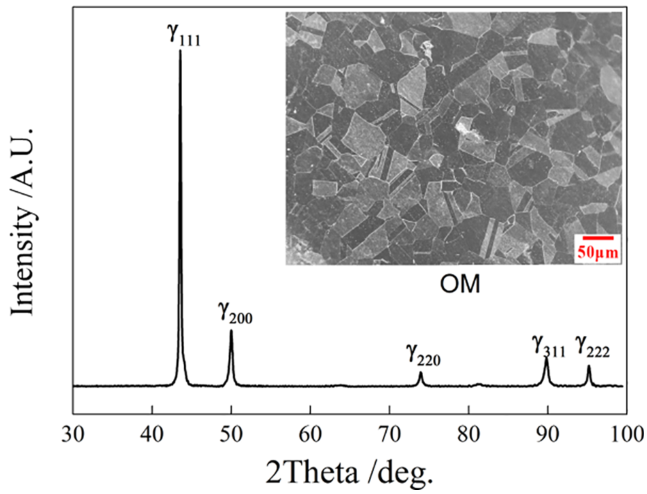

Fig. 1. Optical microscopy and X-ray diffraction of hot-rolled 316L austenitic stainless steel.

Experiments and inverse finite element analyses

Experimental details

The material used in this study was hot-rolled 316L austenitic stainless steel plate with 3 mm in thickness. Due to the excellent resistance to corrosion and good processing performance, 316L austenitic stainless steel is widely used in chemical equipment industries [19]. The microstructure of the as-received material was observed by optical microscopy (OM VHX-700F). The corrosion solution was hydrochloric acid (HCI) and nitric acid (HNO3), which was prepared according to the volume ratio 3:1. The grain size of the material was evaluated using intercept method. The phase transition in austenitic stainless steel was analyzed by X-ray diffraction (XRD, APEX II DUO). XRD measurements were conducted between 30° and 100° at room temperature using diffractometer with a Cu-Kα radiation operating at a step size of 0.02°. Fig. 1 shows the XRD pattern and OM observation of 316L austenitic stainless steel. It indicates that only single austenite phase is identified in the as-received material, and the grain size of austenite phase is about 50–80 μm.

The miniature specimen used in small punch test was a circular sheet with 10 mm in diameter and 0.5 mm in thickness shown in Fig. 2(a). The diameter of a punching ball was 2.4 mm and the inner diameter of a lower die was 5 mm. The displacement speed was controlled at 0.5 mm/min. In order to verify the rationality of the whole stress-strain relationship obtained by small punch test, the standard tensile test was carried out on a universal testing machine with the tensile strain rate of $5 \times 10^{-4}\,s^{-1}$. Standard tensile specimens with 100 mm × 15 mm × 3 mm were cut from as-received 316L austenitic stainless steel plate according to ASTME8M-04 [20] shown in Fig. 2(b). Small punch testing fixture mainly includes a punch, a ball, the upper and lower specimen holders, a loading device and a data acquisition system. The small punch testing fixture was developed in the foundation of a tensile testing machine. The material of small punch testing fixture is GH4169, which is one of the nickel-based alloys. Fig. 2(c) shows the schematic illustration of small punch test equipment. The displacement in small punch test and the strain in standard tensile test were measured by two displacement sensors.

Inverse finite element analyses for small punch test

It is well known that small punch test cannot directly obtain the mechanical properties of materials from a load-displacement curve. Rodríguez et al. [21] and Ruan et al. [22] used small punch test to determine mechanical parameters of different metallic materials by empirical correlations, which lacked theoretical basis and could not obtain the whole stress-strain curve. In order to solve this problem, inverse finite element technology was applied in small punch test. In this paper, ABAQUS finite element simulation software was used to establish the two-dimensional axisymmetric finite element model shown in Fig. 3. According to the geometry and deformation characteristic of small punch test, the specimen was defined as deformable, the ball and the dies were modelled as rigid bodies. The element type used is CAX4R, which represents a four-node, bilinear, axisymmetric, quadrilateral and reduced integration element. The miniature specimen was meshed with left half side size of 0.05 mm per cell and right half side size of 0.1 mm per cell.

Inverse finite element simulation is an effective tool in the prediction of constitutive parameters. In this work, inverse finite element was used to obtain the elastoplastic parameters of Hollomon model and the damage parameters of GTN model. The process was divided into two steps as follows:

a) For the undamaged stage of load-displacement curve: firstly, a series of stress-strain curves are constructed based on Hollomon model, and the finite element simulations of small punch tests are carried out based on the constructed stress-strain curves. Then, the databases of stress-strain curves and load-displacement curves are established. Through the training of Back Propagation (BP) neural network [23], the parameters of Hollomon model can be obtained by inputting the experimental data into the neural network.
b) For the damaged stage of load-displacement curve: firstly, the range of parameters f_N, f_c and f_F in GTN damage model are determined.

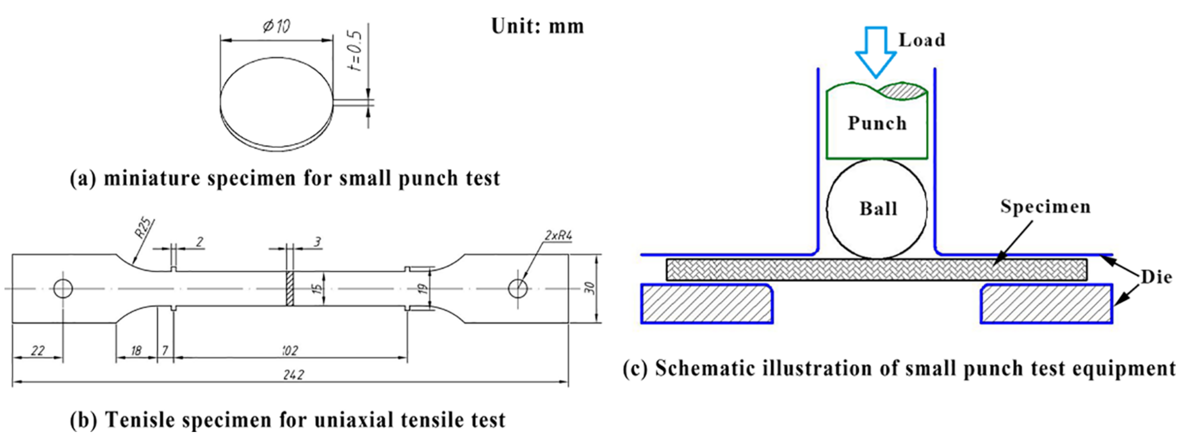

Fig. 2. Geometry and dimension of specimens: (a) miniature specimen for small punch test and (b) tensile specimen for uniaxial tensile test; (c) schematic illustration of small punch test equipment.