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Mechanical properties of pre-strained austenitic stainless steel from the view of energy density

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ABSTRACT

The effect of pre-strain on mechanical properties was investigated for 316L austenitic stainless steel over pre-strain value ranging from 0% to 35%. The effect of pre-strain on energy density of tensile curve was focused, and pre-strain enhances elastic energy density while reduces fracture energy density. Moreover, an energy dissipation variable was proposed based on fracture energy density as a damage parameter of pre-strained material. The relationships between energy dissipation variable and tensile mechanical properties were discussed. Finally, based on energy dissipation variable, an improved Hollomon model considering pre-strain damage is developed to predict mechanical properties of pre-strained 316L austenitic stainless steel.

Introduction

Due to the excellent ductility and relatively low yield strength of austenitic stainless steel, strain strengthening technology is used for pressure equipment with austenitic stainless steel to weight reduction. There is an urgent need to understand the effect of pre-strain on mechanical properties of austenitic stainless steel. Researchers paid attention to the effect of pre-strain on microstructural evolution [1–3] and macroscopic properties, such as hydrogen embrittlement [4–6], low-temperature carburization [7] and tensile strength [8]. Based on the effects of pre-strain and strain rate on dislocation, mechanical twinning and α'-martensite of 304L, Lee et al. [4] explained the variation of mechanical parameter with pre-strain and strain rate. Ji et al. [5] studied the effect of pre-strain on hydrogen embrittlement of 310S stainless steel and found that the pre-strain increased the resistance to hydrogen embrittlement by suppressing the fracture transition. The effect of pre-strain on low-temperature surface carburization of 304 austenitic stainless steel were studied by Peng et al. [7], and they found the carburized 304 stainless steel has an outstanding surface hardness with compressive residual stress, and the carburizing strengthening was independent of plastic pre-strain.

Besides microstructure and mechanical properties of materials, strain energy is an important parameter to understand physical properties of materials. Energy density was used to study tensile behavior [9,10], fatigue failure [11,12] and damage variable [13,14] of metallic materials. Lazzarin and Zambardi [10] re-formulated and applied the equivalent strain energy density approach to predict the stress intensity factors of V-shaped notch specimens on the basis of the linear elastic stress distribution. Koh [11] predicted the fatigue life of high pressure tube steel using cyclic strain energy density with a good correlation with the experimental life. Guu et al. [13] studied the effect of electrical discharge machining on surface characteristics and machining damage of AISI D2 tool steel, and they introduced strain energy density into damage variable to study the electrical discharge machining damage. Strain energy density is a useful parameter with physical meaning and can be applied for the analyses of mechanical parameters. Hollomon model was widely used to characterize the stress-strain curve of materials owing to its simplicity and effectiveness [15-19]. Zhang et al. [15] studied the effects of cold rolling on microstructure evolution and mechanical hardening of Inconel 690 alloy and used Hollomon model to describe stress-strain curves. Colla et al. [18] used Hollomon model to describe strain hardening behavior of dual-phase steels.

In order to understand mechanical properties of pre-strained 316L austenitic stainless steel from the view of energy density, strain energy density will be applied to analyze the variation laws of strength parameter and elongation parameter. Moreover, an energy dissipation variable, which reveals the damage evolution of pre-strained material with pre-strain, will be proposed based on damage theory and fracture energy density. At last, an improved Hollomon model based on the energy dissipation variable considering pre-strain damage will be constructed and applied to the pre-strained 316L austenitic stainless steel.

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Table 1
Composition of 316L austenitic stainless steel (wt%).

Steel	C	Si	Cr	Fe	Ni	Mo	P	S	Mn
316L	0.03	0.55	18.52	68.50	9.06	1.46	0.03	0.02	1.83

Experiments and results

Experimental details

The as-received 316L austenitic stainless steel is hot-rolled steel plate with 3 mm thickness, and the composition is listed in Table 1. The average austenite grain size of the material is about 18 µm.

Tensile specimens shown in Fig. 1 were machined from as-received metallic plate with length 35 mm × width 6 mm × thickness 3 mm, which meet the testing standard of ASTM E8M-04 [20]. Tensile specimens were stress relief annealed at 753 K with 2 h. Then specimens were polished with 1500 grit emery papers to achieve the same surface roughness. In order study the effect of pre-strain on the mechanical properties of 316L austenitic stainless steel, as-received specimens and pre-strained specimens with eight pre-strain levels 4%, 8%, 12%, 16%, 20%, 24%, 28%, 35% were considered in this study. Pre-strained specimens were achieved by tensile testing system (EHF-EG250-40L) shown in Fig. 1 with the strain rate 5e − 4/s at room temperature. The calculation equation of pre-strained value ε_{pre} is given as follows:

$$\varepsilon_{\text{pre}} = \frac{L_{\text{pre}} - L_0}{L_0} \tag{1}$$

where, L_{pre} is the initial gauge length of pre-strained specimens and L_0 is the initial gauge length of as-received specimen. Then tensile tests of as-received and pre-strained specimens were carried out with strain rate of 5e − 4/s at room temperature. When the strain is less than 5%, the tensile strain was measured by a strain extensometer shown in Fig. 1, and when the strain is larger than the measurement range, strain was determined by the ratio of the displacement to the parallel length of specimen.

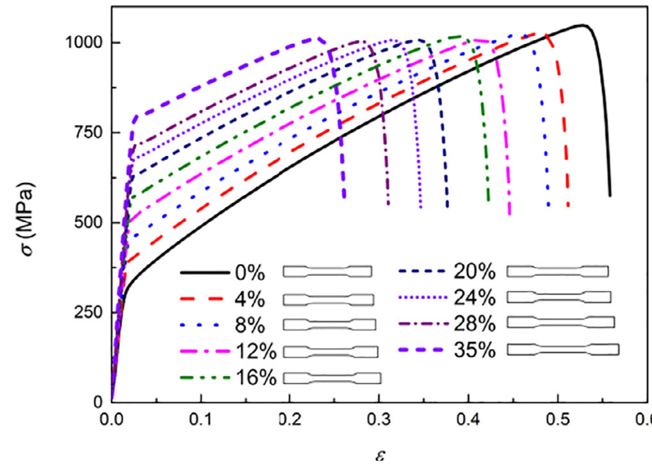

Fig. 2. Stress-strain curves of 316L austenitic stainless steel with different pre-strains.

Experimental results

Fig. 2 shows the true stress-strain (σ-ε) curves of 316L austenitic stainless steel with different pre-strains at room temperature. It indicates that the yield strength of 316L austenitic stainless steel increases significantly with the increase in pre-strain, but the ultimate tensile strengths of different pre-strained specimens are almost constant. Some studies also found that, the yield strength of metallic material was strengthened by pre-strain with the reduction of plasticity [21,22]. In addition, as shown in Fig. 2, stress-strain curves of 316L austenitic stainless steel can be divided into three stages: elastic stage, work hardening stage and fracture stage. With pre-strain increasing, the elastic stage is significantly enlarged, but substantial work-hardening stage is narrowed. When the stress reaches ultimate tensile strength, the specimen is necked down and fractured. The fracture strain decreases with the increase in pre-strain.

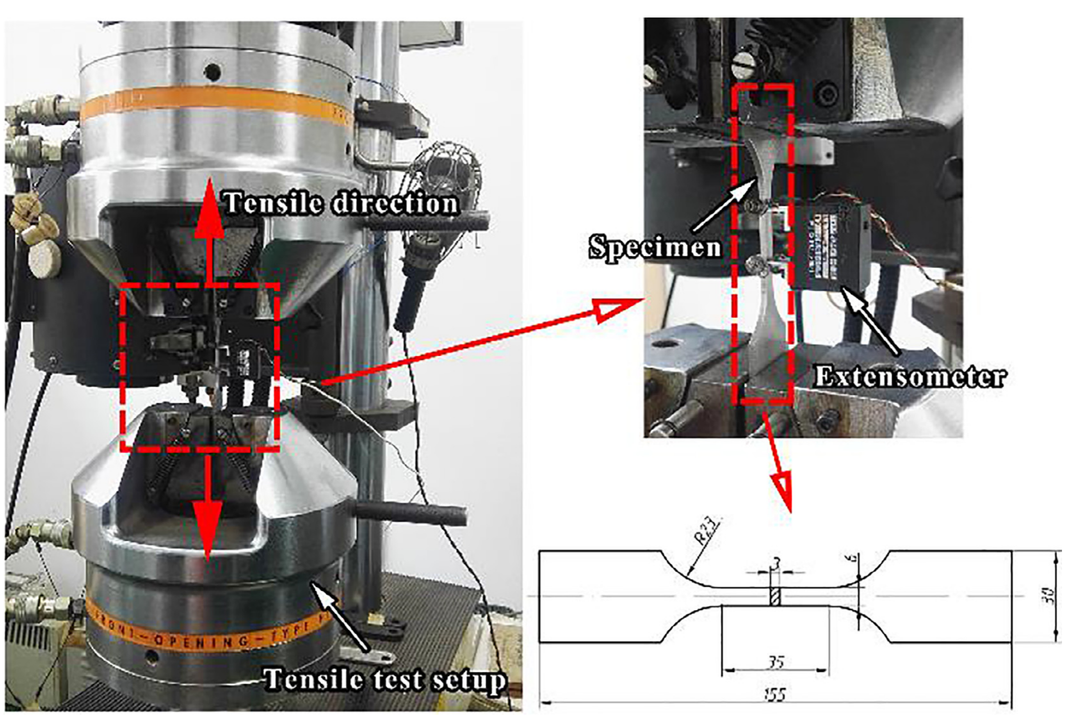

Fig. 1. Tensile test platform and tensile specimen dimensions (mm) used in this work.