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Mechanical Behavior of 316L Stainless Steel after Strain Hardening

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Abstract. The effects of strain hardening on the mechanical behavior of 316L stainless steel were studied in the paper. The original and different strain hardening materials were compared to investigate the mechanical behavior. The results demonstrate that the yield strengths increase with the magnitude of strain hardening significantly, but the ultimate strengths of the original and different strain hardening materials are closed. In addition, the plastic parameters of 316L stainless steel including fracture elongation and fracture surface shrinkage decrease with the magnitude of strain hardening. Finally, the Ramberg-Osgood equation is used to predict the stress-strain curves after strain hardening, and the results indicate that the predicted values agree with the experimental values.

1 Introduction

Austenitic stainless steel, used for important structure of pressure equipment, retains high strength and excellent ductility from cryogenic to elevated temperatures [1, 2]. 316L austenitic stainless steel, a common structural material, meets requirements for high-pressure vessels, pipes, valves, etc. [3]. But the mechanical behaviour of 316L stainless steel will change after strain hardening. The influences of strain hardening on mechanic behaviour including strength and plastic parameters of austenitic stainless steels have been studied in recent years. Tensile tests of 316H stainless steels with strain hardening up to 4%, 8% and 12% at room temperature in Ref. [4] found that the values of Young's modulus and the ultimate strengths are similar for different strain hardening, but the yield strengths increase with the magnitudes of strain hardening at different temperatures. Wang et al investigated fatigue properties and damage mechanisms of pre-strained plasticity steel, and found that the yield strengths increase with magnitudes of pre-strain [5]. Moreover, the relationship between stress and strain needs to predict according to constitutive equations. Ramberg and Osgood [6] proposed a technique of describing and predicting the relationship between stress and strain in metallic materials. Skelton and Maier [7] predicted the stress-strain relationship under variable loading conditions by the Ramberg-Osgood equation. Hight and Brandeau [8] using the Ramberg-Osgood relation, developed a mathematical equation of the stress-strain rate behavior. But the Ramberg-Osgood equation discussed above is without considering strain hardening, and cannot predict the tensile curve with strain hardening.

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2 Specimen design and experimental procedure

Tensile tests were performed using commercially available 316L stainless steel. Figure 1 shows that the plate specimen used in the tests. Firstly, plate specimens were pre-deformed to 5% and 10% at room temperature. Then, tensile tests were operated at room temperature with a strain rate of 5e-5/s. Finally, the differences of mechanical behavior among original and 5% and 10% strain hardening materials was analyzed according to strength and plastic parameters. The fracture surface of original and 5% and 10% strain hardening specimens were examined using the scanning electron microscope (SEM). Figure 2 shows the tensile testing machine used in the tests.

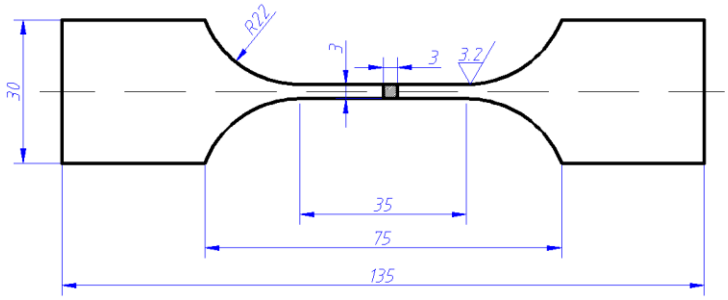

Figure 1. Dimension of tensile sample (unit: mm).

Figure 2. Tensile testing machine.

3 Results and discussion

3.1 Effect of strain hardening on strength parameter

Figure 3 shows the tensile stress-strain curves of original and 5% and 10% strain hardening specimens at room temperature, and the yield strengths and ultimate strengths are shown in Table 1. With comparison among the original material and strain hardening materials, the yield strength increase from 339 MPa to 370 Mpa with with the magnitude of strain hardening. But ultimate strengths are basically unchanged with the magnitude of strain hardening at room temperature.

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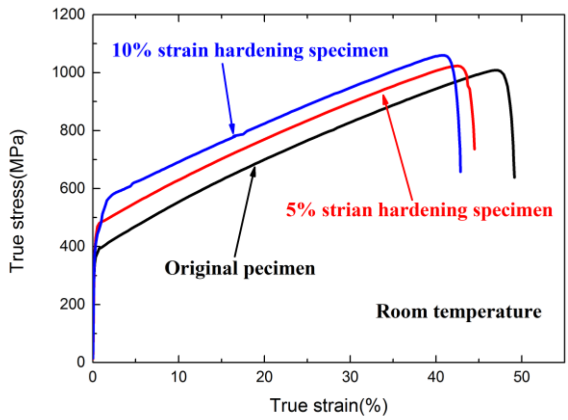

Figure 3. Tensile curves of original, 5% and 10% strain hardening specimens at room temperature.

Table 1. Yield strength and ultimate strength of original, 5% and 10% strain hardening specimens.

Specimens	Original	5% strain hardening	10% strain hardening
Yield Strength (MPa)	339	353	370
Ultimate Strength (MPa)	1008	1018	1024

3.2 Effect of strain hardening on plastic parameter

Figure 4 shows plastic parameters of 316L stainless steel including fracture elongation and fracture surface shrinkage with the magnitude of strain hardening at room temperature. Both fracture elongation and fracture surface shrinkage decrease with the magnitude of strain hardening. The fracture elongation and fracture surface shrinkage are approximately proportional to the magnitude of strain hardening. It indicates that strain hardening can increase the yield strength, but decrease the plastic parameter of 316L stainless steel.

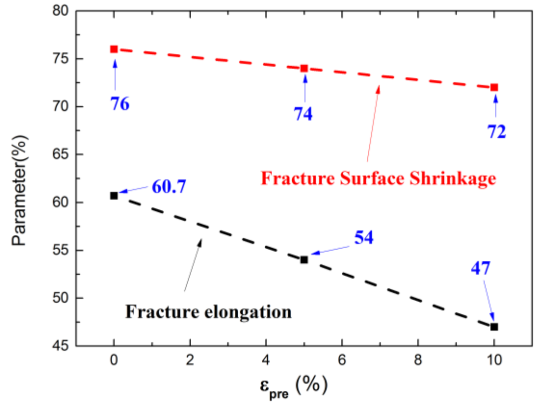

Figure 4. Fracture surface shrinkage and fracture elongation with different strain hardenings.

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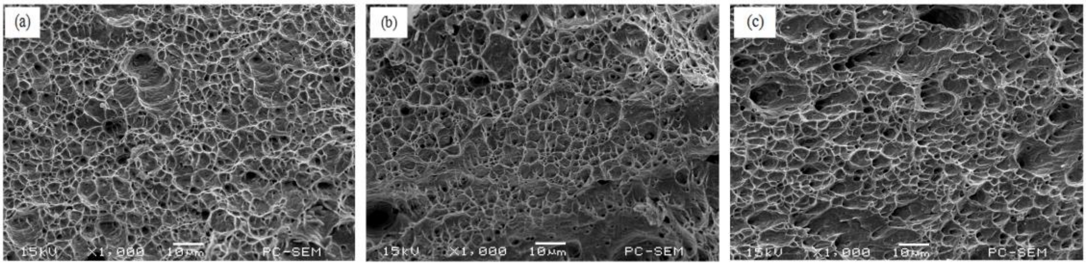

Figure 5. SEM images of tensile fracture surfaces of (a) original; (b) 5% strain hardening; (c) 10% strain hardening specimens at room temperature.

Figure 5 shows the SEM images of original, 5% and 10% strain hardening specimens at room temperature. The tensile fracture surfaces of specimens are filled with dimples, which are a typical ductile failure mode at room temperature. But the tensile fracture surfaces have no obvious change with the magnitudes of strain hardening. It indicates that strain hardening will not change the ductile failure mode of 316L stainless steel.

3.3 Analysis of strain hardening by the Ramberg-Osgood equation

Ramberg-Osgood is a theoretical equation to predict and describe the relationship between stress and strain of the metallic material near its yield point. In this paper, Ramberg-Osgood equation is used to analyze the change of stress index of 316L stainless steel after strain hardening.

The general form of the Ramberg-Osgood equation in tensile experiments is as follows:

$$\varepsilon = \sigma / E + \alpha \cdot \sigma_0 / E \cdot (\sigma / \sigma_0)^M \tag{1}$$

Where, σ_0 is the reference stress (MPa), E is the initial elastic modulus (MPa), α the material constants and its value is 3/7 normally, M is the stress index which indicates strengthening behavior of materials after yielding. By taking transposition and logarithm, Eq. (1) can get the expressions of the stress index:

$$\ln(\varepsilon - \sigma / E) = M \cdot \ln \sigma + \ln(\alpha / E) - (M - 1) \cdot \ln \sigma_0 \tag{2}$$

The relative plot lnσ-ln(ε-σ/E) is used to fitting a straight line based on tensile curves and the initial elastic modulus (E). The stress index (M) values and the reference strain (σ_0) can be calculated according to the slope and intercept of the straight line. The fitting process is shown in Figure 6 and the values of stress index (M) are shown in Table 2, which shows that the values of stress index increase with the magnitudes of strain hardening. The phenomenon indicates that the hardening behavior is more and more obvious and the deformation capacity of 316L stainless steel decreases with the magnitudes of strain hardening.

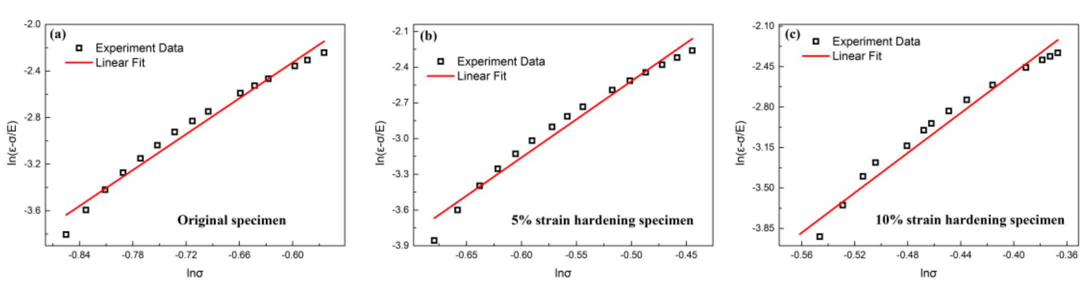

Figure 6. The linear fitting of stress index of (a) original; (b) 5% strain hardening; (c) strain hardening specimens.

Table 2. The values of stress index of original, 5% and 10% strain hardening specimens.

Specimens	Original	5% strain hardening	10% strain hardening
Stress Index	5.14	6.42	8.63

Figure 7 shows the plots of experimental values and the lines of predicted values by Ramberg-Osgood equation, and most of the experimental values are close to the predicted values. It illustrates that Ragberg-Osgood equation is feasible in tensile test of original, 5% and 10% strain hardening specimens. But it is obvious that the difference between the experimental data and the predicted values began to enlarge with the magnitudes of strain hardening.

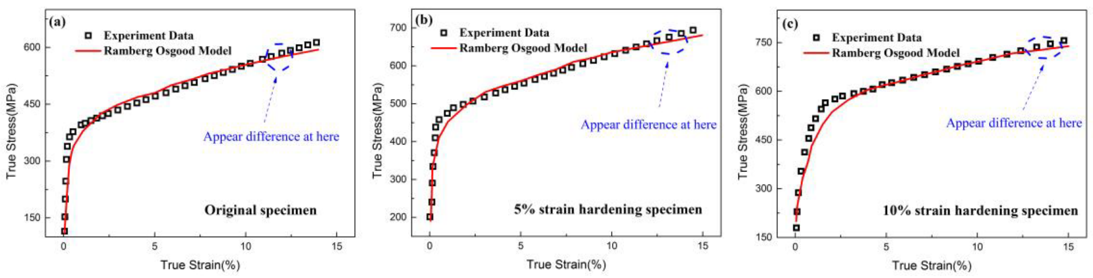

Figure 7. Comparison between the experimental data and predicted values by Ramberg-Osgood equation.

4 Summary

For the strength parameters of original, 5% and 10% strain hardening specimens at room temperature, the yield strength increases significantly but the ultimate strength is almost unchanged with the magnitudes of strain hardening. For plastic parameters of 316L stainless steel, the fracture elongation and fracture surface shrinkage have the same changed trend, which decreases with the magnitudes of strain hardening.

The Ramgerg-Osgood equation was applied to predict the stress strain curve of original, 5% and 10% strain hardening specimens, and the values of stress index increases with the magnitudes of strain hardening.

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