Biaxial Path Dependence of Deformation Substructure of Type 304 Stainless Steel

D. L. McDOWELL, D. R. STAHL, S. R. STOCK, and S. D. ANTOLOVICH

Although martensitic transformations in austenitic stainless steels have been studied rather thoroughly for uniaxial monotonic and cyclic loading, data are scant for biaxially loaded specimens. In particular, recent nonproportional straining experiments have indicated a significant increase in cyclic hardening beyond that observed in uniaxial tests at equivalent strain levels. In this paper, a link is made between the additional hardening and microstructural uniformity of transformation product. This link is expressed through a micromechanical viewpoint via increased latent hardening associated with rotation of the principal stress and plastic strain rate directions.

I. INTRODUCTION

Changes in straining direction can affect cyclic deformation at both microscopic and macroscopic levels. This study was undertaken to investigate these effects on type 304 stainless steel using axial-torsional specimens tested at room temperature and subjected to proportional and nonproportional straining sequences at controlled effective strains and strain rates. Subsequent to testing, specimens were examined using advanced metallographic techniques to identify deformation substructures.

It has been observed in several experimental studies that nonproportional strain cycling may result in cyclic hardening beyond the extent observed in uniaxial tests at the same peak effective strain level. For materials which cyclically harden markedly in uniaxial tests, such as the stainless steel in the current investigation, the additional hardening can be quite pronounced during nonproportional strain cycling. There is evidence to indicate that materials which cyclically soften during uniaxial tests may harden during nonproportional cycling. Logically, a link should exist between cyclic deformation substructure within each grain and polycrystalline stress-strain response. If the deformation substructure and any associated transformation products are dependent upon a rotation of the stress and strain fields with respect to each grain, then the extent of isotropic hardening observed in the polycrystalline material should reflect this dependence, and vice versa.

II. EXPERIMENTAL PROCEDURES

A. Material

The material chosen for this study was type 304 stainless steel with the composition shown in Table I. This material exhibits a plastic strain range-dependent transformation from metastable fcc austenite to bcc $\alpha'$-martensite during cyclic$^{7,8}$ in addition to $\varepsilon$-martensite, an hcp form which is associated with the formation of stacking faults on (111) slip planes.$^{9,10}$ The stacking fault energy of type 304 stainless steel is low (= 23 mJ/m$^2$)$^{11}$, promoting the formation of wide stacking faults and planar slip at room temperature. Type 304 stainless steel exhibits marked cyclic hardening response dependent on the strain range and nonproportionality of straining in the plastic region.$^{12}$

B. Specimens

Tubular axial-torsional specimens were machined from as-received bar stock (50.8 mm diameter), as shown in Figure 1. The wall-thickness to outside diameter ratio of 0.11 was found necessary from experience to prevent buckling for cyclic loading at significant levels of plastic strain. Finite element analysis and strain gage studies have shown that the variation in axial strain along the gage length was less than three percent.

A set of uniaxial and axial-torsional specimens was heat-treated at 1000 °C for 40 minutes in a vacuum and furnace cooled to achieve the relatively equiaxed grain structure shown in Figure 2 with an ASTM grain size number of 4. There were approximately 25 grains across the wall thickness of the axial-torsional specimen shown in Figure 1.

Uniaxial specimens were machined from radial and longitudinal directions of the bar stock with a gage diameter of 3 mm, approximately that of the axial-torsion specimen wall. Five monotonic tension tests in the longitudinal direction resulted in a mean true fracture strength of 612 MPa with a standard deviation of ±7 MPa. The mean percent reduction in area for the longitudinal specimens was 64.8 pct with a standard deviation of ±5.7 pct. The corresponding values of mean true fracture strength and percent reduction in area for four radial specimens were 628 MPa and 56.3 pct, with standard deviations of ±1 MPa and ±4.0 pct, respectively.

In addition, completely reversed, strain-controlled fatigue tests were run at comparable strain ranges on five specimens machined in the longitudinal direction and six specimens machined in the radial direction. The stable cyclic stress amplitudes for radial and longitudinal specimens were essentially the same for a given strain amplitude $\Delta e$.

The results are shown in Table II. From the tensile and fatigue tests, it is apparent that initial anisotropy effects in the axial-torsional specimens are minor.
C. Testing Procedure

The biaxial, strain-controlled tests were performed on an axial-torsional load frame. A PDP 11-23 processor/interface was used for independent servohydraulic, closed-loop control of axial and torsional deflection channels and for simultaneous data acquisition.

An internal extensometer[13] was placed inside the specimen with a gage length of 25.4 mm. A linear variable differential transformer (LVDT) was used to measure axial displacement between contact points at the gage length, while a rotary variable differential transformer (RVDT) measured the relative angle of twist. Extensometer backlash and interaction between axial and torsional channels were negligible. The deviation from linearity for both axial and shear displacement channels was less than one percent of full scale. Alignment was verified over a wide range of axial and rotational movements of the servohydraulic ram with respect to the fixed crosshead.

Axial strain $\varepsilon$ was defined as the gage length displacement divided by the original gage length. The engineering shear strain $\gamma$ was obtained by dividing the angle of twist by the gage length and multiplying by the mean radius. Engineering strain is virtually indistinguishable from true strain at the low strain levels of this study.

Axial stress $\sigma$ and shear stress $\tau$ were calculated from the axial load $P$ and torque $T$ as

$$
\sigma = \frac{4P}{\pi(D_o^2 - D_i^2)} \quad \text{and} \quad [1]
$$

$$
\tau = \frac{12T}{\pi(D_o^3 - D_i^3)} \quad \text{.} \quad [2]
$$

with the assumption that the stresses are uniform across the wall thickness. $D_o$ and $D_i$ are the gage section outside and inside diameters, respectively. This assumption obviously involves some error, but the deformation theory of plasticity cannot be used to estimate the stress distribution during nonproportional loading. Brown and Miller[4,15] showed that the error in maximum shear stress is small for proportional or nonproportional loading, particularly if there is significant cyclic plasticity present.

A computer program was written so that any combination of line segments in $\varepsilon$-$\gamma$ strain space could be joined end-to-end to define a loading cycle. A block was defined as an arbitrary number of identical cycles. Furthermore, the program allowed the user to define any number of blocks, each containing a different cycle loading path. The von Mises effective strain rate $\dot{\varepsilon} = (\dot{\varepsilon}^2 + \dot{\gamma}^2/3)^{1/2}$ was kept constant along each segment.

The computer program was written to accomplish the following objectives:

(a) Permit generation of a number of successive blocks of different nonproportional cyclic paths interactively with the computer. A desired effective strain rate was specified and the entire history plotted prior to running the actual test.

(b) Run initial shear and axial modulus checks at small elastic strains to compute $G$ and $E$ prior to the imposed history.

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<th>Table I. Composition of 304 SS (Wt Pct)</th>
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<td>C</td>
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<td>AISI 0.08 pct max.</td>
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<td>Actual 0.05 pct</td>
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<tr>
<th>Table II. Summary of Uniaxial Fatigue Tests</th>
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<tr>
<td>Specimen Type</td>
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<tr>
<td>Longitudinal Radial $\varepsilon_{\varepsilon}$ $N_f$</td>
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