Materials Science & Engineering A 614 (2014) 326–337

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Deformation path effects on the internal stress development in cold worked austenitic steel deformed in tension

I.I. Ahmed*, B. Grant, A.H. Sherry, J. Quinta da Fonseca

Material Performance Centre, University of Manchester, Manchester, UK

ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form
27 May 2014
Accepted 5 July 2014
Available online 14 July 2014

Keywords:
Stainless steel
Strain path
Cold work
Peak width
Bauschinger effect
Stress corrosion cracking

ABSTRACT

The effects of cold work level and strain paths on the flow stress of austenitic stainless steels, including Bauschinger effect and associated internal stresses were investigated with both mechanical testing and neutron diffraction techniques. The main objective was to assess the effects of cold rolling: to 5%, 10%, 20% and 40% reduction and uniaxial straining on the evolution of the internal strains during the re-straining to 5% tensile strain in-situ, which is relevant for stress corrosion cracking (SCC) studies. The results of mechanical testing showed that the yield strength of material increased when it was reloaded in the forward direction and decreased well below the flow stress when the loading direction was reversed, showing a strong Bauschinger effect. The magnitude of Bauschinger effect is independent on whether tensile or compressive prestraining comes first but rather on the amount of prestrain. The assessment of the effect of prestraining methods showed that the magnitude of yield asymmetry was higher in the material prestrained by uniaxial deformation than those prestrained by cold rolling. Neutron diffraction test results showed that the elastic lattice strain difference between the maximum and minimum strain values increased consistently with the applied stress during the re-straining to 5% tensile strain in-situ along the 3 orthogonal directions of the rolled plate. It also emerged that, following the in-situ loading of cold rolled materials to 5% tensile strain, the largest strain difference occurred in the material prestrained to 20% reduction. In cold rolled samples, the peak width increased with cold work levels and during re-straining to 5% along rolling, transverse to rolling and normal directions which simulated reversed condition. In contrast to the cold rolled samples, there was neither increase nor decrease in the peak width of samples prestrained by uniaxial deformation on re-straining in reverse direction. This was rationalised in terms of the development of intragranular and intergranular stresses in the two cases and implications to SCC susceptibility were discussed.

1. Introduction

Austenitic Stainless Steel (ASS) used in components is often cold worked through the plastic deformation at ambient temperature. Cold work may be carried out for a number of reasons, including: the enhancement of the surface properties, shaping and joining, thinning and strengthening of the material. During the cold work process, the strength of material increases significantly at the expense of ductility due to increasing dislocation density, formation of deformation twin bands and strain induced martensite [1,2]. However the effects of prestraining on the strength of the material are not simple. The uniaxial re-straining of prestrained material in the forward direction does indeed cause the yield strength to increase markedly depending on the level of prestrain, although there is a slight reduction in the flow stress due to a small permanent softening that occurs during the unload and reload. On the other hand, when the re-straining direction is reversed, the yield strength of material appears much lower than the prior flow stress. The reverse flow stress also appears much lower than the forward flow stress, evident in the much higher permanent softening [3,4]. This is an example of the Bauschinger Effect (BE), which has origin on the development of internal stresses caused by the heterogeneous nature of deformation at the microstructural scale [5], often observed in dual phase materials. These internal stresses can have important effects on the performance of the material in service but their development and deformation path dependence are not well understood.

The internal stress evolution in multiphase structure of stainless steels 316L, containing austenite matrix and martensite phase, generated by prestraining at cryogenic temperature was studied by Spencer et al. [5]. Their results demonstrated the development of internal stresses from the compatibility between the elastic deformation in the hard phase-martensite and the plastic

* Corresponding author. Current address: Department of Materials and Metallurgical Engineering, University of Ilorin, P.M.B. 1515, Ilorin, Nigeria.
Tel.: +234 7018271354.
E-mail address: ismaila.ahmed@yahoo.com (I.I. Ahmed).

http://dx.doi.org/10.1016/j.msea.2014.07.005
0921-5093/

deformation in the relatively less stiff austenite phase. The magnitude of the strain heterogeneity between the 2 phases is an indication of the internal stresses in the material. The internal stresses can play an important role in material failure including Stress Corrosion Cracking (SCC). Tensile stresses acts as a driving force in the SCC and its magnitude depends on the amount of prestrain and the subsequent loading direction. The significance of loading orientations was obvious from the high temperature stress corrosion test carried out on cold rolled ASS, Type 304 by Tice et al. [6]. Their results following cyclic and constant loading SCC tests showed that rolling direction was the most susceptible to the SCC propagation while the normal direction was the least susceptible. Similarly, Raquet et al. [7] carried out Constant Extension Rate Test (CERT) in high temperature water environment, on austenitic stainless steel, Type 304L prestrained by bending into V-hump shape. They found evidence of crack initiation and propagation (predominantly intergranular) in the compressive region of the V-hump. This result highlights the suggestion that material pre-strained and subsequently re-strained in reverse direction tends to show greater susceptibility to SCC.

The aim of this work was to study the change in yield and flow stress and internal strain evolution during cold-working and re-straining, along different directions, of austenitic stainless steel annealed and prestrained by two different methods: uniaxial deformation and cold rolling. The objective was to measure the effects of path change on the internal strains and its possible link to material performance, in particular the directional susceptibility to SCC. The assessment of internal strain evolution was carried out following in-situ loading to 5% tensile strain along the 3 orthogonal directions. The benchmark of 5% tensile strain was chosen because 5% plastic strain is typical for material failure by stress corrosion cracking [8]. The difference between prestraining methods, namely uniaxial deformation and cold rolling, and their effects on lattice strain evolution upon re-straining to 5% tensile strain were investigated. Mechanical testing was used to determine the yield strength anisotropy for different paths and directions in the rolled material. Neutron diffraction was used to measure the lattice strain during in-situ loading to the 5% tensile strain along the three orthogonal directions and during reverse loading (Bauschinger effect). Neutron diffraction was used for its non destructive strain measurement capability and because it has higher penetration power than X-rays [9,10]. Although there are a number of excellent studies concerning the development of intergranular strains in stainless steel [11–15], ours is the first to compare the response of rolled material with that strained uni-axially and the first to discuss differences in peak broadening evolution.

2. Experimental

2.1. Material

The material used for this study was low carbon grade austenitic stainless steel, Type 304L. The chemical composition of the material is shown in Table 1. The ASS plate ($300 \times 100 \times 30$ mm^3) was initially solution annealed at 1050 °C for 30 min and quenched in water. Fast cooling was done to prevent probable intergranular precipitation of the chromium carbide by sensitisation process described elsewhere [16,17]. The material was subsequently heat treated at 400 °C and furnace cooled to partially relieve internal stresses and to remove martensite which may have formed due to fast cooling. Preliminary tests carried out on the annealed sample showed that, the average grain size and 0.2% offset yield strength of the annealed material were 68 μm and 290 MPa respectively. The annealed material was

Table 1
Chemical composition (wt%) of alloying elements in stainless steel Type 304L.

C	Cr	Mn	N	Ni	P	S	Si
0.030	18.387	1.804	0.086	8.133	0.034	0.005	0.411

subjected to prestraining by two methods. One batch of the annealed material was subjected to 10% uniaxial tension and compression, and another batch was subjected to prestraining by cold rolling to various degrees: 5%, 10%, 20% and 40% reduction in thickness by multipass uniaxial rolling at room temperature. Each rolling pass corresponds to thickness reduction of 0.5 mm and the final thickness of rolled plates reduced from 30 mm to: 28.5 mm, 27.0 mm, 24.0 mm and 18.0 mm. Prestraining by cold rolling was used because the method is often used to introduce cold work into material that is to be subsequently tested e.g. for stress corrosion cracking susceptibility, as it allows samples to be manufactured for testing along different orientations. The four levels of cold reduction were used to study the effect and correlation between the amounts of prestrain and lattice strain evolution during the in-situ loading. The schematic illustration of the prestraining and the subsequent restraining with methods used are shown in Fig. 2.

2.2. Test method

2.2.1. Load cycle tests after uniaxial deformation and cold rolling

The mechanical test procedures used are categorised into two sets: the first comprises of samples prestrained by uniaxial deformation, which are mainly annealed samples subjected to tension–tension and compression–tension load cycles. The second category contains the samples prestrained by cold rolling and re-strained to 5% in tension or compression along the 3 orthogonal directions. The samples used for uniaxial deformation were machined from longitudinal direction of the annealed, while cold rolled samples were machined from the middle of the cold rolled plates along the three orthogonal directions namely: Rolling direction (RD), Transverse to the rolling direction (TD) and Normal to the rolling direction (ND) (Fig. 1). The material was not long enough along the ND to obtain a full tensile specimen; it was therefore Electron Beam Welded (EBW) on both sides with super Duplex Stainless Steel (DSS) material, UNS S32760. The choice of DSS with relatively higher yield strength was made to allow load transfer to the ASS in the gauge length region. The electron beam welding was used to minimise the heat input to the parent materials. The tensile specimen was then machined from the assembly. The naming code used for the test samples defines the method and the direction of re-straining. For example 20% CW + 5% T corresponds to sample prestrained to 20% cold worked and subsequently re-strained to 5% in tension. The schematic diagram of the tension/compression samples and their respective dimensions are shown in Fig. 3.

The load cycle test was carried out on an Alliance-RT/100 model of Material Testing Solutions (MTS). The test machine was equipped with a 100 kN load cell. The strain was measured with 10 mm gauge length extensometer attached to the specimen gauge length. The test was carried out at a cross head speed of 8×10^{-4} mm/s (strain rate of 8.9×10^{-5} s^{-1}) in line with ASTM standard E 8M-04 [18]. In the first load cycle test, two samples were both prestrained to 10% by uniaxial deformation, one in tension and the other in compression followed by unloading. Both samples were subsequently reloaded to 5% strain in tension and then unloaded to simulate Tension-Tension (T-T) and Compression-Tension (C-T) load cycles respectively. These tests were carried out to study the yield strength anisotropy and the BE following a prestraining by uniaxial deformation.