Materials Science and Engineering A 528 (2011) 3261–3269

Contents lists available at ScienceDirect

Materials Science and Engineering A

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

Dislocation structure evolution and its effects on cyclic deformation response of AISI 316L stainless steel

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ARTICLE INFO

Article history:
Received 18 August 2010
Received in revised form 5 January 2011
Accepted 6 January 2011
Available online 13 January 2011

Keywords:
Low cycle fatigue
AISI 316L
Dislocation structure
Cellular structure
TEM

ABSTRACT

The cyclic deformation response of an austenitic stainless steel is characterised in terms of its cyclic peak tensile stress properties by three stages of behaviour: a hardening stage followed by a softening stage, and finally a stable stress response stage. A series of tests have been performed and interrupted at selected numbers of cycles in the different stages of mechanical response. At each interruption point, specimens have been examined by transmission electron microscopy (TEM) with different beam directions by means of the tilting function in order to investigate the formation and the development of dislocation structures from the as-received condition until the end of fatigue life. A new 3D representation of dislocation structure evolution during cyclic loading is proposed on the basis of the microstructural observations. The 3D representation provides a deeper insight into the development of dislocation structures in AISI 316L during low cycle fatigue loading at room temperature. By investigating the dislocation evolution, the study shows that the hardening response is mainly associated with an increase of total dislocation density, whereas the softening stage is a result of the formation of dislocation-free regions. Further development of the dislocation structure into a cellular structure is responsible for the stable stress response stage.

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1. Introduction

Austenitic stainless steels are widely used in industrial applications due to their outstanding corrosion resistance at low temperatures, and high oxidation resistance and superior creep-fatigue resistance at high temperatures. It is therefore important to understand the material characteristics responsible for their performance in service, in particular their cyclic deformation response. During the last decades, there have been numerous studies investigating the cyclic deformation properties of these alloys. Depending on testing conditions and the initial state of the material, austenitic stainless steels exhibit either cyclic hardening or cyclic softening response or both [1–10]. There have been intensive studies of the relationship between cyclic deformation properties and dislocation structures of austenitic stainless steels [2–4,6–8,10–14]. However, these studies have mainly concentrated on investigating the microstructures existing at failure for different strain amplitudes [1,4,6–9,11–14]. These investigations have shown that the dislocation structures induced by cyclic loading depend on imposed plastic strain amplitude. Specifically, if a well-annealed austenitic stainless steel is cyclically strained at low plastic strain amplitudes, the dislocation structure is present in the form of planar arrangements (associated with stacking fault, pile-ups, etc.) until failure, which is almost similar to the initial condition except the dislocation density is higher at the end of life. At intermediate plastic strain amplitudes, persistent slip bands and veins coexisting with dislocation-free regions (i.e. channels) are observed at failure. At high plastic strain amplitudes, well-organised structures, namely wall/channel or cellular structures, are observed at failure.

While there are existing comprehensive investigations on dislocation structure evolution and its correlation with cyclic deformation response [2,15–18], these are either more focused on the microstructure condition present after a high number of cycles or at failure. It is shown in this paper that the fatigue response of austenitic stainless steels like some other metals [19] significantly changes during the first cycles. For AISI 316L at a temperature of 20 °C, the cyclic hardening stage occurs only during the first cycles, occupying a small fraction of lifetime (Fig. 1). For some conditions, the subsequent softening response stage also occupies a relatively small fraction of life. Subsequently, dislocation structures are present in a complex form comprising co-existing sub-domains of well defined wall/channel structure, fragmented wall/channel

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doi:10.1016/j.msea.2011.01.015

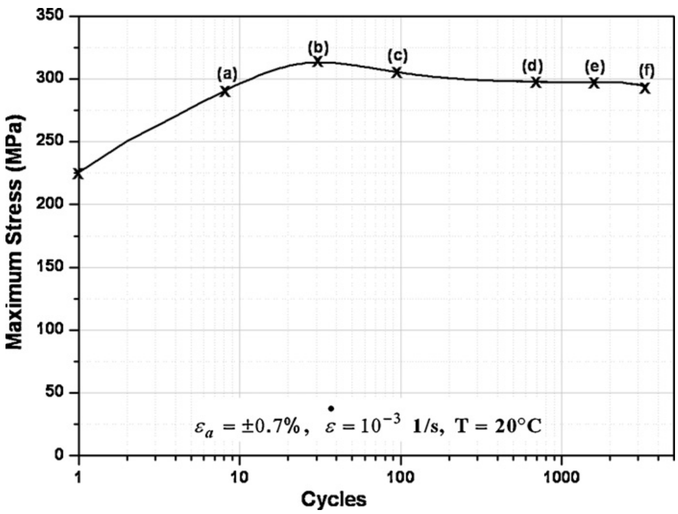

Fig. 1. Three stages of cyclic deformation response of AISI 316L steel (ε_a: total strain amplitude).

structure, and cells [15]. Transmission electron microscopy (TEM) provides only a 2D projection of a small portion of the actual microstructure along a certain beam direction. It can therefore be difficult to appreciate the development of actual dislocation structures. There have been a number of studies which examine the spatial arrangement of dislocations during cyclic loading by observing thin foils whose planes are oriented to certain angles with respect to the loading axis [2–4,7,12]. These studies provide a comprehensive knowledge of the spatial arrangement of dislocations. However, the existence of different families of structure types, fragmented wall/channel structures, etc. during cyclic loading has not been clearly explained by models developed in these investigations. Evolution of the dislocation microstructure throughout life and in particular during the first cycles has therefore received more careful examination.

In this study, test conditions responsible for the austenitic stainless steel AISI 316L exhibiting cyclic hardening, cyclic softening and a stabilised response have been investigated. The dislocation structures evolving during cyclic loading have been carefully studied in order to construct a new 3D model to represent the observed changes. Ultimately, the mechanical response of the material is to be characterised by considering its correlation with the evolution of dislocation microstructure.

2. Experimental procedure

The AISI 316L austenitic stainless steel was evaluated in this study. The composition of the steel is shown in Table 1 The material originated from a hot finished primary cooling circuit pipe which had been quenched in water from 1050/1080 °C. This solution treatment was responsible for an austenite grain size of 60 μm.

Cylindrical testpieces, with a parallel length of 20 mm, a gauge diameter of 8 mm and with threaded end-grips, were machined from the pipe with an axial orientation, in accordance with the requirement of ISO 12106. The testpieces were fatigue loaded with a constant total strain amplitude of ±0.7% and strain rate of 10^{-3} 1/s at room temperature using a servo-controlled electromechanical 50 kN machine. A Class-0.5 side-entry contacting extensometer with a gauge length of 15 mm was attached to the testpiece parallel length to control and measure strain during cyclic loading.

Tested specimens were sectioned in parallel to the loading axis using a diamond cutting machine in order to prepare samples for microstructural observations. The samples were mechanically polished to produce thin plates of 0.1 mm thickness which were then punched out to produce discs having a diameter of 3 mm. These were marked to indicate the loading direction. The discs were then electrolytically polished using a double jet device (TenuPol5) with an electrolyte solution of acetic acid and perchloric acid to provide specimens for TEM investigation. Thereafter, samples were observed in a Philips CM30 transmission electron microscope at 300 kV with a double tilt holder. The mark of the loading direction (LD) was aligned along the holder axis in order to preserve the loading direction during observations. Selected area electron diffraction and Kikuchi patterns were used to identify the grain orientation relative to the loading axis. In addition, the samples

Table 1
Material composition.

C (%)	Mn (%)	P (%)	S (%)	Cr (%)	Mo (%)	Ni (%)	Cu (%)	B (%)	Co (%)	N (%)
0.014	1.630	0.030	0.002	16.730	2.120	11.090	0.600	0.0011	0.090	0.060

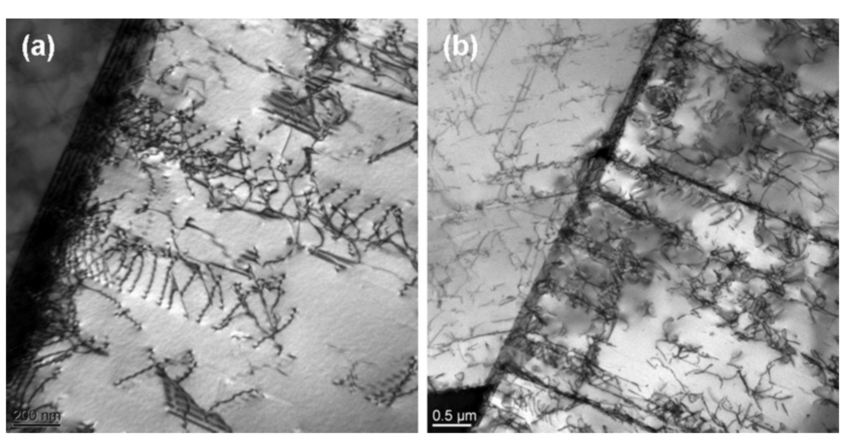

Fig. 2. Dislocation structures in the as-received (solution treated) condition observed in the [0 0 1]-beam direction. (a) Planar structures (dislocation pile-ups and stacking faults); (b) evidence of active slip planes.

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