International Journal of Fatigue 81 (2015) 299–308

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Effect of strain rate on low cycle fatigue of 316LN stainless steel with varying nitrogen content: Part-I cyclic deformation behavior

G.V. Prasad Reddy [a,*], R. Kannan [a], K. Mariappan [a], R. Sandhya [a], S. Sankaran [b], K. Bhanu Sankara Rao [c]

[a] *Mechanical Metallurgy Division, Indira Gandhi Centre for Atomic Research, Kalpakkam 603102, India*
[b] *Dept. of Metallurgical & Materials Engg., Indian Institute of Technology Madras, Chennai 600036, India*
[c] *Dept. of Metallurgical & Materials Engg., Mahatma Gandhi Institute of Technology, Hyderabad 500075, India*

ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form 23 June 2015
Accepted 26 July 2015
Available online 10 August 2015

Keywords:
316LN stainless steel
Nitrogen
Low cycle fatigue
Dynamic strain aging
Dislocation structure

ABSTRACT

The effect of strain rate and nitrogen content on cyclic deformation and substructural changes in 316LN stainless steel is investigated at temperatures 773, 823 and 873 K. Dynamic strain aging (DSA) and/or thermal-recovery processes are observed to control cyclic deformation, and the regimes of their predominance are mapped. An increase in nitrogen content and DSA enhanced cyclic stress and are found to offset thermal-recovery induced cyclic strength reduction. In addition, strain localization in the form of slip-bands impinging on grain boundary is observed. The predominance of thermal-recovery over DSA manifested as dislocation-poor channels, dislocation cells within and in-between planar slip-bands.

1. Introduction

316LN stainless steel (SS) with 0.06–0.08 wt.% nitrogen has been the backbone structural material for many primary side components (main vessel, intermediate heat exchanger, inner vessel, etc.) and piping system of Prototype Fast Breeder Reactor (PFBR) under construction at Kalpakkam, India. The section thickness of some of the components reaches up to 30 mm. Also, austenitic stainless steels in general are sensitive to high temperature fatigue owing to their low thermal conductivity coupled with a high thermal expansion coefficient. Accordingly, intense thermal stresses can be induced during thermal transients. Hence, from the perspective of cost and thermal stresses, it is necessary to reduce the section thickness of components which in turn requires the use of nitrogen enhanced 316LN stainless steel with superior resistance to high temperature low cycle fatigue (LCF) failure (LCF being one of the design considerations). Indeed, nitrogen enhanced 316LN SS has been envisaged for the structural components of future Commercial Fast Breeder Reactor (CFBR) of India.

Low cycle fatigue studies reported previously on high nitrogen 316LN SS were carried out at strain rates of the order of $10^{-3}\ s^{-1}$ [1–5]. These studies demonstrated the beneficial effect of nitrogen in 316LN SS in improving the fatigue life, and the increase in life is attributed to an increase in slip planarity with increasing nitrogen content. Accordingly, an optimum nitrogen content corresponding to the maximum in LCF life is reported at 0.12–0.14 wt.% N [1–5]. At temperatures in the range of 773–873 K and at strain rates of the order of $10^{-3}\ s^{-1}$, the predominant mechanisms controlling the cyclic deformation and fatigue life are identified to be dynamic strain aging (DSA) and/or secondary cyclic hardening (SCH) for the total strain amplitudes $\leqslant 0.6\%$ [5,6]. DSA causes localized planar slip and enhances the matrix hardening (i.e., increase in cyclic stress) that has been reported to result in drastic reduction in LCF life [7,8]. SCH also increases the degree of hardening over and above that caused by DSA [5,6]. It is important to mention here that the studies reported at strain rates of the order of $10^{-3}\ s^{-1}$ cannot invoke significant damage due to other time-dependent processes such as thermal recovery, creep, oxidation and cyclic strain induced precipitation which occur inherently at low strain rates [9]. Moreover, there is no open literature on the LCF behavior of high nitrogen 316LN stainless steels at low strain rates such as less than $10^{-3}\ s^{-1}$. Hence, it is of utmost importance to study the LCF behavior and optimize the nitrogen content in 316LN SS under these low strain rate conditions. Accordingly, LCF tests were conducted to investigate the combined influence of nitrogen content and strain rate, on low cycle fatigue deformation and life in 316LN SS alloyed with nitrogen contents of 0.07, 0.11, 0.14 and 0.22 wt.%, at temperatures 773 K, 823 K and 873 K. The test temperature range employed in the present study encompasses the FBR steady state operating temperature (~820 K). The results presented in this manuscript are the first of its kind on the combined

---

[*] Corresponding author. Fax: +91 44 27480075.
E-mail address: prasadreddy@igcar.gov.in (G.V. Prasad Reddy).

http://dx.doi.org/10.1016/j.ijfatigue.2015.07.033
0142-1123/

influence of strain rate, temperature and nitrogen content on LCF behavior of 316LN SS. The study is presented in two parts: Part-I (current manuscript) deals with the cyclic deformation behavior and associated substructural changes, and Part-II details LCF life variation as a function of nitrogen, strain rate and temperature [10].

2. Material and experimental details

The chemical composition of four heats of 316LN SS with 0.07, 0.11, 0.14 and 0.22 wt.% nitrogen (henceforth designated as N07, N11, N14 and N22 respectively) is given in Table 1. The carbon content in all heats was maintained at around 0.03 wt.%. The production methodology of the four heats was given elsewhere [11]. Rectangular blanks of dimension 115 × 24 × 22 mm were cut in the rolling direction, and solution annealed at 1363 K for 60 min followed by water quenching. Equiaxed grains free of precipitates and delta-ferrite have been observed in the microstructure, and the average grain size measured through mean lineal intercept method is 102, 98, 85 and 76 μm for N07, N11, N14 and N22 steels respectively, i.e. in the range 89 ± 13 μm, as shown by the distribution in Fig. 1 for N07, N14 and N22 (N11 is not shown in Fig. 1 for clarity). The effect of grain size variation (within this narrow range) on fatigue life is presumed to be negligible, as in the similar studies on nitrogen alloyed 316LN SS [1–4]. Specimens with 25 mm cylindrical gauge length and 10 mm gauge diameter were used for LCF tests and tests were conducted in total strain control mode at temperatures 773 K, 823 K and 873 K with strain rates of $3 \times 10^{-3}\ \mathrm{s}^{-1}$, $3 \times 10^{-4}\ \mathrm{s}^{-1}$ and $3 \times 10^{-5}\ \mathrm{s}^{-1}$. All the tests were performed at total strain amplitude of ±0.6%. Transmission electron microscopy (TEM) studies were carried out on thin foils prepared by twin jet-thinning with the electrolyte comprising 10% perchloric acid in methanol (in the ratio of 1:9). The foils were examined with 120 kV TEM (CM 12 Philips). Dislocation structures in the heat treated samples consisted of randomly distributed dislocations and stacking faults with partial dislocations at all the nitrogen contents [11]. In addition to this, 316LN SS with 0.14 and 0.22 wt.% N are found to consist of dislocation pairs [11].

3. Results and discussion

Cyclic deformation behavior in the present study is discussed in terms of cyclic stress evolution during cycling and associated deformation microstructures, taking into account the influence of time-dependent processes.

3.1. Cyclic stress response behavior

The influence of strain rate on cyclic stress response (CSR) is shown in Fig. 2, for N07 and N22 steels. As apparent from Fig. 2a–d, CSR curves portrayed initial cyclic hardening followed by softening and/or quasi-saturation of cyclic stress depending on the combination of nitrogen content, test temperature and strain rate. At temperatures 773 K and 823 K, initial hardening is followed by gradual/rapid softening as shown in Fig. 2a and b (at 773 K), whereas at 873 K cyclic hardening with or without quasi-saturation is observed (Fig. 2c and d) before the rapid stress drop associated with macrocrack propagation. In addition, negative strain rate sensitivity (SRS) of the cyclic stress evolution i.e. an increase in stress with decrease in strain rate (below $3 \times 10^{-3}\ \mathrm{s}^{-1}$) is noticed for all the steels at temperatures 773 K and 823 K, as shown in Fig. 2a and b for N07 and N22 steels respectively at 773 K. It is important to mention that the negative SRS is a characteristic manifestation of occurrence of DSA which causes significant hardening of the material as discussed in the subsequent Section 3.1.2. On the other hand, at temperature 873 K only N22 steel has shown such behavior (Fig. 2d) while the other steels have exhibited a decrease in CSR at $3 \times 10^{-5}\ \mathrm{s}^{-1}$ below that of $3 \times 10^{-4}\ \mathrm{s}^{-1}$, the decrease being significant for N07 steel (Fig. 2c). This implies the diminishing effect of DSA at the test condition 873 K/$3 \times 10^{-5}\ \mathrm{s}^{-1}$ at all the nitrogen contents in 316LN SS except at 0.22 wt.% N. To further confirm this, stress–strain hysteresis loops are plotted to identify the presence of DSA manifestations i.e. serrations (stress drops) in the hysteresis loops. It must be pointed out here that, serrations in the plastic portion of hysteresis loops are observed at all the temperatures and strain rates, irrespective of the nitrogen content, as shown in Fig. 3a and b. This signifies the fact that strain hardening caused by DSA in the LCF tests at 873 K/$3 \times 10^{-5}\ \mathrm{s}^{-1}$ could possibly be offset by simultaneous reduction in matrix strength that caused the decrease in CSR at $3 \times 10^{-5}\ \mathrm{s}^{-1}$ below that of $3 \times 10^{-4}\ \mathrm{s}^{-1}$. The above findings therefore point out to the occurrence of thermal recovery processes (i.e. thermally activated dislocation motion by climb and cross-slip) and cyclic strain induced precipitation (that can decrease the solutes responsible for solid solution strengthening), both of which can contribute to the decrease in cyclic stress. It thus appears from the above CSR curves that depending on the combination of nitrogen content and test parameters, the relative dominance of either of the time-dependent processes (DSA, thermal recovery, precipitation) could control the observed cyclic deformation behavior.

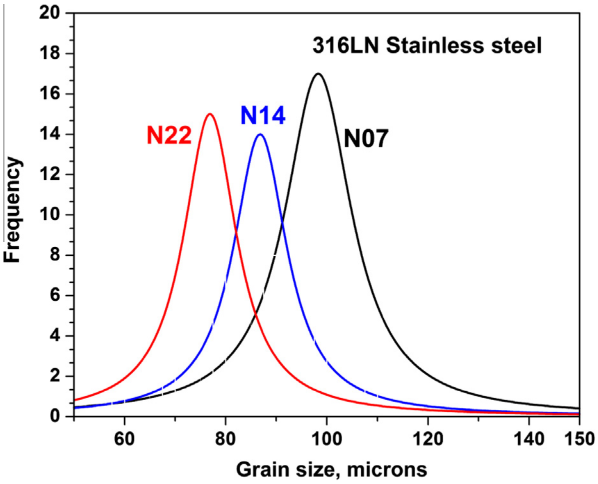

Fig. 1. Grain size distribution as a function of nitrogen content in 316LN stainless steel.

Table 1
The chemical composition (in wt.%) of nitrogen alloyed 316LN stainless steels.

Designation	C	Cr	Ni	Mo	N	Mn	Si	S	P	Fe
N07	0.03	17.5	12.2	2.49	0.07	1.7	0.22	0.0055	0.013	Bal.
N11	0.03	17.6	12.2	2.51	0.11	1.78	0.21	0.0055	0.015	Bal.
N14	0.03	17.5	12.1	2.53	0.14	1.74	0.20	0.0041	0.017	Bal.
N22	0.03	17.5	12.3	2.54	0.22	1.7	0.20	0.0055	0.018	Bal.