International Journal of Fatigue 61 (2014) 1–9

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Metallurgical aspects on the fatigue of solution-annealed austenitic high interstitial steels

Michael Schymura, Alfons Fischer *

Materials Science and Engineering, University of Duisburg Essen, 47057 Duisburg, Germany

ARTICLE INFO

Article history:
Received 3 September 2013
Received in revised form 17 November 2013
Accepted 19 November 2013
Available online 5 December 2013

Keywords:
Austenitic high interstitial steels
Fatigue
Stacking fault energy
Density of free electrons

ABSTRACT

Austenitic stainless steels have been used for over 100 years for their combination of strength and ductility. In order to further improve the mechanical and chemical properties of austenitic high nitrogen steels (AHNS) were developed. Ni reduces the solubility of N and, therefore, was substituted by Mn in order to allow for up to 1 weight-% N to be alloyed. AHNS show an even higher strength for the solution annealed state, which can be increased further by cold working. Unfortunately the endurance limit did not follow this trend as it is known to for cold-worked Ni-containing steels. The solution annealed Ni-containing austenites allow for wavy slip and the generation of dislocation cells while the Mn-alloyed AHNS only show planar slip with twins and stacking faults. While the stacking fault energy was thought to be the main reason for planar slip, early results showed that there must be other near-field effects. The density of free electrons, which is mainly influenced by the sum and the ratio of C and N, might be responsible. Strain-controlled fatigue tests were carried out in CrMn-alloyed austenitic steels with different sums (C + N: 0.65–1.2) and ratios (C/N: 0.13–∞) of C and N. Manson–Coffin analyses revealed distinct differences in the fatigue behaviour to CrNi-alloyed C + N steels investigated earlier. This contribution presents these differences and discusses them in relation to microstructural characteristics as well their alterations under cyclic loading.

1. Introduction

Austenitic stainless steels provide a favourable combination of strength and ductility and, therefore, are applied in many different areas of mechanical, process, automotive, and biomedical engineering [1–7]. Of these the corrosion-resistant CrNiC-austenitic steels offer mechanical and chemical properties that can be further improved by cold working and/or adding nitrogen [8,9]. Adding interstitial alloying elements like C and N, which both stabilize the austenitic phase, has been suggested to be more effective than cold work [10]. Unfortunately the solubility of N in the melt is low and the alloying elements as well the production methods had to be adjusted in order to allow for a sufficient amount of N in solution [11]. Thus the CrMn-based austenitic high nitrogen steels (AHNS) with up to 1 weight-% N were developed to provide a high strength combined with a high ductility by solid solution strengthening of N. Nitrogen strengthening also improved the endurance limit of solution annealed AHNS [12–15]. Cold working also increased the strength, but the endurance limit did not follow (Fig. 1) this trend [12,13] to the extent as it does for CrNi-austenitic steels with and without N [8,16].

The reasons were attributed to the differences in sliding behaviour of CrNiCN and CrMnCN-steels. CrNiC steels show wavy slip under fatigue leading to the generating of dislocation cells. In CrNiCN steels the N-content up to 0.4 weight-% promotes planar slip but wavy slip still governs the cyclic properties under reciprocating sliding wear [17]. In general such steels show a cyclic hardening behaviour, which after some cycles and depending on the strain amplitude alters into cyclic softening [16]. In contrast the Ni-free CrMnCN steels always show planar slip and cyclic softening over all fatigue cycles [12]. Recently developed CrMnCN-steels [18–20] with a different amount and ratio of C and N also showed a higher endurance limit in rotating bending tests in the solution annealed state, which could be further improved by 20% cold-working [21]. In these austenitic high-interstitial steels (AHIS) both C and N are of similar importance for all mechanical properties [22].

Now the question appears which metallurgical features rule the slip behaviour. The stacking fault energy (SFE) of a CrNiCN-steels is quite similar to that of AHNS while that of AHIS ranges in between [22]. It is clear that the SFE is increased by C and Ni but lowered by Cr and Mn, while the effect of N on SFE depends on Ni, Mn and C contents [23–29]. Another strong factor for wavy or planar slip is the density of free electrons D_F as shown for Cu-alloys [30]. Here wavy slip prevails, if SFE decreases with increasing D_F. If SFE is constant over D_F planar slip governs. Obviously D_F is as important as SFE. This might be a reason why the AHIS, which have the highest

* Corresponding author. Address: University of Duisburg-Essen, Materials Science and Engineering, Lotharstr. 1, 47057 Duisburg, Germany. Tel.: +49 203 379 4372; fax: +49 203 379 4374.

E-mail address: alfons.fischer@uni-due.de (A. Fischer).

0142-1123/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijfatigue.2013.11.018

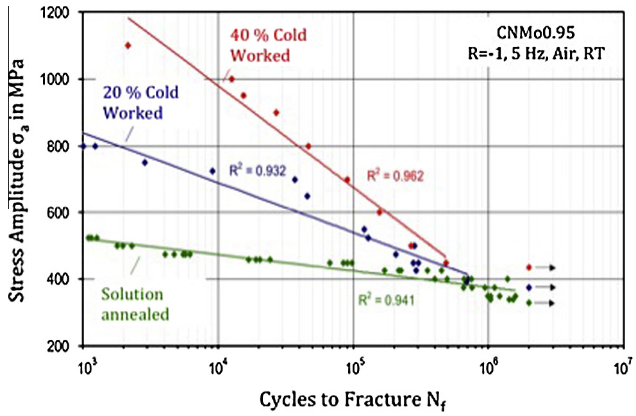

Fig. 1. S–N-curve for solution annealed and cold-worked AHNS 1.4452, X13CrMnMoN18-14 3 (here CNMo0.95) under axial fatigue loading [12].

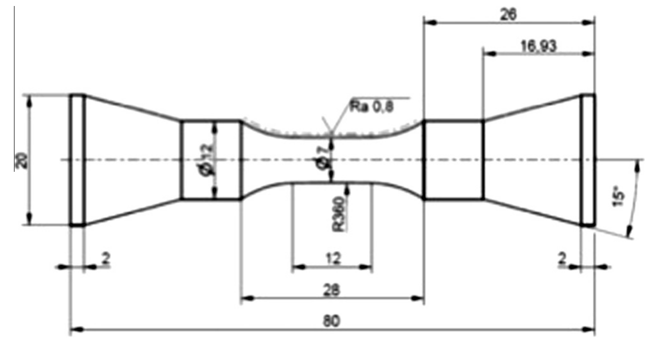

Fig. 2. Specimen for strain-controlled axial fatigue tests.

D_F among CrMnCN-steels by a tailored sum and ratio of C and N, show a stronger capability to increase the endurance limit by cold working [21,31]. Finally strong Mo–N interactions might be another reason for planar slip [32]. These interactions cannot be ruled out for some of the AHNS but the AHIS are Mo-free.

Planar slip allows for the extreme work-hardening capability of AHNS and AHIS. Despite high ductility the fatigue properties remain inferior. Some lattice defects from cold-working might even disappear [13]. Ni-containing AHNS-steels, which fatigue under wavy slip characteristics, do not allow for such high alloying amounts of interstitials and, therefore, show a lower strength. Still such steels can be work-hardened for an increase of the fatigue limit but at the sacrifice of a loss of ductility [16].

In order to investigate the influence of Mn, C, and N on the fatigue behaviour different grades of AHIS with and without N are solution annealed and axially fatigued under strain-control. In this contribution the fatigue behaviour is described, compared to that of CrNiCN-steels and related to the microstructures and their alterations under load.

2. Materials and methods

2.1. Materials

Six AHIS with varying sums and ratios of C and N were. The chemical composition is given in Table 1. The designation was chosen in according to Berns et al. [18–20] as to the sum of the interstitials C and N.

The blanks before solution annealing were wrought bars in case of CN0.85, CN0.96, CN1.07, CNMo0.95, a wrought retaining ring in case of CN0.72, and centrifugally cast tubes in case of GC1.20. After heat treatment the grain size, hardness, and tensile properties were measured according to DIN 50601, DIN EN ISO 6507-1, and DIN EN 10002, respectively.

2.2. Fatigue tests

The fatigue specimens (Fig. 2) were machined from a Ø 20 × 100 mm blank and afterwards ground and polished within the reduced length of 28 mm. Grinding was carried out solely in axial direction using SiC-emery paper down to 1200 mesh size in order to remove any remaining circumferential machining marks. Polishing was carried accordingly with a 1 μm grain size diamond paste. Finally the specimens were inspected by means of a light microscope at 5× magnification in order to avoid any surface scratches which may influence the fatigue behaviour.

Uniaxial total strain ($\varepsilon_{a,t}$) controlled tension–compression sine-wave loading at $R_\varepsilon = \varepsilon_u/\varepsilon_o = -1$ was chosen after mounting the specimens into the load frame of a commercial servo hydraulic test rig (MTS Bionix 858, MTS Systems GmbH, Berlin, Germany). The loading frequency was controlled in order to maintain a maximum temperature increase of 50 K. Thus at $\varepsilon_{a,t} \geqslant 0.8\%$ tests were run at 0.5 Hz while at $\varepsilon_{a,t} < 0.8\%$ 2.5 Hz was preferred. All tests were run in laboratory air at room temperature either until fracture (N_f) or up $2 \cdot 10^6$ load cycles (N). The cyclic stress–strain hystereses were analyzed by standard methods [12,16] as to the total stress

Table 1
Chemical composition in weight.-% of the AHIS.

Brand name	Hadfield steel	P900[a]	CARNIT			P2000[a,b]
Designation	GC1.20	CN0.71	CN0.85	CN0.96	CN1.07	CNMo0.95
C	1.200	0.086	0.260	0.344	0.489	0.075
Cr	0.10	18.16	18.26	18.20	18.82	18
Cu	0.02	0.03	0.03	–	–	0,13
Fe	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.
Mn	12.17	19.32	18.52	18.89	18.88	14
Mo	0.00	0.06	0.04	0.06	0.07	3,5
N	–	0.627	0.590	0.614	0.578	0.875
Nb	–	0.00	0.01	–	–	–
Ni	0.05	0.35	0.26	0.34	0.41	0.12
P	0.01	0.02	0.02	0.02	0.02	0.01
S	0.004	0.001	0.002	0.003	0.002	0.002
Si	0.42	0.40	0.26	0.30	0.43	1.12
N/C	0.000	7.291	2.269	1.782	1.183	11.667
C/N	∞	0.137	0.441	0.561	0.845	0.086
C + N	1.200	0.713	0.850	0.958	1.067	0.950

[a] Brand names are trademarks of ETE GmbH, Essen, Germany.
[b] All data of CNMo0.95 are taken from [12].