Materials Science & Engineering A 626 (2015) 41–50

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Relationship of grain size and deformation mechanism to the fracture behavior in high strength–high ductility nanostructured austenitic stainless steel

R.D.K. Misra [a,*], X.L. Wan [a], V.S.A. Challa [a], M.C. Somani [b], L.E. Murr [a]

[a] *Center for Structural and Functional Materials Research and Innovation and Department of Metallurgical and Materials Engineering, University of Texas at El Paso, 500W University Avenue, El Paso, TX 79968, USA*

[b] *Materials Engineering Laboratory, Center for Advanced Steels Research, The University of Oulu, P.O. Box 4200, 90014 Oulu, Finland*

ARTICLE INFO

Article history:
Received 6 November 2014
Received in revised form
9 December 2014
Accepted 12 December 2014
Available online 19 December 2014

Keywords:
Austenitic stainless steel
Grain size
Deformation mechanism
Fracture
Austenite stability

ABSTRACT

In this study we underscore the dependence of grain structure and deformation mechanism on the fracture behavior in a high strength–high ductility bearing nanograined/ultrafine-grained austenite stainless steel. In high strength nanograined steel, deformation twinning contributed to excellent ductility, while in the low strength coarse-grained steel, the high ductility is attained as a consequence of strain-induced martensite transformation. Interestingly, the differences in deformation mechanism of steels deformation mechanisms of steels with different grain structures but with similar elongations influenced the mode of fracture, a behavior that is governed by the change in austenite stability with grain size. The areal density of voids and their average diameter in the fracture surface also increased with increasing grain size, which ranged from 320 nm to 22 μm.

1. Introduction

The continued interest in advanced high-strength steels, including stainless steels, has led to the consideration of innovative processing routes. While grain refinement [1,2], microalloying addition [3–7], and severe plastic deformation [7,8] continue to represent a pragmatic approach to enhance the strength of existing metals and alloys, it is clear and widely agreed that the limitation of the mean path of gliding dislocation by the nanocrystalline structure constitutes the origin of limited ductility in high strength nanostructured alloys. There is also a significant interest in increasing the stability of austenite phase to delay the onset of necking and benefit from the strain-induced transformation of austenite to martensite to obtain high ductility.

In order to increase the strength through grain refinement without compromising the ductility, we have recently developed an ingenious concept of phase reversion annealing to obtain nanograined/ultrafine-grained (NG/UFG) structures in metastable austenitic stainless steels. The concept involves extensive cold deformation (60–75%) of austenite to obtain strain-induced martensite. In the subsequent step, referred as phase-reversion annealing, martensite transforms back to austenite via diffusional or shear reversion mechanism [9–13]. Using this approach, NG/UFG structure was obtained having high yield strength and elongation of 900–1000 MPa and 30–40%, respectively [9–13]. These properties were superior to that of the coarse-grained (CG) counterpart that was characterized by yield strength typically in the range of 350–450 MPa and elongation of the order of ~40% [9–13].

In 1995, Christian and Mahajan [14], critically assessed the relationship between deformation twinning and fracture. In bcc metals and alloys, high stress concentration induced by deformation twins was recognized as the potential reason for initiation of fracture at twin–twin intersections. The fcc metals and alloys are ductile at room temperature. But, at sub-zero temperatures, significant amount of deformation occurred by twinning in austenitic stainless steels having low stacking fault energy (SFE), and as a consequence micro-cracking was observed at twin–twin intersections [14]. It was proposed that the twinning and fracture were independent phenomena. However, the above analysis by Christian and Mahajan dealt with conventional coarse-grained structure. To the best of our understanding there is no report on the fracture behavior in a single material processed using identical processing parameters that exhibits a distinct transition in deformation mechanism from strain-induced martensite formation to twinning, when the grain size changes from CG to NG/UFG. It is in this regard that the study described here is unique and provides new knowledge in nanocrystalline materials. In high strength NG/UFG steel, deformation twinning contributed to the excellent

* Corresponding author. Tel.: +1 915 747 8679; fax: +1 915 747 8036.
E-mail address: dmisra2@utep.edu (R.D.K. Misra).

http://dx.doi.org/10.1016/j.msea.2014.12.052
0921-5093/

ductility and high strain hardening rate, while in the low strength CG steel, the high ductility and strain hardening ability were associated with strain-induced martensite. Interestingly, the differences in the deformation mechanism of CG and NG/UFG steels influenced the fracture behavior. Thus, the objective of the study described here is to understand the interplay between grain size and deformation mechanism as they relate to the fracture behavior in austenitic stainless steel from the CG to NG regime.

2. Experimental procedure

The experimental steel was a *commercial* Type 301LN austenitic stainless steel of ~1.5 mm thickness with a nominal composition (in wt%) of Fe–0.017C–0.52Si–1.3Mn–17.3Cr–6.5Ni–0.15Mo–0.15N. Samples of stainless steel strips were cold-rolled in a laboratory rolling mill to ~62% reduction (~0.6 mm thick) via a number of passes and subsequently reversion-annealed in the temperature range of 700–900 °C for 10–100 s in a Gleeble 1500 thermo-mechanical simulator to obtain different grain sizes from NG to CG regime. The reversion annealing experiments were carried out on specimens of dimensions 120 mm × 25 mm cut from the cold rolled samples. The experimental details are given elsewhere [9–13]. The grain structure was examined in a transmission electron microscope (TEM) operated at 120 kV.

Keeping in view the grain size distribution, the weighted average grain size $\overline{d}_w$ was determined [15]. Here, about 100 grains were distributed in bins of 250 nm (0.25 μm) in size. A bin of 250 nm was so selected in order to optimize the statistical data. A small bin size is expected to result in poor statistical accuracy, while a large bin size may mask the effect of small grains. Thus, an optimum bin size of 250 nm (0.25 μm) was selected, keeping in view the grain size range of samples. Denoting the number of grains in the ith bin as n_i and dividing it by the total number of grains, N, the weight of the ith bin is [15]:

$$w_i = \frac{n_i}{N} \tag{1}$$

Table 1
Tensile properties of phase reversion-induced austenitic stainless steel with different grain size and average distance between striations measured from the scanning electron fractograph. Striations were absent in the CG structure.

	Weighted average grain size, $\overline{d}_w$	Average yield strength (MPa)	Average elongation (%)	Distance between striations (μm)
NG/UFG	320 nm	768	34	3.2
SMG	757 nm	722	38	6.1
FG	2132 nm	667	41	8.2
CG	22 μm	350	40	–

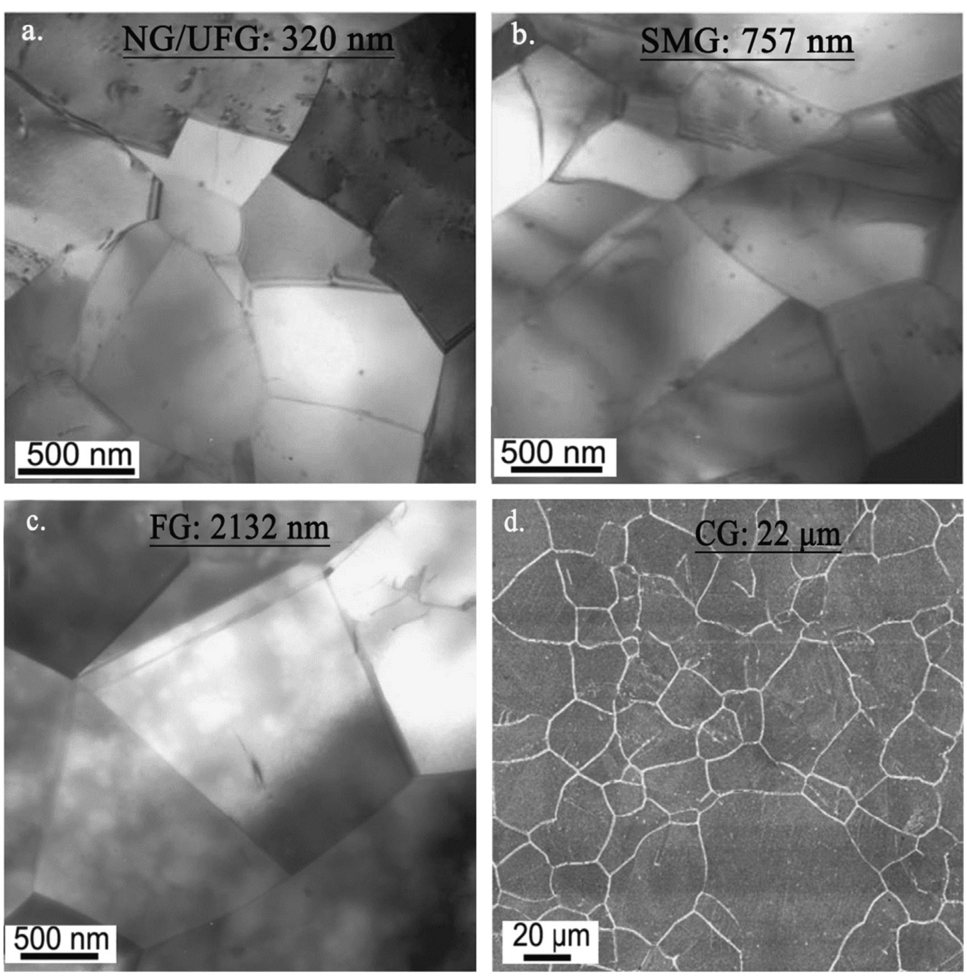

Fig. 1. (a–c) TEM micrographs of phase reversion annealed 301LN type austenite stainless steel with varying grain size from NG/UFG regime to fine-grained (FG) regime and (d) light micrographs of CG steel. The average weighted grain size $\overline{d}_w$ was determined from a number of micrographs and is indicated on each of the micrographs. NG/UFG: nanograined/ultrafinegrained, SMG: sub-micron-grained, FG: fine-grained, and CG: coarse-grained steels (adapted from Ref. [13]).