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Fatigue behaviors of high nitrogen stainless steels with different deformation modes

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A B S T R A C T

In this work, high-cycle fatigue property of high nitrogen steels which have different deformation modes was explored. The samples, Fe-18Cr-10Mn-0.4N (0.4N) and Fe-18Cr-10Mn-0.6N (0.6N), were fabricated under different nitrogen partial pressures in order to obtain the different deformation modes by controlling stacking fault energy: Deformation-Induced Martensite Transformation (DIMT) in 0.4N and deformation twins in 0.6N. Owing to solid solution strengthening of nitrogen, the fatigue limit of 0.6N is higher than that of 0.4N. However, a ratio of the fatigue limit to the yield strength of 0.6N is lower than that of 0.4N. This result is ascribed to the different influence of the deformation modes on fatigue damages. The DIMT formed in 0.4N could restrict the path of moving dislocations, and thus the fatigue property was relatively improved with the decrease of the fatigue damages by the DIMT. The deformation twins, on the other hand, were not clearly activated during fatigue of 0.6N, and therefore did not affect the fatigue damages.

1. Introduction

High nitrogen austenitic stainless steels (HNS) have been regarded as a potent substitutional material for conventional stainless steels due to their properties such as their good ductility, appropriate strength, and high corrosion resistance [1–8]. In particular, Nickel (Ni) – free Fe-Cr-Mn-N series steels have the advantages in biocompatibility and in economical aspect by eliminating Ni, because Ni could induce allergy in human organism and its price results in the high cost of conventional austenitic stainless steels [9–13]. Nitrogen, as an austenite-forming element instead of Ni, contributes to the improvement of tensile strength by solid solution strengthening and of the resistance to localized corrosion by retardation of the anodic dissolution or the oxidation of Fe [3,13,14].

Furthermore, nitrogen plays an important role in controlling stacking fault energy (SFE) of austenitic stainless steels [15–17]. According to Lee et al. [18], SFE increases along with nitrogen contents when the steel contains nitrogen content over 0.1 wt%. A value of the SFE is correlated with deformation modes under plastic deformation: the deformation mode is transited from Deformation-Induced Martensite Transformation (DIMT) to deformation twins with increasing nitrogen content. Sufficient stress and strain transform metastable austenite into ε martensite which could subsequently transform into α' martensite [19,20]. The transformation is called the DIMT which causes outstanding work-hardening and ductility of the materials. The deformation twins, formed during plastic deformation under a high stress condition, produce a favorable combination of mechanical properties by increasing an inherent resistance to the movement of dislocations [18,20]. Namely, the DIMT and the deformation twins, as strengthening mechanisms activated under the plastic deformation, enhance the mechanical properties of HNS.

Fatigue fracture is known as a critical factor of reliability of materials, which accounts for approximately 70% of the total fracture accidents of structural materials [21]. For safety-related issues, many researchers have regarded the fatigue limit as an important property, and thus have paid attention to effects of the strengthening mechanisms on the fatigue limits. Extensive literatures are available on fatigue properties of TRansformation-Induced Plasticity (TRIP) steels [22–28] and TWinning-Induced Plasticity (TWIP) steels [29–34]. However, the previous works on the DIMT and the deformation twins in these steels have been separately treated due to their dissimilar chemical compositions of the TRIP and TWIP steels. Hence, the comparative analysis on the correlation between the deformation modes in austenite stainless steels and their fatigue properties has been limited. The deformation modes in Fe-Cr-Mn-N series, contrastively, can be controlled by nitrogen contents without changing the substitutional solute contents

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[17,20].

Therefore, the effects of the DIMT and the deformation twins on the fatigue limits can be investigated by using Fe-Cr-Mn-N HNS. The purpose of this research is to figure out the fatigue behaviors of the austenitic stainless steels with the different deformation modes. Two Fe-18Cr-10Mn-0.59N (0.6N) and Fe-18Cr-10Mn-0.38N (0.4N) having the different deformation modes were fabricated for a comparative study by control of nitrogen contents. For confirming the effect of nitrogen contents and the deformation modes on the fatigue properties, the correlation between the mechanical properties and the fatigue limits of the samples was analyzed with their microstructures. Based on the results and the analysis of the samples having the different deformation modes, the difference between their fatigue behaviors was discussed.

2. Experimental procedures

The samples of 0.4N and 0.6N were fabricated by using a pressurized induction meting process (VIM 4III P, ALD Vacuum Technologies AG, Germany). The ingots were hot-rolled into plates with 3 mm in thickness. After they were normalized at 1100 °C for 1 h, and then quenched into room temperature in order to acquire similar grain size of the samples which is a critical factor for fatigue properties [35,36]. Table 1 presents the compositions of the samples. Tensile tests were conducted 4 times for each sample according to ASTM E-8 at a crosshead speed of 2 mm/min using a tensile test machine (INSTRON 5882, Canton, MA).

Based on the tensile properties, fatigue tests were performed in a tension-tension mode at room temperature by using a fatigue testing machine (INSTRON 8802, Canton, MA). In high-cycle fatigue tests, the loading axis was parallel to the rolling direction of the specimens. The sinusoidal-cyclic stresses with a stress ratio (R) of 0.1 were applied at a frequency of 10 Hz. The specimens of a plate type for the tests were designed and prepared in accordance with ASTM E-466, as shown in Fig. 1 [37,38]. Referring to the result of the tensile testing, maximum stresses from 575 MPa to 450 MPa were applied to the fatigue specimens. The fatigue test was finished when the cycle number arrived at 10^7 or the specimens were fractured.

A microstructure analysis and the fractographs of the specimens were investigated mainly using Field-Emission Scanning Electron Microscopy (FE-SEM, JSM-7001F, JEOL, Japan). Electron Back-Scattered Diffraction detector (EBSD, NordlysNano, OXFORD Instruments, UK) and Transmission Electron Microscopy (TEM, JEM-2100F, JEOL, Japan) were used to characterize changes in the microstructures of the tested samples. Specimens for FE-SEM with EBSD were prepared after Ni-plating to protect the fracture surface, and then polished with emery papers (from #200 to #2400, diamond suspension (3 μm, 1 μm)) and colloidal silica (0.025 μm). A focused ion beam machine (FIB, JIB-4601F, JEOL, Japan) was used to prepare thin foil TEM samples beneath the fractured surface.

3. Results and discussion

3.1. Initial microstructures and mechanical properties

Fig. 2 shows microstructures of the tested steels obtained by using EBSD. The steels consist of an austenite single phase with annealing twins, and their grain sizes are similar; the grain sizes of the steels with

Table 1
Chemical composition (in wt%) of the investigated alloys.

Alloy	Fe	N	C	Mn	Cr	N+C
0.4N	Balance	0.38	0.013	10.04	18.04	0.393
0.6N	Balance	0.59	0.017	10.39	18.11	0.607

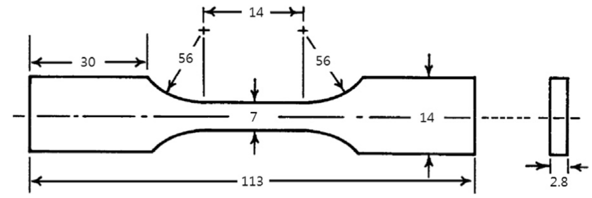

Fig. 1. Dimension of fatigue specimen (in mm) in accordance with ASTM E466.

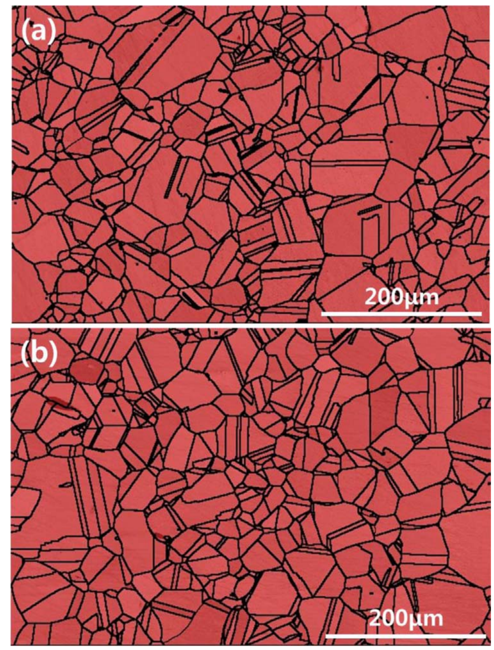

Fig. 2. EBSD band contrast images of (a) 0.4N and (b) 0.6N.

Table 2
Tensile properties of the investigated alloys.

Alloy	YS, MPa		UTS, MPa		Elongation, %	
	Value	Standard deviation	Value	Standard deviation	Value	Standard deviation
0.4N	445	13.2	935	5.2	77.5	2.1
0.6N	537	7.4	928	5.8	70.3	2.2

twin boundaries are measured to be approximately 20 μm by ASTM E112. As shown in Table 2, ultimate tensile strength (UTS) of 0.4N is similar to that of 0.6N even though yield strength (YS) of 0.4N is inferior to that of 0.6N. In the case of the YS, considering the similarity of the grain size and the composition of substitutional elements, the difference between the YS values results from solid solution strengthening by the different nitrogen content. The effect of nitrogen on the YS by the solid solution strengthening is estimated to be approximately 351.73 MPa/wt% [39].

However, the result of the UTS of the samples is attributed to the different deformation modes which are related to stacking fault energy (SFE) of the steels. According to Lee et al. [17], SFE of austenitic Fe-18Cr-10Mn steels can be estimated by an equation considering the contribution of both C+N and C/N; SFE (mJ/m^2) =−5.97+39.94(C+N in wt%) +3.81(C/N). The SFE of 0.4N is calculated to be 9.8 mJ/m^2 which is low enough to form DIMT during plastic deformation, and the SFE of 0.6N is 18.5 mJ/m^2 that could form the deformation twins. In Fig. 3, contrary to the work-hardening rate of 0.6N, the rate of 0.4N increases over 20% of true strain. The tendency of the work-hardening rates indicates that the DIMT of 0.4N is more effective on strengthening than the deformation twins of 0.6N. It is plausible that the DIMT