Materials Science and Engineering A 528 (2011) 7257–7266

Contents lists available at ScienceDirect

Materials Science and Engineering A

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

Correlation of austenite stability and ductile-to-brittle transition behavior of high-nitrogen 18Cr–10Mn austenitic steels

Byoungchul Hwang*, Tae-Ho Lee, Seong-Jun Park, Chang-Seok Oh, Sung-Joon Kim

Korea Institute of Materials Science, 797 Changwondaero, Changwon 641-831, Republic of Korea

ARTICLE INFO

Article history:
Received 5 April 2011
Received in revised form 21 May 2011
Accepted 7 June 2011
Available online 14 June 2011

Keywords:
High-nitrogen austenitic steels
Ductile-to-brittle transition
Austenite stability
Deformation-induced martensite
Brittle fracture

ABSTRACT

Ductile-to-brittle transition behavior of high-nitrogen 18Cr–10Mn austenitic steels containing different contents of Ni, Mo, Cu as well as nitrogen is discussed in terms of austenite stability and associated deformation-induced martensitic transformation (DIMT). Electron back-scattered diffraction and transmission electron microscopy analyses of cross-sectional area of the Charpy impact specimens fractured at −196 °C indicated that the brittle fracture planes were almost parallel to one of {1 1 1} slip planes and some metastable austenites near the fracture surface were transformed to α′-martensite by localized plastic deformation occurring during crack propagation. Quantitative evaluation of deformation-induced martensite together with characteristics of true stress–strain and load–displacement curves obtained from tensile and Charpy impact tests, respectively, supported that DIMT might take place in high-nitrogen austenitic steels with relatively low austenite stability. The occurrence of DIMT decreased low-temperature toughness and thus increased largely ductile-to-brittle transition temperature (DBTT), as compared to that predicted by empirical equations strongly depending on nitrogen content. As a result, the increased DBTT could be reasonably correlated with austenite stability against DIMT.

1. Introduction

The development of high-nitrogen austenitic steels has been largely driven by the fact that these materials provide a unique combination of high strength, good ductility, non-ferromagnetism, and enhanced corrosion resistance because of the beneficial effect of nitrogen [1–8]. Nitrogen as a strong austenite stabilizer is expected to replace Ni which is expensive and results in an allergic reaction in human skin. Furthermore, nitrogen alloying, especially together with Mo, improves the resistance to localized corrosion and general corrosion in some environments [1,5,7]. Therefore, high-nitrogen austenitic steels have been regarded as one of the most promising structural materials from the economic and body-friendly viewpoints.

Some high-nitrogen austenitic steels, however, undergo a ductile-to-brittle transition by unusual brittle fracture at low temperatures due to high nitrogen content, even though they have a face-centered cubic (fcc) structure [9–20]. Defilippi first observed the low temperature brittle fracture of high-nitrogen austenitic steels and suggested that deformation faulting was involved in the brittle fracture mechanism [9]. After that, many investigators explained the fracture mode in terms of slip band cracking [10–14], fracture along twin lamella [14], deformation twin intersection [15,17], and ε-martensite formation [19] with respect to fracture initiation. Even so, most of them agree with the fact that a strong planarity of dislocation slip along {1 1 1} plane is closely concerned with transgranular brittle fracture at low temperature when it comes to fracture propagation [9–20].

With ever increasing environmental requirements, on the other hands, studies on the reduction of alloying elements such as Mn, Ni, and Mo have been steadily carried out in high-nitrogen Cr–Mn austenitic steels. In the steels with reduced amounts of alloying elements including nitrogen, however, some austenites can transform to martensite phase due to a decrease in austenite stability, which is referred to as deformation-induced martensitic transformation (DIMT) [16,20–23]. When a large amount of plastic deformation occurs during Charpy impact tests, therefore, DIMT may affect the toughness and ductile-to-brittle transition temperature (DBTT) of high-nitrogen Cr–Mn austenitic steels [9,16]. It is well established that the DIMT is dependent on chemical composition, temperature, plastic strain, applied stress state, grain size, strain rate, and deformation mechanism [6,21–23]. The M_{d30} temperature where 50% α′-martensite formed after 30% tensile deformation has been widely used as a quantitative criterion to estimate austenite stability against DIMT and some empirical equations that consider chemical composition have been proposed [6,24].

The objective of the present study is to elucidate the correlation of austenite stability and ductile-to-brittle transition behavior of high-nitrogen 18Cr–10Mn austenitic steels containing different

* Corresponding author. Fax: +82 55 280 3599.
E-mail address: entropy0@kims.re.kr (B. Hwang).

0921-5093/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2011.06.025

contents of Ni, Mo, Cu as well as nitrogen. Instrumented Charpy impact test and fractographic analysis were performed to examine the fracture mode and ductile-to-brittle transition behavior. In addition, transmission electron microscopy (TEM) and electron back-scatter diffraction (EBSD) analyses were carried out on the cross-sectional area beneath the fracture surface of Charpy impact specimens tested at low temperatures in order to understand the ductile-to-brittle transition behavior in terms of brittle crack propagation and deformation microstructure.

2. Background

In materials low-temperature brittle fracture is comprehensively associated with the temperature sensitivity of yield stress [1,25,26]. Peierls stress (τ_p), a shear stress required to move a dislocation through a crystal lattice in a particular direction, is a key factor responsible for the low-temperature brittle fracture. The Peierls stress has been shown to depend to a large extent on the dislocation width ($w = a/1-\nu$), which is involved in atomic structure and the nature of atomic bonding forces, and the distance between atoms in the slip direction (b) in the form below [25,26]

$$\tau_p \approx \frac{2G}{1-\nu} e^{-2\pi w/b} \approx \frac{2G}{1-\nu} e^{[-2\pi a/(1-\nu)b]} \tag{1}$$

where a refers to the distance between slip planes and ν to Poisson's ratio.

From Eq. (1), the Peierls stress for a given plane tends to decrease with increasing distance between planes. Because the distance between planes increases with planar atomic density, slip is preferred on closely packed planes. Since the Peierls stress is affected by the short-range stress field of the dislocation core, it is sensitive to the thermal energy in the lattice and thus to the test temperature [25,26]. At low temperatures where thermal enhancement of dislocation motion is restricted, therefore, the Peierls stress is relatively large, compared to that at elevated temperatures. In fcc metals that have wide dislocations, however, the variation in Peierls stress with decreasing temperature is insignificant because the Peierls stress is very small to begin with. Thus, there is negligible temperature sensitivity of yield stress in fcc metals such as aluminum, copper, and austenitic steels.

However, high-nitrogen austenitic steels with fcc structure have exceptionally a strong temperature dependence of yield stress since nitrogen gives rise to a large increment of yield stress in the low temperature region, which is quite different from the behavior of conventional fcc metals. It has been well known that the temperature dependence of yield stress increases with increasing nitrogen content and decreasing grain size [1,2,11,14]. Sandström and Bergqvist [27] were the first to attribute the influence of nitrogen at low temperatures to the control of plastic flow by a thermally activated process. They suggested that nitrogen generates some obstacles for dislocation slip or enhances the effectiveness of the already existing obstacles which need the thermal energy to be overcome. A substantial understanding of the low-temperature properties of high-nitrogen austenitic steels was achieved from precise mechanical tests performed by Obst and Nyilas [28], and showed that a temperature dependence of yield stress is typical for fcc metals with low stacking fault energy (SFE).

Fig. 1 represents a schematic illustration showing the temperature dependence of yield and fracture stresses of high-nitrogen austenitic steels. The occurrence of ductile or brittle fracture at a given test temperature depends on whether the yield stress or the fracture stress reaches first. As the fracture stress of metals is mostly higher than the yield stress and hardly depends on test temperature, the temperature dependence of yield stress is more significant. Since higher nitrogen content increases the temperature sensitivity of yield stress, a ductile-to-brittle transition occurs at point A where yield stress and fracture stress intersect.

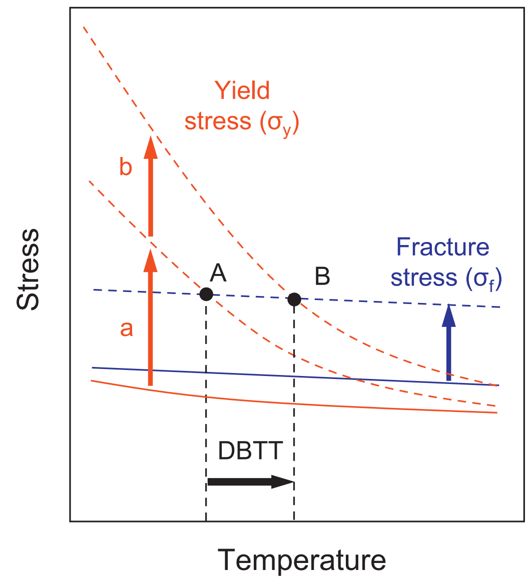

Fig. 1. Schematic illustration of temperature dependence of yield and fracture stresses high-nitrogen austenitic steels. The 'a' and 'b' indicate an increase in yield stress caused by temperature sensitivity and grain boundary strengthening, respectively. The contribution of grain boundary strengthening shifts a DBTT to higher temperature (from point A to point B).

Although the grain boundaries of austenitic steels are generally not effective strengtheners, on the other hand, increasing nitrogen content largely enhances grain boundary strengthening because planar slip is expected to increase the efficiency of grain boundary to dislocation motion due to higher nitrogen content [1,11]. The contribution of grain boundary strengthening increases with decreasing temperature and increasing nitrogen content [1,2,14]. Thus, a further increase in yield stress brings about a shift of DBTT to higher temperature (from point A to point B). To summarize, there are two main factors for the influence of nitrogen on DBTT, *i.e.* a temperature sensitivity of yield stress and a strong grain boundary strengthening. For these reasons, nitrogen content can significantly affect the ductile-to-brittle transition behavior of high-nitrogen austenitic steels.

So far, it has been reported that two empirical equations to predict the DBTT of Ni-free high-nitrogen Cr–Mn austenitic steels are predominantly dependent on nitrogen content and only to a smaller extent by the carbon content as follows (elements in weight percent) [3,4,7,8].

$$\mathrm{DBTT} = 300 \quad [\%\mathrm{N}] - 303 \quad [^\circ\mathrm{C}] \tag{2}$$

$$\mathrm{DBTT} = 300 \quad [\%\mathrm{N}] + 100 \quad [\%\mathrm{C}] - 303 \quad [^\circ\mathrm{C}] \tag{3}$$

According to these equations, nitrogen content can be a limiting factor for the application of Ni-free high-nitrogen austenitic steels at low temperatures. For instance, when the DBTT required is acceptable at approximately $-60\,^\circ$C, *i.e.* below room temperature and close to polar regions, the nitrogen content should be less than about 0.8 wt.%. By the way, it has been previously recognized that the addition of Ni alleviates the problem relevant to DBTT due to an increase in SFE or has no any influence on DBTT [4,11,29]. Nevertheless, few systematic studies on the effect of austenite stabilizing elements such as Ni and Cu on low-temperature toughness and DBTT have been carried out yet.