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The fracture and plastic deformation of aluminum alloyed Hadfield steels

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ABSTRACT

The plastic deformation and fracture behavior of Fe–Mn–Al–C cast Hadfield steels were studied. According to the Al, Mn and carbon contents, five different compositions of Hadfield steels were selected in order to study the orange-peel phenomenon, plastic deformation and fracture modes of the alloys using the tensile test. It is observed that Al addition increases the yield strength but decreases the ultimate tensile strength and the elongation. In addition, Al addition decreases or disappears the peeling of the surface and suppresses the twinning induced by plastic deformation. The fractographies of tensile specimens show that in the fractured surfaces of standard and 1.5% Al Hadfield steels, there are many secondary micro- or nano-dimples between the primary large dimples and shear rupture do not involve. But, the cleavage fractures with intergranular cracks appeared when more Al is added.

1. Introduction

Hadfield steels are well known for their high strain hardening, good toughness and their application in the severe service combining abrasive and heavy impact [1,2] such as in excavators, mineral crushing equipment and railroad rail [3]. They have austenitic (FCC) structure and a low stacking fault energy (SFE), $\gamma = 23\,\mathrm{mJ/m^2}$, for a 12% Mn concentration, with nominal composition of Mn 13 wt.% and C 1.2 wt.% [1].

In the recent works, the unusually high strain hardening of aluminum-free Hadfield steel have been attributed to the formation of twin boundaries that provided strong barriers to dislocation motion [1–5]. In addition, other reasons such as the dynamic strain aging, brought about by the reorientation of carbon members of C–Mn couples in the cores of dislocations, have been put forward to explain the unusual work-hardening behavior [1].

The low SFE and high concentration of interstitial atoms (5–8 at.% C) have pronounced effects on the yielding and strain hardening of this material. The low SFE promotes the formation of deformation twins, while the high concentration of carbon interstitials dramatically increases the friction stress influencing the twin nucleation stresses [4,6]. Versus some old researchers [1,2], austenite-to-martensite transformation cannot occur by plastic deformations in the steel [3]. Some extensive single crystal studies by the Karaman et al. [2,6,7] have elucidated the competing effects of slip and twinning in the steel. They showed the splitting of grains or single crystals into twinned and untwined regions and the ensuing interference of deformation by these twinned boundaries account for the “ultra” strain-hardening behavior.

By knowing the effect of short length diffusion of carbon in the dislocation cores and on the dislocation locking in the Hadfield steels, a new strategy for improvement of mechanical properties is introduced. It is addition of an element that do not creates any carbides, dissolves in the austenitic matrix and decreases carbon activity in the austenite [1,8–10]. Thus, some recent studies [8–10] proposed that aluminum is added to austenitic manganese steel because it increases the SFE.

The main objective of this study is the characterization of fracture and deformation processes occurring in cast austenitic manganese (Hadfield) steels that alloyed with aluminum.

2. Experimental procedure

According to Table 1, five cast Hadfield steels with different Al, Mn and carbon contents were used. The steel samples were manufactured by 30 kg induction furnace in Ar atmosphere. The cast samples were solid solution treated at 1070 °C for 90 min and then water quenched. After the heat treatment, the specimens exhibited a single austenite phase by grain sizes about 150–200 μm. Tensile tests were done under strain rate control ($2 \times 10^{-3}\,\mathrm{S}^{-1}$) at the room temperature. An average of three measurements was performed on each alloy. A video system was used for recording of macroscopic deformation behavior.

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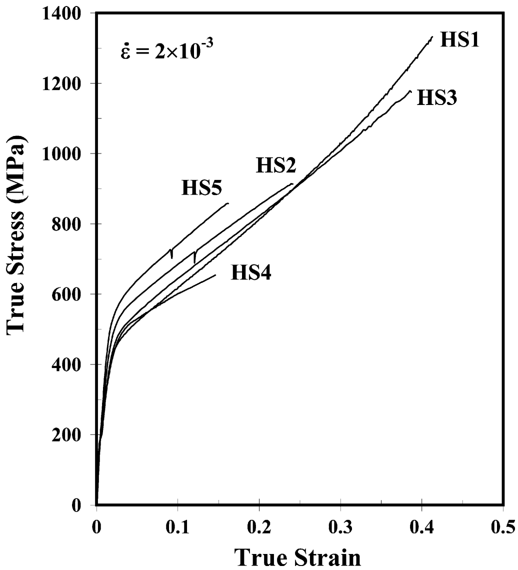

Fig. 1. The true stress–true strain curves of experimental alloys at the room temperature.

The optical microscopy and scanning electron microscopy (SEM) were used for microstructural studies before and after deformation and fractography. The metallographic specimens were cut vertically from the cross-section of tensile samples and then cold mounted and ground to 1200 grit by SiC papers. Then they were polished with 1 and 1/4 μm grit alumina powders. To distinguish twins from slip bands, the specimen surfaces were repolished and electroetched with a 30% solution HCl in ethanol. In this method, only the twinning marks and grain boundaries are visible [11].

Table 1
Chemical composition of experimental steels.

Steel code	Steel code	Alloying element (wt.%)						
		Al	Mn	C	Si (max.)	Ni (max.)	Cr (max.)	Fe
HS1	133	max = 0.1	14	1.4	0.3	0.03	0.06	Bal.
HS2	223	1.5	12	1.4	0.3	0.03	0.06	Bal.
HS3	232	1.5	14	1.2	0.3	0.03	0.06	Bal.
HS4	322	3	12	1.2	0.3	0.03	0.06	Bal.
HS5	333	3	14	1.4	0.3	0.03	0.06	Bal.

3. Results and discussion

3.1. Tensile behavior

Fig. 1 shows the true stress–true strain curves of experimental alloys. It is obvious that the chemical composition has significant effects on the tensile behavior of Hadfield steel. Especially, Al addition can increase the tensile strength but decrease the total elongation and the ultimate tensile strength. The decreasing effect of Al on the UTS and elongation are growing with increasing the Al content and decreasing the manganese content. On the other hand, it can be seen that yield strength of HS4 alloy (with 3 wt.% Al) is lower than other Al alloyed Hadfield steels (HS5, HS3 and HS2).

The phase transformations and the mechanical properties of stainless, Hadfield and other highly alloyed austenitic steel grades are closely related through the transformation-induced plasticity (TRIP) effect or twining-induced plasticity (TWIP) effect [12]. Indeed, during straining, the metastable austenite transforms into martensite or twining, enhancing the ductility and the resistance. The transformations are governed by two parameters: the thermodynamic relative stability of the different phases which depends on the chemical composition and the temperature and the stack-

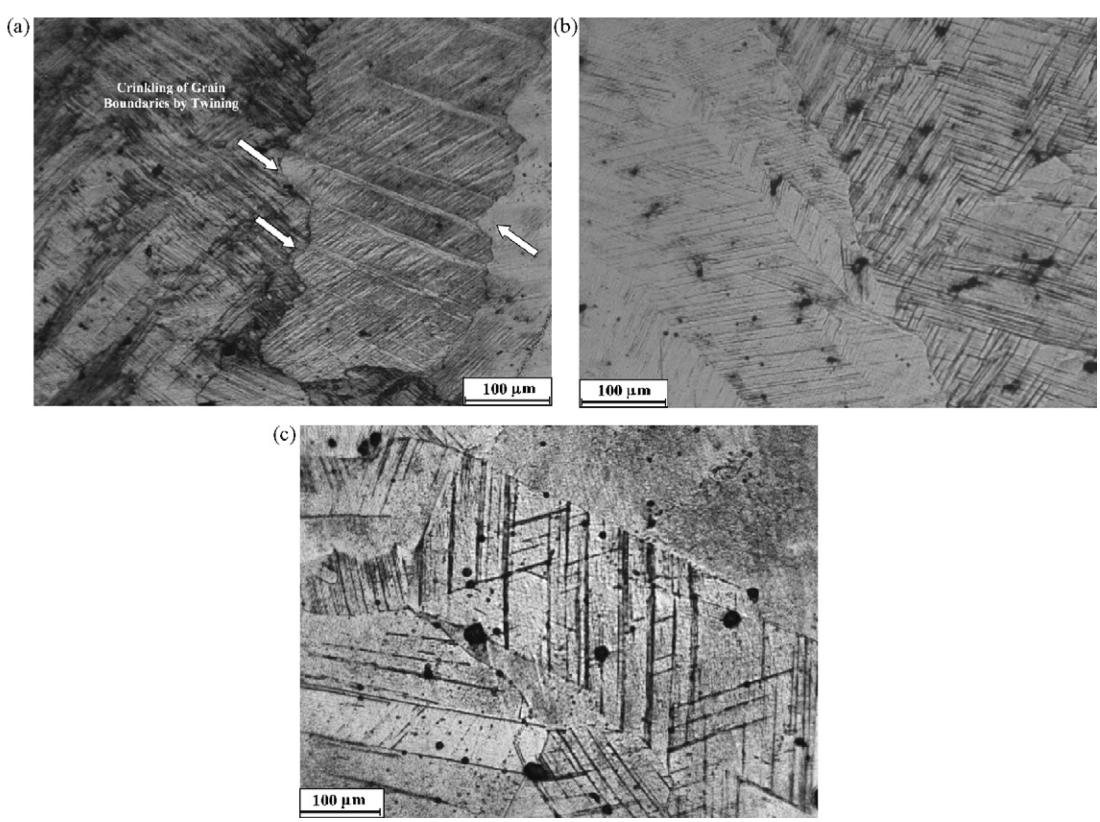

Fig. 2. The optical microscopy image of the microtwin formation in the tensile specimens: (a) HS1 (b) HS2 and (c) HS5 alloys after fracture (electroetched by HCl).