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Deformation, fracture, and wear behaviours of C+N enhancing alloying austenitic steels

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ABSTRACT

The deformation, fracture, and wear behaviours of two new C+N enhancing alloying austenitic steels (CNEASs) for railway crossings under high speeds and heavy loads were investigated by tensile, Charpy impact, and sliding wear tests, in comparison with the traditional Hadfield austenitic steel. The main plastic deformation mechanism of the CNEASs was deformation twinning due to its low stacking fault energy (SFE). The enhanced strength and plasticity resulted from the large amounts of ultra-fine nano-twinning that occurred during plastic deformation, while the oversaturation effect of nitrogen on CNEASs further increased the hardness and work hardening capacity. Contrary to the increased ductile to brittle transition temperature (DBTT) caused by nitrogen in austenitic steel, the new studied steel exhibited a lower DBTT as compared to the Hadfield steel, because the combined alloying with C+N enhanced the metallic character of the interatomic bonds, increasing the fracture-resistance under cryogenic temperatures. Sliding wear tests showed that abrasive wear dominated the wear behaviour of the CNEASs. The remarkable improvement of wear resistance in the steels enhancing alloyed with C+N, particularly at high temperatures, was attributed to the formation of thick tribo-oxides on the worn surface under the effect of Cr and nitrogen. Therefore, the results demonstrated that the experimental steels possessed a higher strength, plasticity, hardness, impact toughness at cryogenic temperatures, work hardening capacity, and wear resistance as compared to the Hadfield steel. This makes the new steel an ideal material for railway crossings under high speeds and heavy loads.

1. Introduction

The traditional Hadfield austenitic manganese steel Mn12C1.2 has been used for railroad crossings for over 120 years due to its high strength, toughness, and impact wear resistance [1]. Today, Hadfield steel is extensively used throughout the world for special crossings and still remains "the metal par excellence for the purpose" and, since its introduction, nothing has been found superior to it [2]. Despite the fact that several bainitic steels without carbides are being used for railway crossings in China [3], industrially developed countries such as America, Russia, and those in Europe still prefer Hadfield steel. However, with increasing rail loads and running speeds, the railroad crossing material must have higher strength, as well as greater work hardening and wear resistance, in order to avoid whole rail deformation with heavy load runs. At the same time, higher impact toughness at cryogenic temperatures should also be required to allow for the use of railway crossings in severely cold areas. Therefore, it is necessary to investigate a new high manganese austenitic steel which possesses excellent and balanced properties of strength, work hardening, wear resistance, and impact toughness at cryogenic temperatures for use in railway crossings at high speeds and heavy load conditions.

Extensive studies have shown that alloying with nitrogen can produce a more noticeable improvement in the strength, work hardening capacity, and wear resistance without loss of toughness in austenitic steels, as compared to alloying with carbon [4–9]. This means that nitrogen is an ideal alloying element for high manganese austenitic steel. Thus, many researchers have recently carried out investigations with austenitic steel alloyed with nitrogen. For example, Degallaix studied the mechanical properties of high nitrogen steels. They observed that the proof stress was increased by nitrogen alloying through a combination of solid-solution hardening and a grain-size effect [10]. Müllner investigated the strengthening and work hardening characteristics of high nitrogen austenitic steel and reported that the onset of deformation twinning was shifted to lower strains and higher stresses with the increase of nitrogen, which resulted in a larger contribution to the total strain [11]. Kim reported that the high wear resistance of the high nitrogen austenitic Cr18Mn18Mo2N0.9 steel was attributed to the solid solution strengthening and high-strain hardening effects of the nitrogen [12]. It has also been recently reported that the addition of low

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nitrogen content in Hadfield steel can improve the tensile and compressive properties in single crystal and polycrystalline steel [13,14], and Hadfield steel weld repairs was strengthened as well [15]. Although nitrogen has many beneficial effects on the conventional mechanical properties of austenitic steel, the deteriorated toughness caused by N-induced cleavage-like brittle fractures at cryogenic temperatures has received increased attention [16–18]. At present, the cleavage-like fracture mechanism in austenitic steel induced by the addition of nitrogen still has an argument, and two generally accepted ideas have been proposed: the decrease of stacking fault energy (SFE) [19] and enhanced localised plasticity [20,21].

In order to obtain better properties, according to studies by Gavriljuk et al., if carbon or nitrogen was substituted for carbon+nitrogen in a face-centred-cubic (fcc) Fe-based solid solution, the free electron concentration would be greater, resulting in an enhanced metallic character of the interatomic bonds. The change not only enhances the work hardening effect caused by the promoted short range atomic ordering and planar slipping, but also increases the strength while maintaining good plasticity and toughness [22–25]. Most of the previous studies have added nitrogen to the austenitic stainless steel with low and ultra-low carbon, but there have been few reports on the effect of the combined C+N enhancing alloying on high manganese austenitic steel.

The solid solubility of nitrogen in pure melted iron is only 0.04 wt%, which rises with the increase of Cr and Mn [26,27]. Therefore, based on the traditional Hadfield steel, two new CNEASs have been melted and designed by increasing the content of Mn and Cr in order to increase the solubility of nitrogen. Since the temperature of the rail and the railway crossings may reach below −60 °C in some severely cold climates as well as up to 70 °C on the surface of the rail in warm climates, the railway crossings must be able to withstand a large temperature range. In addition, the temperature may rise to 100–800 °C on the surface of crossings during its usage [28–31]. Thus, the crossing material must possess a higher wear resistance at high temperatures and a better toughness at cryogenic temperatures. Taking into account these applied backgrounds, the objective of this paper is to investigate the deformation, fracture, and wear behaviours of the new CNEASs through tensile and Charpy impact tests in a temperature range from −196 to 20 °C, as well as a sliding wear test at 20 °C and 300 °C in comparison with Hadfield steel.

2. Materials and experimental procedure

The Hadfield steel Mn12C1.2 was melted in a common vacuum induction furnace, then forged and heat treated at 1050 °C for 1 h followed by water quenching. On the other hand, the CNEASs were obtained at a high pressure of gaseous nitrogen, forged and treated at 1100 °C for 2 h in order to entirely dissolve the carbides and nitrides, followed by water quenching. The microstructures of the investigated steels are shown in Fig. 1. The matrix of all the alloys were formed such that they were in a single austenitic phase and the grain boundary was straight and smooth, typical of the recrystallisation of austenite. It was also observed that the grain size of CNEASs was smaller than Mn12C1.2 steel.

The chemical compositions of the experimental alloys are presented in Table 1. The equation of solubility of nitrogen in liquid steel proposed by Li et al. [32] is as follows:

$$\begin{aligned}\lg[\%\mathrm{N}] = & 1/2\lg(p_{\mathrm{N}_2}/p^{\theta}) - 188/T - 1.17 - (3280/T - 0.75) \\ & \times(0.13[\%\mathrm{N}] + 0.118[\%\mathrm{C}] + 0.043[\%\mathrm{Si}] - 0.024[\%\mathrm{Mn}] \\ & + 3.2\times10^{-5}[\%\mathrm{Mn}]^2 - 0.048[\%\mathrm{Cr}] + 3.5\times10^{-4}[\%\mathrm{Cr}]^2 \\ & + \delta_{\mathrm{N}}^{p}\lg\sqrt{p_{\mathrm{N}_2}/p^{\theta}}) \end{aligned} \quad (1)$$

where δ_N^p is the modified coefficient of influence N_2 partial pressure on N_2 activity. Here, $\delta_N^p = 0.06$ when $p_{N_2}/p^{\theta} \geq 1$ and $\delta_N^p = 0$ when $p_{N_2}/p^{\theta} < 1$. The melting temperature of the liquid steels is 1600 °C, for $p_{N_2} = 0.081$ MPa and $p^{\theta} = 0.1$ MPa.

According to Eq. (1), the maximum solubility of nitrogen was calculated to be 0.16 and 0.20 wt% when carbon was 0.8 and

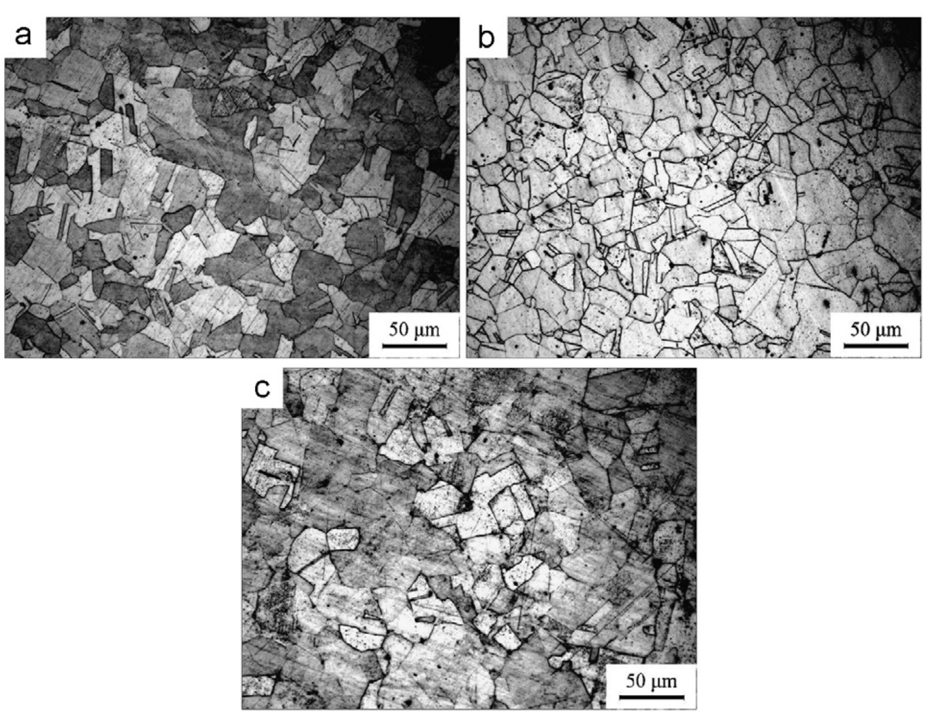

Fig. 1. Optical microscopy micrographs of steels showing single austenite (a) C0.6N0.3; (b) C0.8N0.2; (c) Mn12C1.2.