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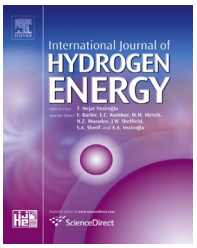

Review Article

# Overview of hydrogen embrittlement in high-Mn steels

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ABSTRACT

Hydrogen and fuels derived from it will serve as the energy carriers of the future. The associated rapidly growing demand for hydrogen energy-related infrastructure materials has stimulated multiple engineering and scientific studies on the hydrogen embrittlement resistance of various groups of high performance alloys. Among these, high-Mn steels have received special attention owing to their excellent strength – ductility – cost relationship. However, hydrogen-induced delayed fracture has been reported to occur in deep-drawn cup specimens of some of these alloys. Driven by this challenge we present here an overview of the hydrogen embrittlement research carried out on high-Mn steels. The hydrogen embrittlement susceptibility of high-Mn steels is particularly sensitive to their chemical composition since the various alloying elements simultaneously affect the material's stacking fault energy, phase stability, hydrogen uptake behavior, surface oxide scales and interstitial diffusivity, all of which affect the hydrogen embrittlement susceptibility. Here, we discuss the contribution of each of these factors to the hydrogen embrittlement susceptibility of these steels and discuss pathways how certain embrittlement mechanisms can be hampered or even inhibited. Examples of positive effects of hydrogen on the tensile ductility are also introduced.



## Contents



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## Introduction

Since the development of Hadfield steel in 1882 [1], high-Mn steels have been recognized to have superior work hardening capacity enabling excellent ductility-strength balance. In particular, the development of twinning-induced plasticity (TWIP) steels, which constitute a class of austenitic alloys characterized by deformation driven twin and – in some cases – martensite formation, created renewed interest in high-Mn steels as candidate materials for manufacturing structural parts for automobiles [2–6]. Moreover, high-Mn steels and compositionally more complex yet related alloys with new functions have been developed, e.g., seismic-resistant alloys [7–9], biodegradable alloys [10–12], and high entropy alloys [13–15]. With this background, various high-Mn steels have been investigated regarding their mechanical response under severe loading conditions and harsh environments such as for instance high speed deformation [16,17], cryogenic temperatures [18,19], and hydrogen atmospheres.

Currently, many countries are undertaking efforts towards developing a hydrogen-based energy supply and consumption chain which is capable of matching the needs of modern mobile and industrialized societies. In this regard, the development of hydrogen-resistant steels as well as hydrogen-containing materials has become a bottleneck technology required for the cost-efficient realization of hydrogen-energy-related generation, storage and processing infrastructures.

From a viewpoint of mechanical properties when exposed to hydrogen charging environments, the low diffusivity of hydrogen in *fcc* austenite high-Mn steels, which suppresses severe dislocation/hydrogen interactions, had been projected to enable the development of a new class of hydrogen-resistant structural materials. For instance, TWIP steels indeed have higher resistance to hydrogen embrittlement when compared to low carbon steels, martensitic steels, dual-phase steels, and transformation-induced plasticity steels [20–22]. However, high-Mn steels may also undergo hydrogen-related fracture in some cases where both, severe mechanical and hydrogen charging conditions apply, such as occurring when the materials are subjected to a high current density [23,24] and to heavy deformation as deep-drawing [25–28]. An example of hydrogen-induced delayed fracture in high-Mn austenitic steels is shown in Fig. 1. Towards the improvement of hydrogen embrittlement susceptibility of high-Mn steels with high strength, it is thus inevitable to better understand the underlying factors and mechanisms affecting the material's resistance to hydrogen embrittlement.

A specific key strategy for enhancing the resistance of high Mn steels to hydrogen embrittlement lies in controlling the thermodynamic stability of the austenite phase through the addition of Mn [29,30]. Slow strain rate tensile tests (SSRT) were conducted using hydrogen-charged specimens of austenitic Fe-high Mn-C steels [24,31,32] for the quantitative evaluation of the material's hydrogen embrittlement susceptibility. The SSRT results demonstrated reduction in tensile ductility and various modes of hydrogen-assisted cracking. Later on similar coupled compositional – mechanical studies revealed that the vulnerability of the alloys to hydrogen-induced delayed cracking can be improved by the addition of Al in solid solution [25,32,33].

Despite numerous attempts to understand all the underlying internal damage effect, the mechanism of hydrogen embrittlement in high-Mn steels has not yet been elucidated, probably due to the many interacting influence factors. In general, hydrogen embrittlement susceptibility of a given material depends on the strength level [34,35], residual stress [25,36], hydrogen content [37,38], and microstructural features such as lattice defect density [39,40]. Moreover, similar to the case of Fe-Cr-Ni austenitic stainless steels [41,42], the formation of $\alpha'$-martensite is a critical factor causing hydrogen embrittlement in high-Mn austenitic steels. In addition, $\varepsilon$-martensite formation, deformation twinning, strain aging, formation of surface oxidation layers, etc. seem to affect the material's hydrogen embrittlement susceptibility. In order to explore the individual effects associated with these factors in detail, several investigations with more systematic composition and microstructure control as well as pertinent simplifications of the embrittlement boundary conditions have been presented in the past [32,43–45].

This review presents an overview of the recent extensive fundamental studies on hydrogen embrittlement of high-Mn steels with aim towards obtaining a comprehensive understanding of the hydrogen embrittlement mechanisms in these materials. More specifically, we discuss four aspects: (1) microstructural cracking sites and crack growth pathways; (2) effects of segregation and its kinetics of interstitial atoms such as hydrogen and carbon; (3) alloying element effects and (4) microstructural and alloying approach for endowing these steels with better resistance against hydrogen embrittlement. All results presented in this overview were obtained at room temperature. All alloy compositions are given in weight percentage.

## Microstructure effects assisting crack formation

Fig. 2a shows the characteristic hydrogen-induced degradation of the tensile ductility in an Fe-18Mn-0.6C austenitic

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