

Simultaneously improving the strength and ductility of coarse-grained Hadfield steel with increasing strain rate

F.C. Liu, Z.N. Yang, C.L. Zheng and F.C. Zhang*

State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, Qinhuangdao 066004, People's Republic of China

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In general, the strength of coarse-grained metals rises with increases in the strain rate, while the ductility decreases. However, the strength and ductility of Hadfield steel increased simultaneously with an increase in the strain rate. A maximum elongation of 64% combined with true strength of 1596 MPa was obtained at a high strain rate of $1 \times 10^1 \text{ s}^{-1}$. This is associated with the fact that Hadfield steel exhibits more strain-induced deformation twins at higher strain rates.

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Simultaneous improvement of the strength and ductility of metals has been pursued for a long time because these properties are attractive for advanced structural applications [1,2]. Over the past two decades, many efforts have been devoted to driving the grain sizes of bulk metals down into the nanometer regime for the purpose of increasing the strength of the metals [3], based on the well-known Hall–Petch relationship [4]. While these nanostructured materials offer high strength compared to their conventional coarse-grained counterparts, their ductility is often inadequate. Recently, several strategies aimed at improving the poor ductility of the metals have been reported [5–7]. Most of these approaches focused on tailoring the nanoscale features present in the nanostructured materials. Despite some encouraging reports, the improvements in ductility remain quite limited. Improving the strength and ductility of metals simultaneously remains a challenge.

In addition to microstructural refinement, one could also change the deformation parameters to increase the strength and ductility of coarse-grained metals. For example, the behaviour of increasing elongation and strength with decreasing tensile temperature in austenitic cryogenic Fe–Mn–Al steels was previously reported [8]. Researchers also showed that the strain-hardening rate increased with increasing strain rate and/or decreasing

temperature in nanostructured metals, and as a result, so did the total tensile strain [9,10]. In general, the strength of coarse-grained materials rises with an increase in the strain rate, while the ductility decreases. However, Wu et al. [11] observed an interesting phenomenon, namely that the ductility of a superaustenitic stainless steel increases significantly with increasing strain rate due to the enhanced strain-induced ϵ martensite transformation at higher strain rates.

The phenomena of transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP) have been widely observed in high-manganese steels which contain 15–30% Mn and additions of Al and Si of about 2–6% (wt.%). These steels exhibit both high strength and ductility combined with high energy absorption capacity as well as good forming properties due to the gradual transformation of austenite to martensite in the TRIP steel and the gradual formation of deformation twins in the TWIP steel during deformation [12,13]. Grassel et al. [13] showed that both TRIP and TWIP steels exhibited total elongations of more than 80% at low strain rates, although a reduction in failure strain with increasing strain rate was observed in both steels.

Austenitic Hadfield steel, which contains 10–14% Mn and 1.0–1.4% C (wt.%), possesses high wear resistance, high toughness and a high strain-hardening rate in polycrystalline form. Owing to these properties it has been widely used to manufacture excavators, crusher jaws, grinding mill liners and railway crossings. Hadfield steel has a low stacking fault energy (SFE, $\sim 23 \text{ mJ m}^{-2}$) [14],

* Corresponding author. Tel.: +86 335 8063949; fax: +86 335 8074568; e-mail: zfc@ysu.edu.cn

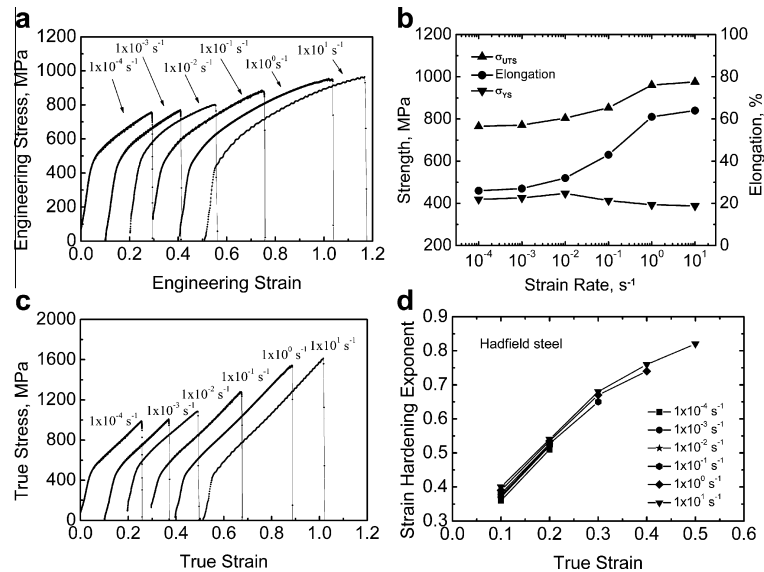


Figure 1. Tensile properties of Hadfield steel at various strain rates: (a) engineering stress–strain curves; (b) correlations between the strength and elongation with the strain rate; (c) true stress–strain curves; and (d) variation of strain-hardening exponent with true strain.

which promotes the formation of deformation twins. Early studies [15,16] demonstrated that twinning is activated in polycrystalline Hadfield steel, particularly at strains of the order of 5–10%. In addition to strain, the strain rates also have an important effect on deformation twinning [17,18]. However, the effect of strain rate on the mechanical properties and microstructural evolution of Hadfield steel is still poorly understood. If the formation of deformation twins and/or the strain-hardening rate were enhanced at high strain rates, it would be possible to achieve a combination of high strength and ductility. Therefore, the structurally related deformation behaviour of Hadfield steel was investigated over a wide strain rate range. The aim was to research the possibility of achieving enhanced ductility with a gradual formation of deformation twins at high strain rates in Hadfield steel.

The chemical composition (in wt.%) of the commercial Hadfield steel used here was 1.2 C, 12.4 Mn, 0.60 Si, 0.016 S and 0.022 P, with the remainder being Fe. A uniform austenitic microstructure was achieved by a water toughening process: the specimens were heated to 1050 °C and then held at that temperature for 1 h followed by quenching in water. Tensile specimens with a gauge length of 30 mm and a diameter of 6 mm were machined from the austenitic Hadfield steel. Room-temperature and high-temperature tensile tests were conducted using a Gleeble 3500 test machine in the strain-rate range of 1×10^{-4} – $1 \times 10^1 \text{ s}^{-1}$. Five specimens were subjected to tensile test at each strain rate. The samples which were cut from the gauge region of the deformed tensile specimens were lightly electropolished to produce a strain-free surface parallel to the tensile axis. Electron backscatter diffraction (EBSD) orientation maps were obtained using a Zeiss Supra 55 operated at 20 kV and interfaced to an HKL Channel EBSD system. Kikuchi patterns were obtained automatically at steps of 0.03 and 1 μm . Fractographs of failed tensile samples were observed by scanning electron microscopy (SEM) with a Hitachi S-4800 operating at 15 kV.

Figure 1a shows the stress–strain curves of Hadfield steels deformed at various strain rates. Both the ultimate tensile strength (UTS) and elongation conspicuously increased with increasing strain rate. The summarized UTS, yield strength (YS) and elongation are plotted in Figure 1b. The YS increased from 419 to 447 MPa when the strain rate was increased from 1×10^{-4} to $1 \times 10^{-2} \text{ s}^{-1}$, and then decreased to 388 MPa with a further increase in the strain rate to $1 \times 10^1 \text{ s}^{-1}$. Both the UTS and elongation increased gently when the strain rate was increased from 1×10^{-4} to $1 \times 10^{-1} \text{ s}^{-1}$ and then exhibited a sharp increase when the strain rate was increased from 1×10^{-1} to $1 \times 10^0 \text{ s}^{-1}$. A maximum elongation of 64% combined with the highest tensile strength of 973 MPa was obtained at a strain rate of $1 \times 10^1 \text{ s}^{-1}$. This trend violates the normal condition that the strength of materials increases with an increase in the strain rate while the ductility decreases.

The true stress–strain curves of Hadfield steel showed that the highest true stress of 1596 MPa was achieved at the strain rate of $1 \times 10^1 \text{ s}^{-1}$ (Fig. 1c). The variation of strain-hardening exponents (n) with true strain for the Hadfield steel deformed at various strain rates is summarized in Figure 1d. For the samples deformed at high strain rates, high values of n were observed at various strains. This corresponded well with the observation that elongation increased with increases in the strain rate.

Figure 2 shows the typical failed tensile specimens deformed at different strain rates. All the specimens showed uniform elongation without observable necking. This indicated that the high ductility of the Hadfield steel originated from its pre-necking elongation.

Figure 3 shows typical fractographs of Hadfield steels after tensile failure. The dominant fracture behaviour of the specimens which failed at a strain rate of $1 \times 10^{-4} \text{ s}^{-1}$ was intergranular fracture. When the strain rate was increased to $1 \times 10^{-1} \text{ s}^{-1}$, the characteristics of both intergranular and transgranular cracks were observed and the areas of microdimples became relatively

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