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Warm ductility enhanced by austenite reversion in ultrafine-grained duplex steel

Guan-Ju Cheng [a], Baptiste Gault [b], Cheng-Yao Huang [a], Ching-Yuan Huang [c], Hung-Wei Yen [a, *]

[a] Department of Materials Science and Engineering, National Taiwan University, Roosevelt Road, Taipei, Taiwan, ROC
[b] Department of Microstructure Physics and Alloy Design, Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf, Germany
[c] Iron and Steel R&D Department, China Steel Corporation, Chung Kang Road, Kaohsiung, Taiwan, ROC

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A B S T R A C T

The current work investigated the relationship between microstructure and warm deformation properties in a strong but ductile Mn-rich steel. A cold-rolled Fe-11.3Mn-0.068C-0.3Si-1.1Al-0.25Mo-0.01P-0.01S-0.0003N (in wt. %) steel was deformed isothermally after inter-critical annealing at temperatures from 550 °C to 720 °C. Deformation at 650 °C led to exceptional ductility, corresponding to total elongation of over 100%. The microstructure was characterized by electron backscattered diffraction, transmission Kikuchi diffraction, and transmission electron microscopy. It was found that the rate of austenite reversion can be accelerated by deformation, and that the transformation makes strained austenite into equiaxed grains. Exceptional ductility can be achieved when warm deformation is accompanied by austenite reversion. This research will provide metallurgical principles for warm deformation of steel under reversed transformation.

1. Introduction

Ultrahigh-strength steels are critical in the automotive, aerospace, shipbuilding, energy and robotics industries to reduce the fuel consumption and greenhouse gas emissions. However, increases in the strength of steel are usually achieved at the expense of ductility. Under loading, a lower ductility leads to less energy absorption, indicating a lower index of passenger safety [1]. Recent work has led to the development of several extremely strong but ductile steels, such as deformation-and-partition steel [2], quench-and-partition (Q&P) steel [3,4], medium manganese steel [5,6], maraging steel assisted by transformation-induced plasticity (TRIP) [7,8], ultrafine-grained (UFG) duplex steel [9], and intermetallics-strengthened low-density steel [10]. These steels have yield strengths of over 1 GPa and total elongations of over 15%. However, producing steels with high yield strengths incurs additional costs due to the facilities and consumables needed to produce high forming loads [11]. Furthermore, elastic spring-back and poor stretch flange ability have been reported for very strong cold-formed steels [11–14]. Hence, hot forming and warm forming are regaining popularity recently, despite their long histories.

In hot or warm forming, the spring-back is markedly reduced when the forming temperature is higher than 450 °C [15]. The required load for forming is much lower when the forming temperature is high. Moreover, the ductility of metal is generally better at elevated temperatures. The typical case is the press-hardened martensitic steels [16,17]. The steel is first heated to about 950 °C for austenization before being stamped into a target shape and cooled to produce a martensitic microstructure at the same time. This simple process produces very strong components. Recently, JFE applied warm forming at 400–600 °C on a high-strength steel with extensive precipitation of nanometer-sized carbides [18]. The hot or warm ductility of austenite can be over 40% [12,19,20], whereas the warm ductility of ferrite is lower than 40% [21,22].

The deformation behaviors of face-centered cubic (FCC) and body-centered cubic (BCC) crystals at elevated temperatures have been extensively studied. The hot or warm ductility can be influenced by the temperature, strain rate, crystal structure, and microstructural behaviors such as dislocation slip, recrystallization, recovery, grain growth, grain boundary sliding, grain rotation, and phase transformation [23–29]. In austenitic steels and ferritic steels, deformation is accompanied by dynamic recrystallization

* Corresponding author.
E-mail address: homeryen@ntu.edu.tw (H.-W. Yen).

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(DRX) at high temperature and dynamic recovery (DRV) at temperatures below 700 °C [28]. Excellent ductility due to DRV is achieved by the formation of polygonized substructures in elongated grains. As temperature increases to a certain range, ductility troughs can occur as a result of grain boundary sliding [24,28]. When the deformation temperature is even higher, ductility can recover as a result of DRX, which repeats the formation of equiaxed grains. The warm deformation of ferrite is more dominantly accompanied by DRV because the occurrence of DRX requires the accumulation of a critical strain [30,31]. However, S. Murty found that DRX could occur at 450–550 °C under large strain at a strain rate of 0.01 s^{-1} in an ultra-low carbon steel [32]. Grain size is also crucial. Two basic requirements are known to achieve superplasticity: a high-forming temperature and a very fine grain size [33]. Exceptional ductility has recently been achieved by grain rotation in an ultrafine-grained ferritic steel subjected to tensile test at 500 °C [34]. When grain growth significantly occurs, the ductility usually drops because of enlarged crack nuclei [27]. In duplex stainless steels [35,36] or Ti-6Al-4V [37], the growth of a duplex microstructure can be suppressed by local thermodynamic equilibrium between two phases such that superplasticity can be achieved at lower temperature. However, during austenite-to-ferrite transformation, the formation of ferritic film along grain boundaries significantly reduces ductility [24,25]. At high temperature, the strength of ferrite is lower than that of austenite, and the significant partition of strain in the ferrite film causes cracks to form along austenite grain boundaries [24,25]. To date, few reports have been published on warm deformation processes with austenite reversion, which is a martensite-to-austenite transformation [38,39].

Here, the effects of austenite reversion on warm ductility were investigated in a Mn-rich UFG duplex steel. The influences of deformation on the final microstructure and austenite stability were studied by scanning electron microscopy (SEM) with electron backscattering diffraction (EBSD), transmission Kikuchi diffraction (TKD), and transmission electron microscopy (TEM). The results and findings regarding the metallurgical principles of plasticity accompanied by martensite-to-austenite transformation are discussed.

2. Experimental procedure

The chemical composition of the studied steel is Fe-11.3Mn-0.068C-0.3Si-1.1Al-0.25Mo-0.01P-0.01S-0.0003N (in wt. %). The principles of alloy design are detailed in Ref. [9]. The addition of aluminum increases the range of temperature for inter-critical annealing. Fig. 1(a) shows the equilibrium phase fractions by weight as a function of temperature, calculated using Thermo-Calc with the TCFE9 database. The M_2C-type carbide was manually retracted from the calculation because it was not found in our microstructure investigations. The temperature range for inter-critical annealing spanned 474 °C to 706 °C. The 50 kg ingot was prepared by vacuum induction melting. This ingot was reheated to 1200 °C for 2 h and then hot rolled into 30 mm-thick plates. The steel plate was homogenized at 1100 °C for 1 h and hot-rolled to a thickness of 3.5 mm, followed by furnace cooling from 850 °C to room temperature. The hot-rolled sheets were further cold rolled into thin sheets with a thickness of 1.0 mm to enhance the accumulation of strain and transform retained austenite into martensite. After proper annealing, the steel can achieve very high yield strength, ultimate tensile strength, and total elongation [9].

The warm tensile tests were carried out on a Gleeble 1500. The schematic thermomechanical treatment is shown in Fig. 1(b). The specimens were treated at 550 °C, 600 °C, 650 °C and 720 °C for 10 min and then isothermally deformed at different strain rates (0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1}, 1 s^{-1}, and 10 s^{-1}) until fracture occurred; importantly, the warm tensile temperatures were identical to the annealing temperatures. Different annealing intervals (5, 30, and 60 min) was also investigated at 650 °C. The geometry of the dog-bone specimens is shown in Fig. 2. The values of total elongation

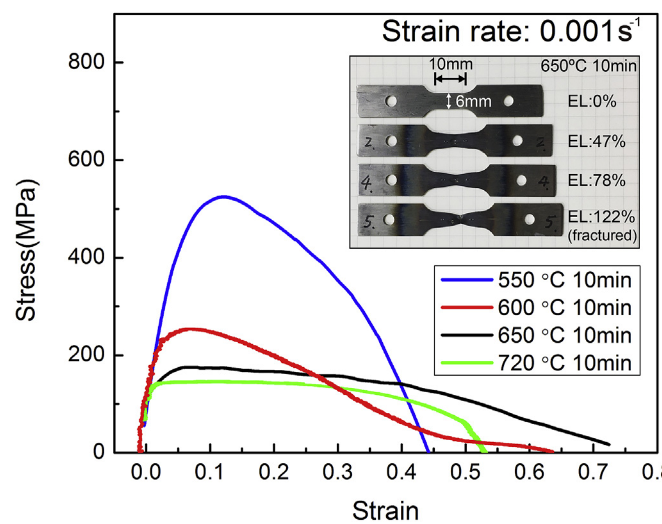

Fig. 2. The stress-strain curves of warm deformation at initial strain rate of 10^{-3} s^{-1} after pre-annealing for 10 min.

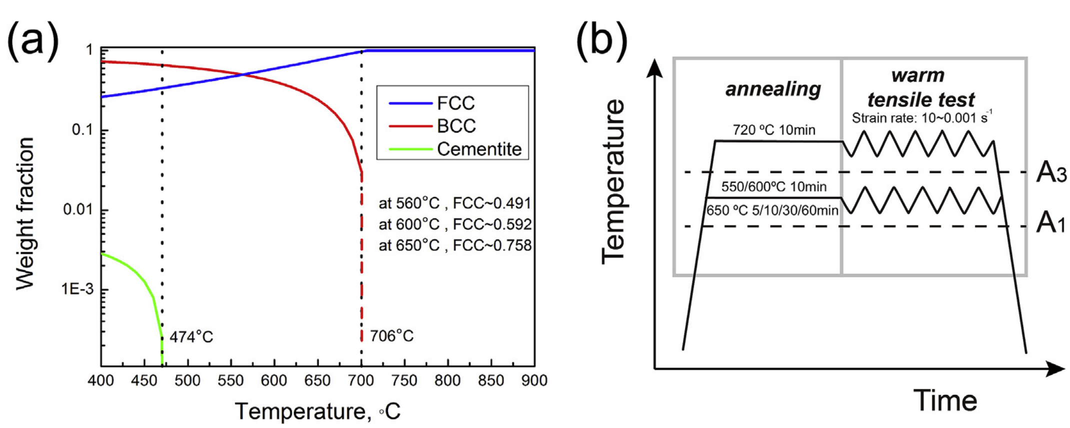

Fig. 1. (a) The equilibrium phase fractions of the alloys at different temperatures, computed using Thermo-Calc with the TCFE9 database, and (b) the schematic diagram showing the thermo-mechanical treatments for warm deformation.