Materials and Design 87 (2015) 640–649

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/jmad

Effect of ultragrain refinement on quenching and partitioning steels manufactured by a novel method

Ran Ding [a], Di Tang [a,b,c], Aimin Zhao [a,b,c,*], Hui Guo [b,c], Jianguo He [a], Chao Zhi [a]

[a] Engineering Research Institute, University of Science and Technology Beijing, Beijing 100083, China
[b] Beijing Laboratory of Metallic Materials and Processing for Modern Transportation, Beijing 100083, China
[c] Collaborative Innovation Center of Steel Technology, Beijing 100083, China

ARTICLE INFO

Article history:
Received 29 May 2015
Received in revised form 4 August 2015
Accepted 17 August 2015
Available online 20 August 2015

Keywords:
Steels
Microstructure
Mechanical property
Ultrafine grain
Retained austenite

ABSTRACT

In this study, ultrafine grained (UFG) quenching and partitioning steels was achieved by using tempered and deformed martensite as the pre-microstructure of the quenching and partitioning treatment. Compared with those manufactured through the conventional routine, superior mechanical properties were realized in UFG steels by using tempered and deformed martensite as the pre-microstructure of the quenching and partitioning treatment. The grain subdivision mechanism during deformation and the microstructure evolution during heating were investigated. Effect of carbide on the grain subdivision and its pinning effect against grain growth is highlighted. The proposed method produced UFG steels with considerable amount of retained austenite, which contributed to the enhanced mechanical properties of investigated steels.

1. Introduction

Throughout the main strengthening mechanisms, grain refinement as the best method enhancing both strength and toughness, have been extensively investigated in recent years. Ultra-fine grained (UFG) steels, which have shown attractive improvement of strength without extensive alloying, draw wide attention for replacing conventional low-alloyed high strength steels. Most existing methods for producing UFG structure in low-alloyed steels are based on severe plastic deformation (SPD) [1–8], in which large accumulated plastic strains were introduced at ambient or elevated temperatures. Representative SPD methods include high pressure torsion (HPT) [2,3], equal-channel angular pressing (ECAP) [4,5] and accumulative roll bonding (ARB) [6,7], etc. Although nanoscaled microstructure is promisingly obtained, specific devices and processes are acquired while the mass production is difficult. One alternative technique for producing UFG microstructures could be warm rolling or temperforming [9,10], which is characterized by large strain warm deformation. UFG grains are obtained through pronounced recovery progress and rearrangement of dislocations during the deformation and subsequent annealings. Another effective strategy depends on low-temperature intercritical annealing of steels with elevated manganese or nickel content [11,12], which is characterized by a desirable ductility due to large amount of retained austenite. With a high alloy content, the intercritical region is lowered thus the grain growth is retarded and UFG duplex microstructure is obtained. Furthermore, manganese or nickel as the stabilizer of austenite dramatically enhances the fraction of retained austenite and improves the ductility of the steel by significant transformation induced plasticity (TRIP) effect.

A new and simple way to produce UFG steels without SPD is characterized by conventional cold rolling of martensite of low-carbon steels, in which only a relatively small rolling reduction is needed to produce the UFG structure [13,14]. The quick grain subdivision during the cold rolling is attributed to the fine and multilevel structure of martensitic microstructure (i.e. the segmentation of prior austenite grain into packets, blocks, sub-blocks and laths), while the interaction of transformation dislocations and deformation dislocations, as well as supersaturated carbon atoms in the martensite are also expected to facilitate grain subdivision by causing inhomogeneous deformation [13,15]. Cold rolling of martensite requires significantly less strain to obtain UFG structures, but the deformation of virgin martensite requires a high loading for cold working and the steels are prone to transverse cracks during cold rolling [16], especially for steels containing higher alloy elements, which has restricted the application of this method.

A common challenge in UFG steels is that the grain refinement below 1–2 μm significantly enhances the strength of steels, but the work-hardening ability during plastic deformation is not increased accordingly and the ductility of UFG steel is deteriorated [1,8]. The

* Corresponding author at: Engineering Research Institute, University of Science and Technology Beijing, Beijing 100083, China.
E-mail address: aimin.zhao@ustb.edu.cn (A. Zhao).

http://dx.doi.org/10.1016/j.matdes.2015.08.073
0264-1275/

lack of work hardening of UFG steels is due to the more pronounced dynamic recovery in fine grains which reduces the accumulation of dislocations inside grains, and consequently decrease the work hardening when compared with the coarse grained counterparts.

Some methods is developed to restore the ductility of UFG steels by means of subsequent heat treatments. One is developing bimodal structures, where the fine grains guarantee the high strength and the coarse grains offer the work hardening by the intragranular dislocation multiplication [17,18]. Another method is introducing fine carbide particles or martensite islands to improve the work-hardening ability by generating geometrically necessary dislocations nearby [19,20]. For example, tempering after ARB process, or cold rolling of martensite can produce UFG ferrite with uniformly distributed carbides with nanosizes [15,21], while intercritical annealing and subsequent quenching of the same pretreatments can give a UFG dual phase steels [9,22]. Furthermore, in the case of UFG TRIP steels with elevated amount of Mn or Ni, high elongations can be realized due to the beneficial effect of retained austenite. Therefore, introducing second phases is an effective method for enhancing the ductility of UFG steels at room temperature.

Multiphase steels are put forward to be ideal solutions that cater to the demand of developing new advanced high strength steels (AHSS), which are employed to meet the restrictions on fuel consumption and safety in the automotive industry. One promising heat treatment process, known as "quenching and partitioning" (Q&P), has been shown to be a novel option for the production of high strength steels with significant amounts of retained austenite, and excellent strength/ductility combinations [23–25]. The Q&P process is characterized by quenching from a partial or fully austenization to a defined temperature between the martensitic start temperature (M_s) and the martensite finish temperature (M_f), to form a certain amount of martensite, and then isothermal holding at a given temperature to motivate the carbon to diffuse from the supersaturated martensite to austenite. Consequently, a multiphase microstructure is realized which is consisted of ferrite (in the case of partial austenization), martensite and retained austenite [26].

In this study, UFG steels with considerable amount of retained austenite was obtained by a new method using tempered and deformed martensite as the pre-microstructure of the Q&P process. The presented process avoided direct cold rolling of as-quenched martensite, thus the loading for cold working and the probability of transverse cracks during cold rolling was lowered, while UFG multiphase microstructure could still obtained. Significant grain refinement was realized after the heat treatment which enhanced the strength of the steels without sacrifice the ductility. The microstructural evolution and the corresponding mechanical property compared with the coarse counterpart were investigated.

2. Experimental

The chemical composition is very important to the property of Q&P steels. Carbon and manganese are important elements stabilizing the retained austenite and increase the hardenability, but excessive of them can deteriorate the weldability. Silicon was added because it does not dissolve in cementite and thus delays carbides precipitation during partitioning process, which could act as sinks of carbon and dilute the carbon enrichment of austenite. The composition of the investigated steel in this work was 0.19C–1.87Si–1.49Mn (wt.%). The A_{C1}, A_{C3} temperatures and M_s temperature corresponding to 820 °C were measured by dilatometry to be 739 °C, 895 °C and 160 °C, respectively. After 50 kg vacuum melting, the ingots were forged and hot rolled, with the final rolling temperature of 870 °C and coiling at 660 °C for 1 h, and then furnace cooled. Ultrafine grained quenching and partitioning steels (UFG Q&P) and its coarse grained counterpart (CG Q&P) were produced by adopting different pre-microstructure before Q&P heat treatment. For UFG Q&P steels, hot rolled steels were austenitized at 950 °C for 10 min, followed by water quenching and tempering at 550 °C for 2 h, and then cold rolled with total reductions of 50%. In comparison, as-hot rolled steels were applied the same cold rolling process with a total reduction of 50% but without prior quenching and tempering for producing CG Q&P steels. Subsequent Q&P heat treatments of both investigated steels were conducted in Gleeble 3500 machine and outlined as Fig. 1. The resulting microstructures were observed by ZEISS AX10 optical microscope (OM) and Zeiss ULTRA 55-type field emission scanning electron microscopy (FE-SEM) after etching with 3% nital. Transmission electron microscopy (TEM) was performed by using Tecnai G2 F30 S-TWIN-type transmission electron microscope and TEM samples were obtained by punching from the same region of the specimens, then followed by double-jet thinning in the electrolyte of 5% perchloric acid and 95% glacial acetic acid, as the voltage was 20 V and the temperature −20 °C. Electron backscattered diffraction (EBSD) equipped in FE-SEM was performed with 20 kV and a step size of 0.06 μm, and the acquired data was processed with Channel 5 software provided by Oxford HKL Technology. X-ray diffraction (XRD) tests were performed using Cu-Kα radiation operating at 40 kV and 150 mA. The volume fraction of retained austenite was obtained based on a direct comparison method of the integrated intensities of the $(200)_\gamma$, $(220)_\gamma$, $(311)_\gamma$, $(200)_\alpha$ and $(211)_\alpha$ diffraction peaks. Samples for EBSD and XRD were ground and electrolytically polished in the electrolyte of 20% perchloric acid and 80% ethanol at 15 V for 30 s. Dog-bone-shaped tensile specimens were machined with a gauge length of 15 mm and a gauge width of 3 mm, with the tensile direction parallel to the rolling direction. The tensile strain and stress were recorded through an extensometer with gauge length of 12.5 mm. Tensile samples were tensioned at strain rate of 10^{-3}/s in an Instron machine at room temperature and the average values from three test samples are reported. Additional interrupted tensile tests at strain of 0.05, 0.10, 0.15, and 0.20 were carried out to estimate the extent of strain induced transformation of austenite to martensite using XRD analysis. The strain-hardening behavior was investigated as an approximation to the Hollomon equation ($\sigma_t = k\varepsilon_t^n$, with σ_t, true strain, ε_t, true stress, k, the strength coefficient and n, the strain-hardening exponent.) between 2% and the uniform elongation. The instantaneous strain-hardening exponent, was calculated from the true stress–strain curves as:

$$n = \mathrm{d}\ln\sigma_t/\mathrm{d}\ln\varepsilon_t.$$

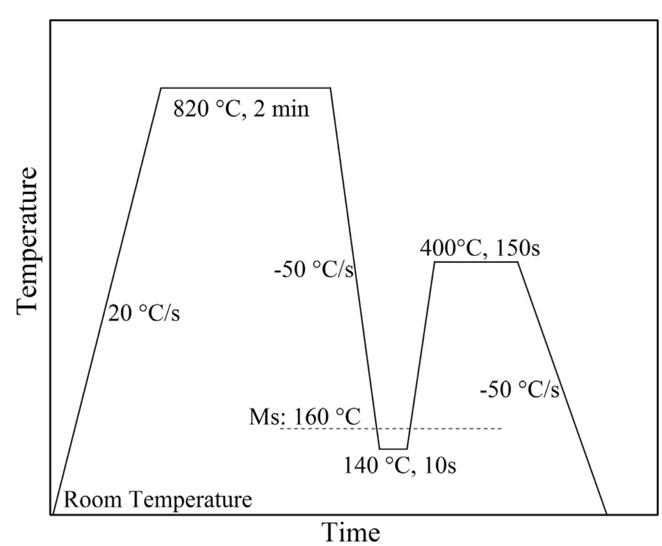

Fig. 1. Quenching and partitioning procedure applied to the investigated steels.