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A novel thermomechanical approach to produce a fine ferrite and low-temperature bainitic composite microstructure

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Abstract

A novel thermomechanical processing was developed in the present study to produce a unique microstructure consisting of fine ferrite grains (i.e. ∼4 μm on average) and low-temperature bainite in a relatively low-carbon steel with a modest hardenability. The thermomechanical route consisted of warm deformation of supercooled austenite followed by reheating in the ferrite region and then cooling to the bainitic transformation regime (i.e. 400–200 °C). The low-temperature bainite consisted of high dislocation density bainitic laths and very fine retained austenite films. This microstructure offered a high work hardening rate leading to a unique combination of ultimate tensile strength and elongation. This was due to the presence of ductile fine ferrite grains and hard low-temperature bainitic ferrite laths with retained austenite films. The microstructural characteristics of bainite were studied using optical microscopy in conjunction with scanning and transmission electron microscopy, electron backscatter diffraction and atom probe tomography techniques.

Keywords: Thermomechanical processing; Fine ferrite; Low-temperature bainite; Atom probe tomography; Electron microscopy

1. Introduction

One of the ongoing requirements in the steel industry is to achieve higher strength levels without sacrificing other properties, such as ductility and toughness. In particular, steels for automotive applications are required to offer a remarkable combination of properties to attain current goals for reduced vehicle weight and improved safety standards. They therefore need to combine high strength for structural reinforcement, good tensile ductility for ease of forming, and high energy absorption for crashworthiness. These requirements motivate the search for new strengthening mechanisms affecting the work hardening rate to increase the strength of steels without deteriorating other properties (i.e. ductility and toughness). Among the different approaches, grain refinement is the key technique to simultaneously improve strength and toughness in metals.

Recently, various thermomechanical processing routes have been developed to produce very fine ferrite microstructures consisting of 1–4 μm ferrite grains and cementite particles distributed throughout the microstructure; hereinafter called ultrafine ferrite (UFF) [1–4]. This microstructure reveals significant improvements in the strength. However, fully UFF microstructures often display a high yield ratio (i.e. the proportion of yield strength and ultimate tensile strength), varying between 0.7 and 1 [1]. Extreme ferrite refinement indeed leads the yield stress to approach the value of the tensile strength, producing flat stress–strain curves (i.e. little work hardening) [5]. As a result, the application of such steels would be limited due to plastic instability. This undesired property has motivated the search for new approaches to design UFF microstructure that possess optimum mechanical properties.

There have been some attempts to overcome this obstacle through inducing a second phase such as martensite in the UFF microstructure [6,7]. It appears that the presence of martensite islands in UFF structure significantly reduces

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the yield ratio to ~0.6–0.7 through the continuous yielding phenomena (i.e. low yield strength and high work hardening rate) [1]. The other alternative as a second phase is bainite, which can play the same role as martensite, but offering higher toughness. More recent bainite structure development in advanced transformation-induced plasticity (TRIP) steels revealed that unique combinations of mechanical properties can be obtained if the bainite transformation takes place at relatively low temperatures (~150–350 °C), resulting in nanosize bainitic laths and retained austenite films, known as a nanobainitic structure [8,9]. These nanostructured bainitic steels are mainly produced in highly alloyed steels, designed based on a thermodynamic approach [8,9]. The main aim of the current research was to employ a novel thermomechanical route to produce a hybrid microstructure containing fine ferrite grains and low-temperature bainite in an alloy with much leaner composition compared with the conventional nanobainitic steels. The microstructure was characterized using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) along with electron backscatter diffraction (EBSD) and atom probe tomography (APT) techniques. The mechanical properties were determined and compared with conventional UFF microstructures.

2. Experimental procedure

The steel composition examined in this study was 0.26C–1.96Si–2Mn–0.31Mo (in wt.%); 1.2C–3.8Si–1.9Mn–0.17Mo (in at.%). The steel has modest quench hardenability. The bainite (B_s) and martensite (M_s) start transformation temperatures were measured to be approximately 500 and 350 °C, respectively, using dilatometery as reported in Ref. [10]. An as-received billet was reduced in thickness by hot rolling to 12 mm at temperatures between 1200 and 1000 °C. Three sets of experiments were conducted in the current study. The first set was designed to obtain an optimum intercritical annealing condition (i.e. temperature and time) in which the maximum ferrite volume fraction was achieved without the presence of any carbide/pearlite. The specimens were reheated to 1000 °C for 10 min and immediately placed in a fluid bed furnace at a temperature between 650 and 750 °C for different times followed by water quenching. In the second set, the optimum intercritical annealing treatment was performed and the samples were then placed in a salt bath furnace at a temperature range of 300–450 °C for 2 h followed by water quenching to form coarse polygonal ferrite plus bainite. This route is, hereinafter, called an isothermal heat treatment process.

For the last set of experiments, a novel thermomechanical processing was developed to obtain a hybrid microstructure consisting of fine ferrite grains and low temperature bainite. Plane-strain compression samples with a dimension of 300 mm × 300 mm × 10 mm were machined out of the hot rolled plate with their long length perpendicular to the rolling direction. The samples were reheated at 5 °C s^{-1} to 1000 °C and held for 300 s. They were then cooled down to 570 °C (i.e. above the B_s and M_s temperatures), and held for 10 s followed by deformation to a strain of 0.3 at a strain rate of 0.1 s^{-1}. The deformed samples were reheated to 650 °C at 10 °C s^{-1} and held for 1 h to partially transform austenite to fine ferrite grains (i.e. ~4 μm on average), followed by cooling at 10 $°C^{-}s^{-1}$ to a temperature between 200 and 400 °C where they were held for 2 h followed by water quenching. The thermomechanical route was partly initiated from a recent work by the current authors to produce ultrafine ferrite through static phase transformation [10]. It should be noted that this is not meant to be an industrially feasible process but rather a fundamental study. Fine ferrite grains could be formed during rolling using dynamic strain induced ferrite transformation, discussed elsewhere [1], but this is more difficult to control, whereas the current static approach allows greater control over the ferrite grain refinement.

The compression device was a servohydraulic thermomechanical treatment simulator apparatus (Servotest, 500 kN) equipped with an automated testing machine including an induction furnace, a muffle furnace and a computer data-acquisition system. Temperature was monitored throughout the testing using a thermocouple embedded into the specimens. A boron nitride lubricant was used to coat the specimens and minimize the friction between the contact surfaces of the specimen and anvils during deformation.

Sub-size tensile specimens with a gauge of 20 mm × 2 mm × 2 mm were machined by wire-cutting out of both the isothermally heat treated and thermomechanically processed samples. For the latter, the tensile axis was perpendicular to the deformation direction. Tensile testing was performed using an Instron tensile testing machine with a crosshead displacement rate of 7.2 mm min^{-1} (i.e. corresponding to a nominal strain rate of 10^{-3} s^{-1}).

Optical metallographic examination was performed using standard mechanical polishing preparation followed by 2% nital solution etching. EBSD and TEM techniques were also used to characterize different microstructural constituents (i.e. bainite and martensite) in the current study. It should be noted that it is difficult to differentiate bainite from martensite phase, specifically isothermally formed martensite from the one transformed on quenching. However, it is possible to distinguish the bainite from martensite using EBSD and TEM techniques. The current steel composition falls into the TRIP steel category and would therefore be expected to have retained austenite present between the bainitic laths, which can be revealed through TEM. In addition, the martensite has a higher dislocation density than bainite, which makes it darker than bainite in the band contrast imaging of the EBSD map.

Samples for EBSD were prepared by standard mechanical polishing and then finished by a colloidal silica slurry polish. EBSD measurements were carried out using a FEG-SEM Quanta 3D FEI scanning electron microscope oper-