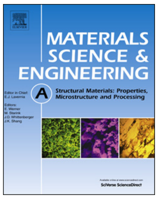
Materials Science & Engineering A 609 (2014) 209–216

Contents lists available at ScienceDirect

Materials Science & Engineering A

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



Structure–mechanical property relationship in a high strength microalloyed steel with low yield ratio: The effect of tempering temperature

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ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form
30 April 2014
Accepted 3 May 2014
Available online 14 May 2014

Keywords:
High strength
Low yield ratio
Impact toughness
Microstructure
TMCP
Tempering

ABSTRACT

We elucidate here the significance of microstructure, in particular, martensite–austenite constituent, in influencing impact toughness and yield-to-tensile strength ratio in a low carbon low-alloyed steel processed via combination of thermo-mechanical controlled processing and tempering. The objective of the study described here is to explore the impact of tempering temperature on the stability of bainite in the attempt to obtain high strength steel with yield strength greater than 600 MPa and yield ratio less than 0.85, together with superior impact toughness. An accompanying objective is to study the striking variation in toughness with tempering temperature, while the strength exhibited insignificant change. The microstructure of the studied steel primarily comprised of fine lath and granular bainite, small fraction of ferrite, together with some martensite–austenite constituent. The morphology of martensite–austenite constituent was granular and stringer-type, and was located between laths or at the bainite/ferrite boundary. With the increase in tempering temperature, the microstructure became coarse and martensite–austenite constituent was decomposed, leading to decrease in tensile strength and impact toughness, while the yield strength continued to remain stable. High strength, good toughness, and low yield ratio was obtained at lower tempering temperature and is attributed to the fine lath-type microstructure and stable martensite–austenite constituent.

1. Introduction

Quenching and tempering (Q&T) is one of the methods to produce high strength steels with yield strength greater than 600 MPa. However, an important drawback of Q&T steels is high yield/tensile strength (referred as yield ratio) and inferior weldability [1–3]. Low yield ratio is also a requirement for good seismic performance. The yield ratio is the ability to resist deformation from yielding to plastic instability and is related to the work hardening rate [2,4]. The lack of adequate strain hardening results in high yield ratio, which is dangerous for construction steels. Thus, it is desirable that the construction steels are characterized by low yield ratio from the view point of safety.

The yield ratio is governed by the microstructure of steel. Steels with single-phase microstructure are characterized by high yield strength and high tensile strength, such as bainite and martensite. If there are two or more microstructural constituents, the yield ratio is lowered [5,6]. Typical examples are ferrite–bainite/martensite dual-phase steels, ferrite–pearlite steels, and transformation-induced-plasticity (TRIP) steels. Undoubtedly, multi-phase microstructure is favorable for obtaining low yield ratio. It is proposed that the optimum microstructure for best combination of strength, toughness, and yield ratio comprises of acicular ferrite or bainite matrix and polygonal ferrite as the second phase [7]. Furthermore, retained austenite contributes to yield ratio through increase in the work hardening rate introduced by transformation-induced plasticity (TRIP) effect [8].

An effective method to obtain low yield ratio is adjusting the fraction of soft and hard phase. Studies devoted to dual-phase steels demonstrated that the presence of hard bainite or martensite in soft ferrite matrix provides low yield ratio [9], where the optimum volume fraction of hard and soft phase is individually proposed to be about 50% [10]. Additionally, the strength difference between the soft and hard phase has an influence on the

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http://dx.doi.org/10.1016/j.msea.2014.05.004
0921-5093/

yield ratio, such that greater the difference in the strength between the two phases, the easier it is to obtain low yield ratio [10,11]. However, this strength difference may be detrimental to toughness because the cracks can easily initiate in this type of microstructure. Thus, currently the focus is on developing steels with acicular or bainitic microstructure.

Thermo-mechanical controlled processing (TMCP) and tempering is commonly employed to obtain high strength steels with low yield ratio [8]. Under this condition, the yield ratio is significantly influenced by the volume fraction of retained austenite and martensite/austenite constituent (MA) [12]. Quenching–intercritical quenching–tempering (Q–Q′–T) process is another approach to lower yield ratio by introducing a multi-phase microstructure of intercritical ferrite, tempered martensite, and retained austenite [13]. More recently, super-OLAC (on-line accelerated cooling) technology reduced the yield ratio through control of fraction of phase-transformation and refinement induced by precipitation [14–16].

From the above discussion, the key process to achieve high strength and low yield ratio is to obtain multi-phase microstructure comprising of acicular ferrite or bainite matrix and ferrite or retained austenite as second phase. The objective of the study described here is to explore the impact of tempering temperature on the stability of bainite in the attempt to obtain high strength steel with yield strength greater than 600 MPa and yield ratio less than 0.85, together with superior impact toughness.

2. Materials and experimental procedure

The high strength steel studied here was produced at heavy plate production line of Wuhan Iron & Steel (Group) Corp. (WISCO), Wuhan, China. The chemical composition of the steel is presented in Table 1. The slab was heated at 1200–1320 °C for complete austenitization and dissolve precipitates that may have nucleated during hot rolling to plate of thickness 20 mm, and then cooled to a lower temperature via accelerated cooling. The percentage of reduction in the non-recrystallization zone was 35–50% and in the recrystallization zone was 50–70%. The cooling rate was 10–30 °C/s to final cooling temperature of 200–500 °C, followed by air cooling to room temperature. Subsequently, the tempering was carried out in the temperature range of 300–650 °C.

Standard tensile tests were conducted at room temperature according to ASTM standards, using specimens machined from the transverse direction of plates. Charpy v-notch specimens of dimensions $10 \times 10 \times 55\ \text{mm}^3$ were cut from the longitudinal direction of the plates, and impact tested at −20 °C. Specimens for metallographic examination were cut from plates, and standard grinding and polishing techniques were employed, followed by etching with nital. Optical microscopy (OM) was used to examine the microstructure at low magnification, while high magnification studies were carried out using combination of scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Transmission electron microscopy was carried out on thin foils prepared by cutting thin wafers from the steel samples, and grinding to ∼45 μm in thickness. Three millimeter discs were punched from the wafers and electropolished using a

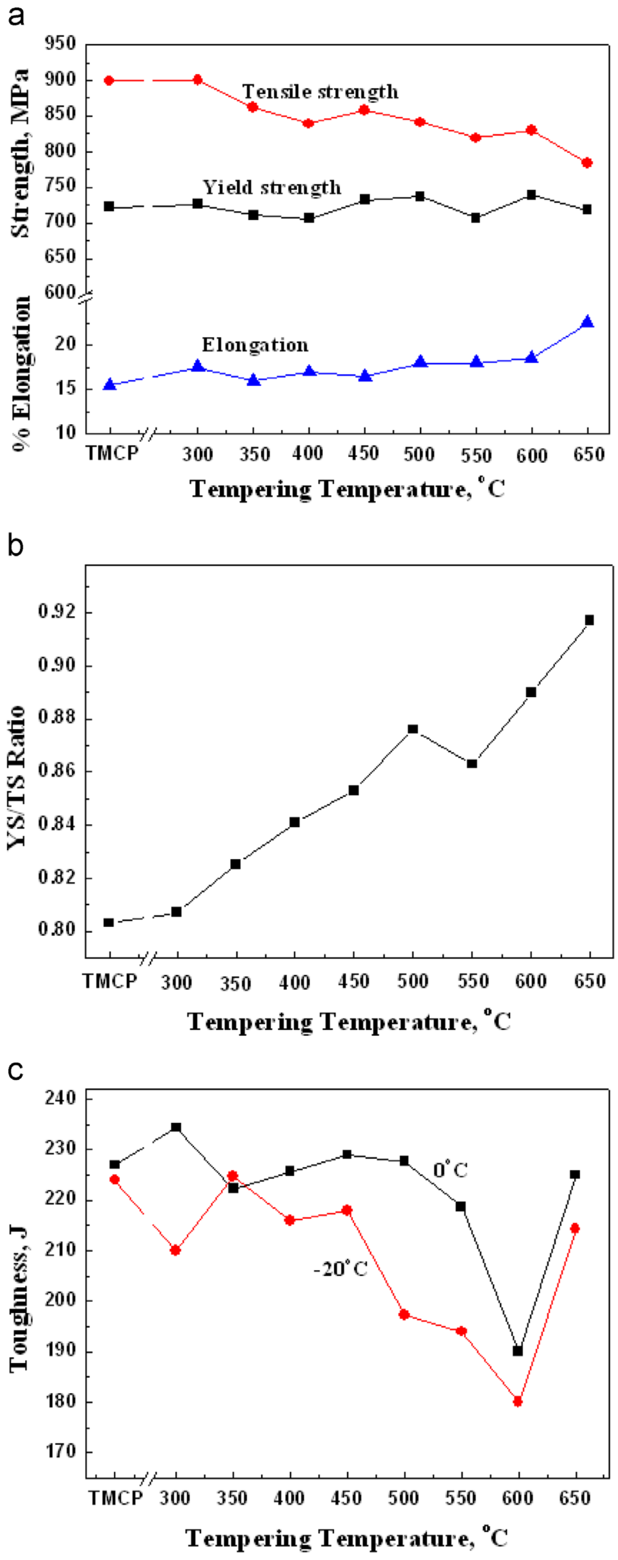

Fig. 1. (a) Yield strength (YS), tensile strength (TS) and % elongation; (b) yield ratio (YS/TS) and (c) impact energy measured at 0 °C and −20 °C as a function of tempering temperature.

Table 1
Chemical compositions of experimental steel in wt%.

C	Si	Mn	P	S	Nb+V+Ti	Ni	Cr+Mo+Cu
0.02–0.08	0.15–0.30	1.50–2.00	≤0.008	≤0.003	≤0.20	≤1.0	≤2.0