

Effect of chemical composition on hardenability of high strength low-C steels

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Abstract

The effect of low-alloy additions on hardenability of high strength low-C steels is reported. Various as-quenched materials with microstructures consisting of low-C (granular) bainitic, mixed bainitic/martensitic and fully martensitic microstructures were produced. Results show that for a given cooling rate, an increase of austenite grain size (AGS) and of Mo and Cr contents decreases the transformation temperatures and promotes martensite formation. Copyright © 2017 VBRI Press.

Keywords: High strength steels, quenching, hardenability, microstructure.

Introduction

High strength steels are more and more required for several applications. Among those, the ones manufactured by a quenching and tempering (Q&T) process are of large use. A rational approach to the design and production of high strength quenched and tempered materials is therefore of large interest and requires a quantitative knowledge of the effects of steel chemical composition and heat treatment conditions on microstructure and mechanical properties [1]. In particular, the quenching step of the process appears to be the quite critical due to the increasing thicknesses requested by the market (in particular for offshore applications). In this paper, the effect of steel chemical composition on hardenability is investigated.

Main novelty of the paper is in the progress which was achieved in the metallurgical design of high strength steels as a result of application of metallurgical modeling and extensive investigations on laboratory steels. Basic aspects are here clarified, in particular those concerning microstructure evolution as a function of heat treatment conditions.

Experimental

The promising steel chemical composition ranges and Q&T conditions were identified on the basis of mathematical models able to predict the strength of Q&T steels [2, 4]. Investigated steels were selected in order to have various. Ceq levels (from 0.41% to 0.56%).

Different combinations of Mn, Mo, Cr and Ni and minor changes for other elements (Table 1) were designed and cast as 80 kg laboratory ingots, hot rolled and subjected to controlled quenching treatments in order to assess changes in microstructure.

Various heat treatments were carried out on the laboratory steels after pilot hot rolling in the thickness range of 16 mm-40 mm.

Austenitizing was performed in a muffle at temperatures of 880 °C to 1050 °C, followed by quenching in stirred water. Cooling rate (CR) was measured by a thermocouple inserted at mid-thickness. Typical investigated CR values were in the range 20 to 80 °C/s. Specimens were machined from the as-rolled materials in order to construct continuous cooling transformation diagrams by dilatometry. Phase transformation characteristics of selected steels (Table 2) were determined, reproducing fine and coarse austenite grains and cooling rates. Microstructures were observed by means of Light Microscopy (LM) and Scanning Electron.

Microscopy (SEM) on polished sections after 2%-Nital etching. The austenite grain boundaries were revealed by etching in a saturated aqueous picric acid solution containing a few drops of a wetting agent and HCl. The austenite grain size (AGS) was measured according to ASTM E112.

Table 1. Chemical composition range of laboratory steels (mass, %).

	C	Mn	Si	Mo	Cr	Ni
Min	0.07	1.2	0.20	0.15	0.20	0.20
Max	0.11	1.6	0.35	0.55	0.55	0.50
	Nb	V	Ti	Al	Ceq	P _{cm}
Min	0.020	0.001	0.001	0.020	0.45	0.21
Max	0.030	0.080	0.008	0.035	0.58	0.26

Results and discussion

Mathematical modeling

The application of mathematical models [5-6] indicated that, in order to attain high yield strength levels (YS > 550 MPa) on the Q&T material, it is necessary to have after quenching a microstructure mainly constituted of low-C martensite (> 30%) and bainite, otherwise too low tempering temperatures are required with possible detrimental effects on toughness.

Table 2. Chemical compositions of laboratory steels (mass, %) selected for dilatometric investigation).

Steel	C	Mn	Cr	Mo	Ni	Nb
S0	0.09	1.28	0.22	0.15	0.37	0.026
S1	0.10	1.54	0.26	0.23	0.44	0.029
S2	0.07	1.70	0.50	0.32	0.51	0.026
S3	0.10	1.30	0.51	0.52	0.22	0.025

Steel	Ti	V	Ceq	Pcm
S0	0.015	0.09	0.41	0.19
S1	<0.002	0.10	0.49	0.22
S2	0.008	0.07	0.56	0.23
S3	0.008	0.10	0.54	0.24

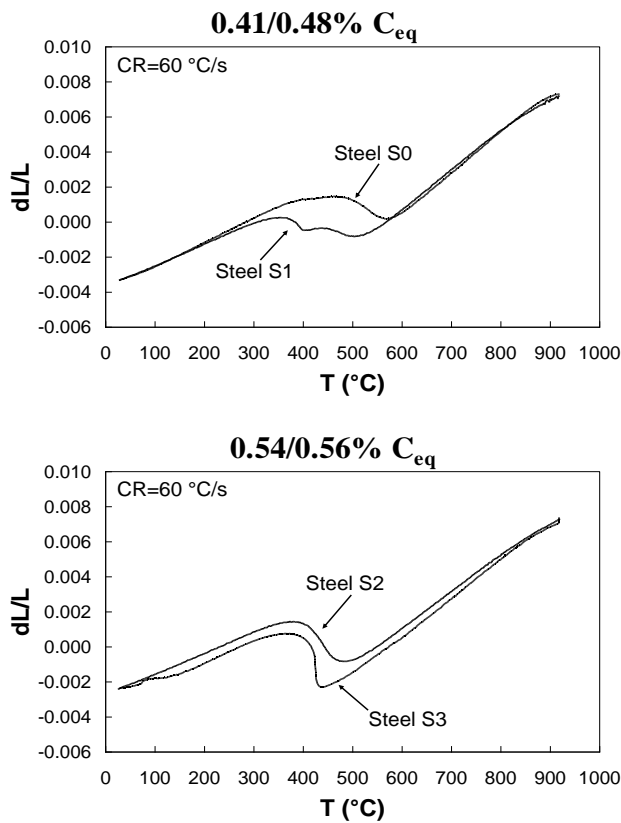


Fig. 1. Dilatometric curves of selected steels. CR= 60 °C/s.

Proper additions of Mn, Cr, Mo and Ni, which corresponds to increasing carbon equivalent (C_{eq}) values and improved hardenability, are needed to develop the required martensite amount for a given AGS and CR. In

particular, the metallurgical models gave the following indications for the promising chemical composition ranges to be investigated by pilot trials in order to assess strength-toughness combinations of low-C Nb microalloyed steels [7]:

- Carbon content from 0.07 to 0.11% and adequate combinations of Mo (0.15-0.50%), Cr (0.2-0.55%), Ni (0.20-0.50%), and Mn (1.2-1.6%) to develop a given martensite and bainite content.
- Microadditions of V to develop precipitation hardening.
- Carbon equivalent from 0.45 to 0.58%, in order to develop adequate strength and maintain good weldability.

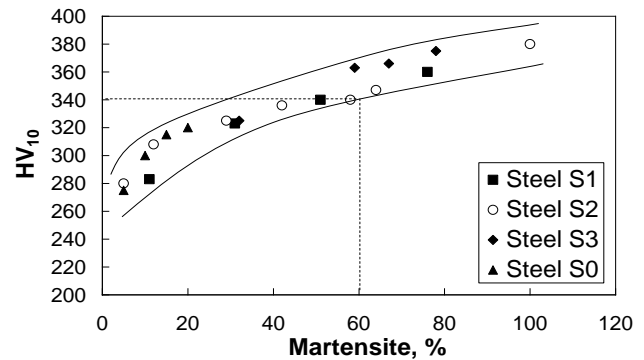


Fig. 2. Hardness as a function of martensite content.

Hardenability

Since the main difference between steels S0-S 1 and S2-S3 is in the Mo content, one of the results from dilatometric curves of selected steels (Table 2) is to show that, for a given CR, an increase of Mo content decreases the transformation temperatures and promotes martensite formation in both steels with 0.41/0.48% and 0.54/0.56% C_{eq} (Fig. 1). A martensite volume fraction higher than 60% corresponds to an average hardness value higher than 340 HV10, independently of chemical composition (Fig. 2).

Increasing Cr and Mo contents (Fig. 3) lead to a lower critical CR in order to reach this hardness value (i.e. $M > 60\%$). For a given C_{eq} (e.g. 0.54%), combined Mo and Cr additions are more effective in developing martensite than Mn addition (see Fig. 3, steel S2 versus steel S3).

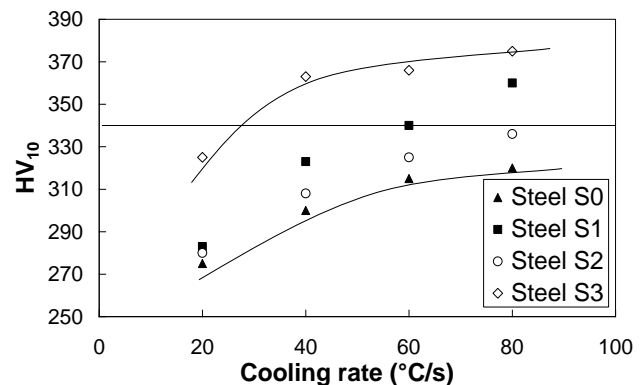


Fig 3. Hardness as a function of cooling rate.

In order to analyze the effect of AGS on phase transformation, the high hardenable steel S3 and the low hardenable steel S0 were considered.

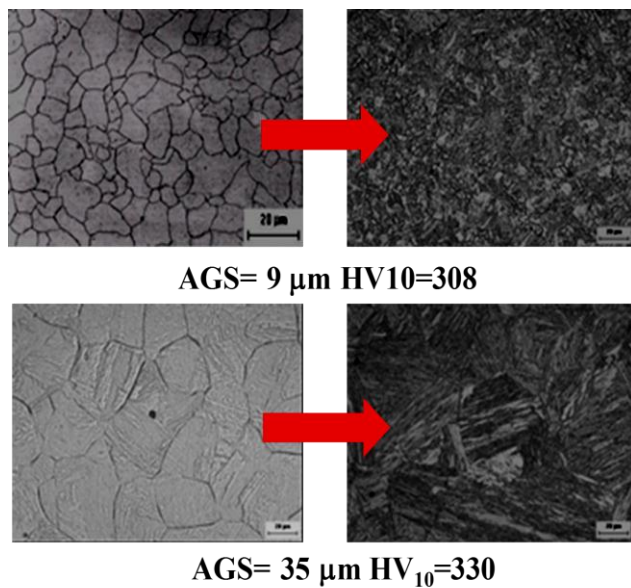


Fig. 4. Effect of AGS on microstructure after continuous cooling (steel S3, CR = 40 °C/s).

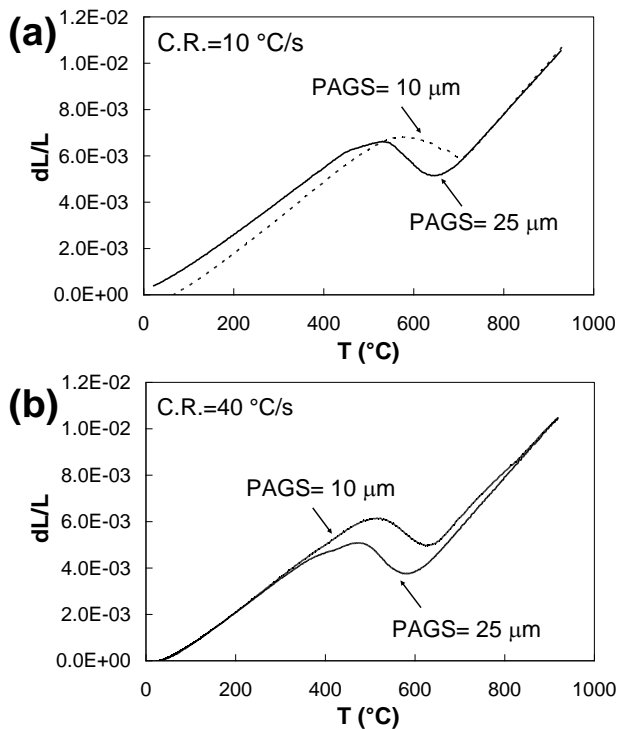


Fig. 5. Effect of AGS on length change of dilatometric specimens during continuous cooling: a) CR = 10 °C/s; b) CR = 40 °C/s (steel S3).

Different austenitic grain sizes were formed by austenitising at different temperatures. Specimens with austenitic grain size lower than 10 μm and higher than 20 μm were obtained, An increase of AGS from 9-10 μm to 25-35 μm (Fig. 4), even in steel S3, lowers the transformation temperatures and leads to a significant

increase in martensite volume fraction, at expenses of bainite (Fig. 5), with consequently higher hardness values at high cooling rates (Fig. 6).

An improvement in hardenability, when coarse austenite is formed, is also observed at low cooling rates because bainite replaces ferrite. For a steel with relatively low hardenability (steel S0) the strengthening due to the AGS increase is almost constant for the whole range of explored cooling rates, because the microstructures are predominantly bainitic (M<50%). For instance, a structure of 9%M-52%B-39%F formed at CR = 40 °C/s with AGS = 10 μm was modified to 38%M-57%B-5%F in the case of 30 μm AGS.

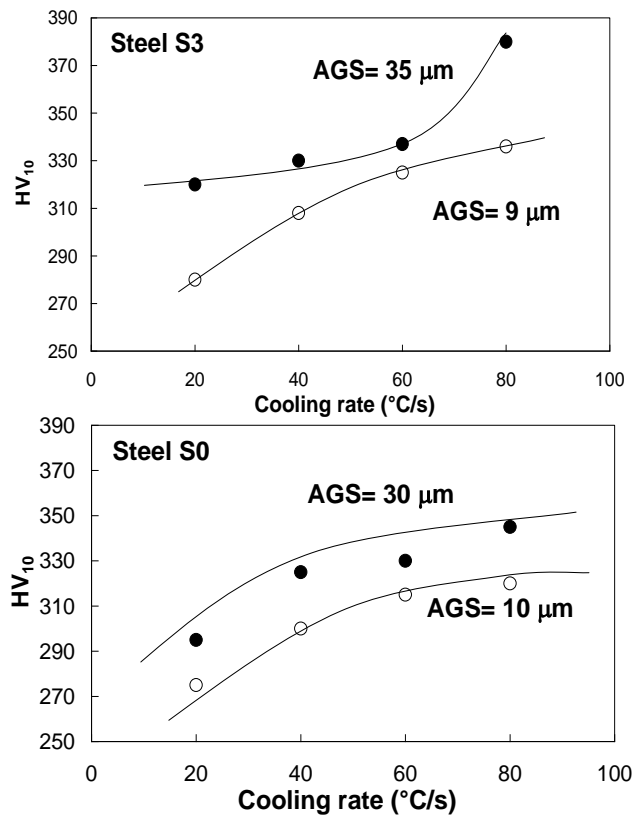


Fig. 6. Effect of AGS on hardenability.

Conclusion

Significant progress was achieved in the metallurgical design of high strength steels as a result of application of metallurgical modeling and extensive investigations on laboratory steels. Basic aspects were clarified, in particular those concerning microstructure evolution as a function of heat treatment conditions;

The following conclusions can be drawn:

- For a given cooling rate, an increase of AGS and of Mo and Cr contents decreases the transformation temperatures and promotes martensite formation.
- For a given CR, an increase of Mo content decreases the transformation temperatures and promote martensite formation.

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