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A. DI SCHINO*#

DILATOMETRIC STUDY OF HIGH STRENGTH STEELS HARDENABILITY

The effect of low-alloy additions on low-C steels hardenability is reported. Various as-quenched materials with microstructures consisting of low-C (granular) bainitic (B), mixed bainitic (B)/martensitic (M) 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.

Keywords: High strength steels, quenching, hardenability, microstructure

1. Introduction

High strength steels are more and more required for several applications. The proper balance between yield strength, $R_{p0.2}$, and ductile to brittle transition temperature, DBTT, has been the main concern during development of high strength engineering steels and the effect of microstructure on impact toughness has attracted a great attention during the last decades [1]. High-strength carbon steels exhibit yield strength values in the range 500 to 1000 MPa or even higher for advanced grades. The combination between $R_{p0.2}$ and DBTT is improved if steels manufactured by a quenching and tempering (Q&T) process are considered. Increased yield strength can be achieved by precipitation mechanisms or by improving hardenability. As far as concerns precipitation strengthening the use of V is normally preferred over Nb because of the solubility behavior which permits the dissolution of VCN particles at lower temperatures [2] further favoring grain size refinement [3]. Concerning the hardenability increase, Mo or Cr are usually added, with increasing costs especially if steels manufactured by a quenching and tempering process are considered. In this case a rational approach to the design and production of high strength quenched and tempered materials requires a quantitative knowledge of the effects of steel chemical composition and heat treatment conditions on microstructure [4], mechanical properties [5,6] and weldability [7,8]. In particular, the quenching of the process appears to be the quite critical due to the increasing thicknesses requested by the market (in particular for offshore applications), where high thickness components are considered.

In this paper, the effect of steel chemical composition on hardenability is investigated.

2. 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 [8,9]. Investigated steels were selected in order to have various C_{eq} 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. Starting from 170 mm thick ingot, hot rolling was carried out down to 40 mm thick plate after homogenization treatment at 1250°C for 2 hours in 4 passes, with finish rolling temperature 1050°C.

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	C_{eq}	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

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

* UNIVERSITÀ DEGLI STUDI DI PERUGIA, VIA G. DURANTI 93, 06125 PERUGIA, ITALY

Corresponding author: andrea.dischino@unipg.it

20 to 80°C/s. Specimens were machined from the as-rolled materials in order to construct continuous cooling transformation diagrams by LINSEISS RITAL78 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. Hardness measurements were carried out by a Wilson Hardness HVD 1000 instrument with 2 kg load.

TABLE 2

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

Steel	C	Mn	Cr	Mo	Ni	Nb	Ti	V	Ceq	Pcm
S0	0.09	1.28	0.22	0.15	0.37	0.026	0.015	0.001	0.41	0.19
S1	0.10	1.54	0.26	0.23	0.44	0.029	<0.002	0.060	0.49	0.22
S2	0.07	1.70	0.50	0.32	0.51	0.026	0.008	0.040	0.56	0.23
S3	0.10	1.30	0.51	0.52	0.22	0.025	0.008	<0.005	0.54	0.24

3. Results and discussion

3.1. Mathematical modeling

The adopted model [9,10] is able calculate to minimum cooling rates for martensite ($vcrM$), bainite ($vcrB$) and ferrite/pearlite formation ($vcrP$) according to:

$$\log_{10} vcr(i) = K_v(i) - \left(\sum_{j=1}^5 F_j(i) \cdot wt\%_j + KP(i) \cdot Pa \right) \quad (1)$$

where $vcr(i)$ is the critical cooling rate in K/h , K_v , KP , F_j are coefficients reported in [8-9] and the quantity $wt\%_j$ represents the weight percent of the element j .

The model is also able to predict the hardness of the single phases, according to:

$$HVM = 127 + 949 C + 27 Si + 11 Mn + 8 Ni + 16 Cr + 21 \log_{10}(vr) \quad (2)$$

($2s = 26 HV$)

$$HVB = -323 + 185 C + 330 Si + 153 Mn + 65 Ni + 144 Cr + 191 Mo + (89 + 53 C - 55 Si + -22 Mn - 10 Ni - 20 Cr - 33 Mo) \log_{10}(vr) \quad (3)$$

($2s = 21 HV$)

$$HVFP = 42 + 223 C + 53 Si + 30 Mn + 12.6 Ni + 7 Cr + 19 Mo + (10 - 19 Si + 4 Ni + 8 Cr + 130 V) \log_{10}(vr) \quad (4)$$

($2s = 12.8 HV$)

where M = martensite, B = bainite and FP is a mixture of ferrite and pearlite.

For a mixed microstructure the hardness is estimated as a weighted average on the volume fraction of the constituents:

$$HV = HVM \cdot (M\%/100) + HVB \cdot (B\%/100) + HVFP \cdot (FP\%/100) \quad (5)$$

The application of mathematical models [8,9] 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.

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:

- 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.

3.2. Hardenability

Results from dilatometric curves of selected steels (Table 2) show that, for a given CR, S1 steel shows a higher hardenability than steel S0 (Fig. 1a) and S3 a steel a higher hardenability than S2 steel (Fig. 1b). Considering steel chemical compositions reported in Table 2 and adopting equations (1-4) it comes out that the increase of Mo content from steel S0 to Steel S1 and from Steel S2 to Steel S3 is the main responsible of the decreases of the transformation temperatures and of martensite formation promotion in both steels with 0.41/0.48% and 0.54/0.56% C_{eq} .

A martensite volume fraction higher than 60% corresponds to an average hardness value higher than 340 HV_{10} , independently of chemical composition (Fig. 2). Microstructural phases identification was realized by LM after selective etching coupled with SEM investigation.

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).

In order to analyze the effect of AGS on phase transformation, the high hardenable steel S3 and the low hardenable steel S0 were considered. An increase of AGS from 9-10 mm to 25-35 mm, even in steel S3, lowers the transformation temperatures and leads to a significant increase in martensite volume fraction, at expenses of bainite (Fig. 4a,b), with consequently

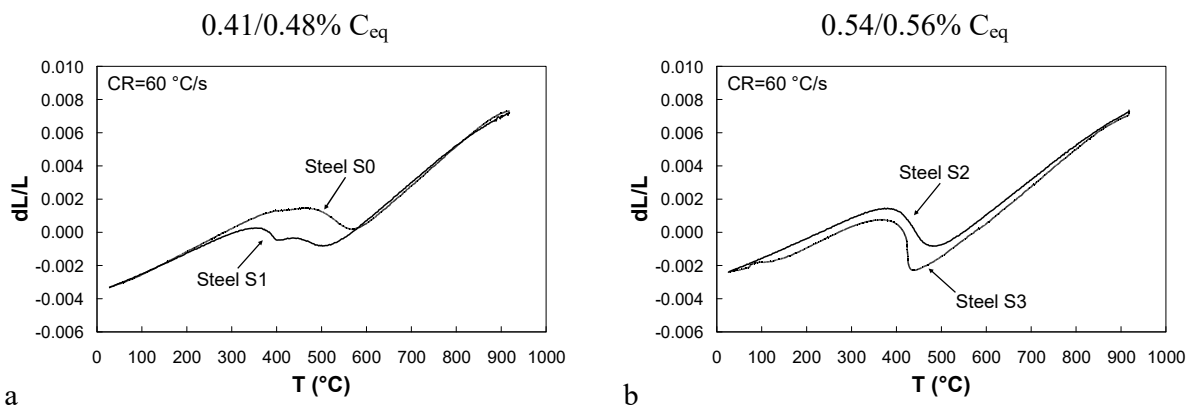


Fig. 1. Dilatometric curves of selected steels. CR = 60°C/s; a) steel with 0.41/0.48% C_{eq} ; b) steel with 0.54/0.56% C_{eq}

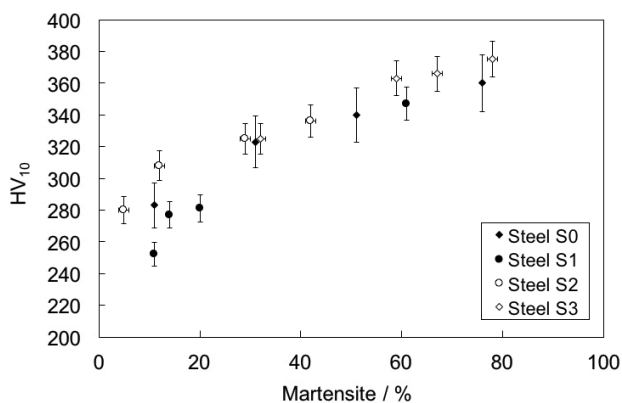


Fig. 2. Hardness as a function of martensite content

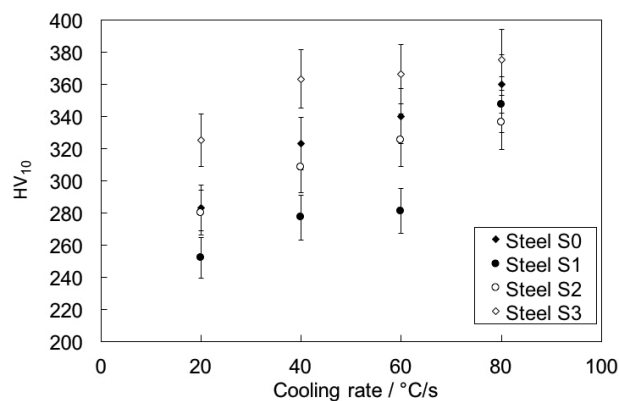


Fig. 3. Hardness as a function of cooling rate

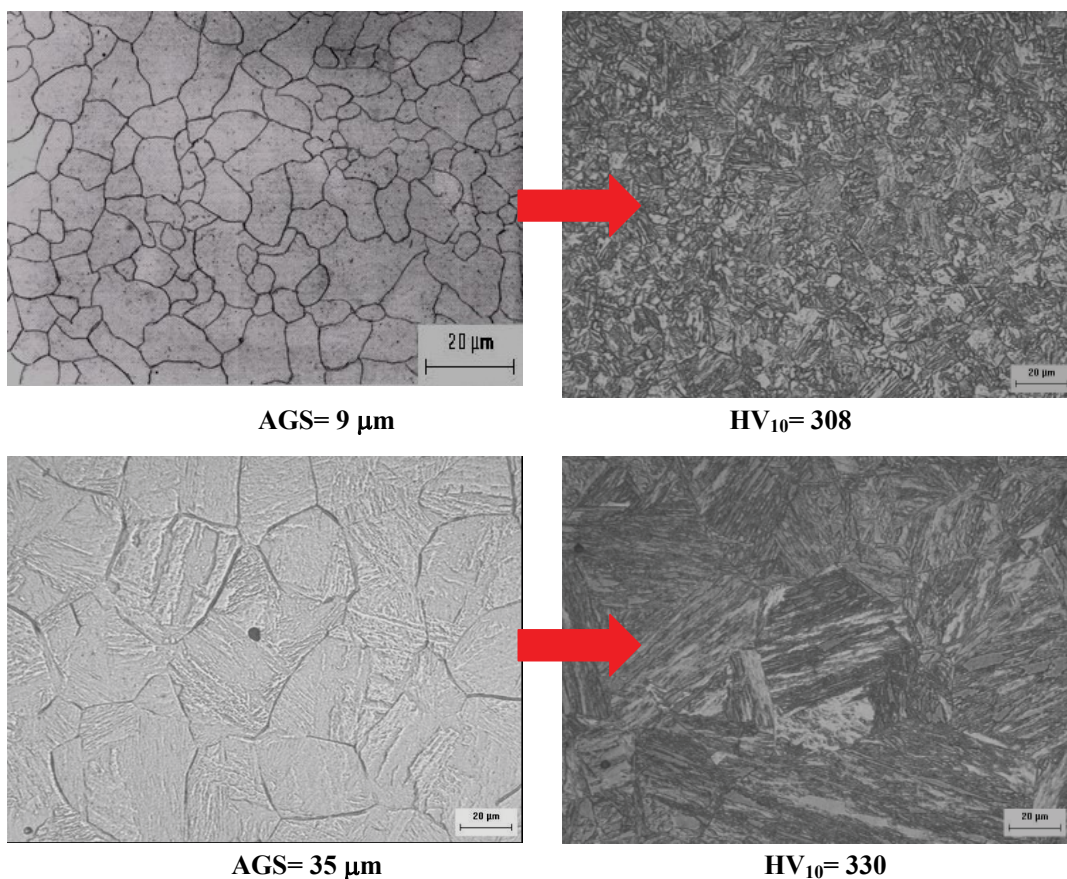


Fig. 4a. Effect of AGS on microstructure after continuous cooling (steel S3, CR = 40°C/s)

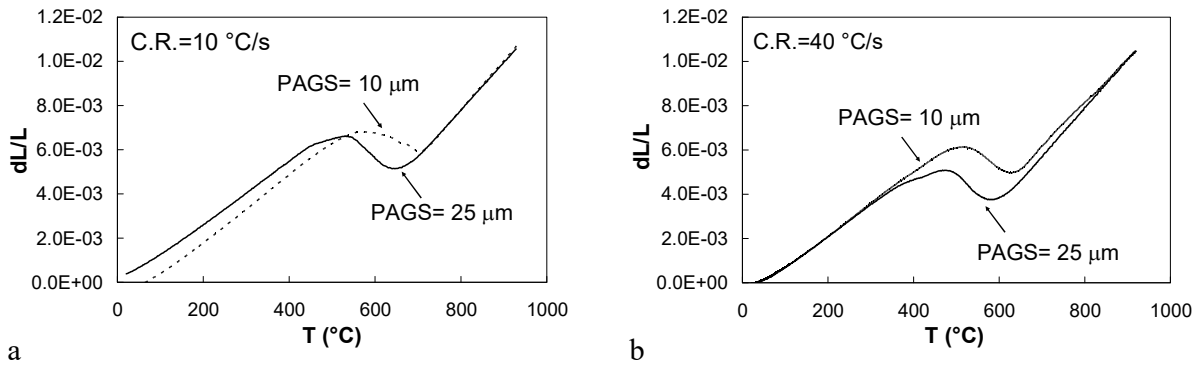


Fig. 4b. Effect of AGS on length change of dilatometric specimens during continuous cooling: a) CR = 10°C/s; b) CR = 40°C/s (steel S3)

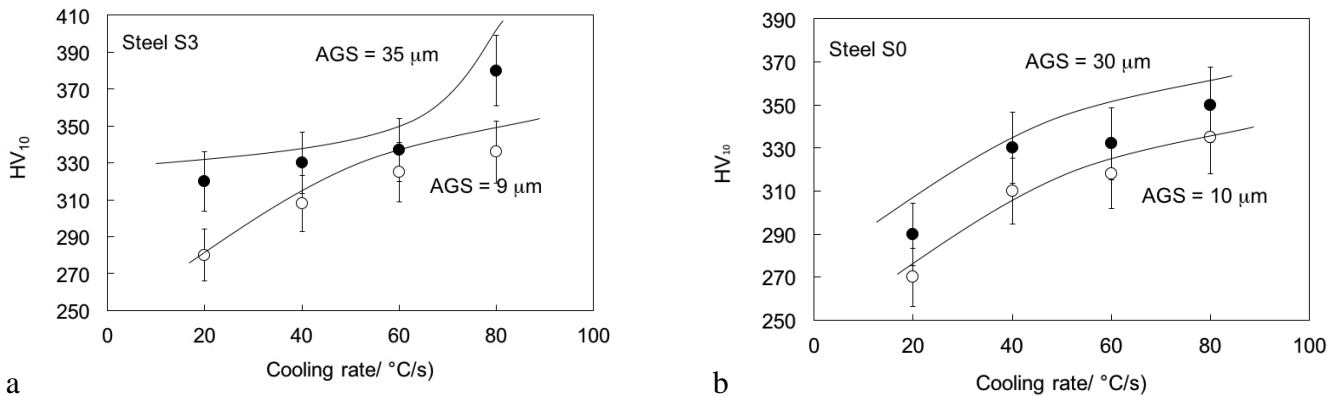


Fig. 5. Effect of AGS on hardenability. a) Steel S3; b) Steel S0

higher hardness values at high cooling rates. This is reported in (Fig. 5a,b) where the hardness dependence of steels S0 and steel S3 as a function of cooling rate is reported. 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 mm was modified to 38% M-57% B-5% F in the case of 30 mm AGS.

4. Conclusions

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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