

ANALYSIS OF PHASE TRANSFORMATION IN HIGH STRENGTH LOW ALLOYED STEELS

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The effect of low-alloy additions on phase transformation of high strength low alloyed steels is reported. Various as-quenched materials with microstructures consisting of low carbon (granular) bainitic, mixed bainitic/martensitic and fully martensitic microstructures were reproduced in laboratory. 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.

Key words: high strength low alloyed steels, quenching, hardness, microstructure

INTRODUCTION

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. High-strength carbon steels exhibit yield strength values in the range 500 to 1 000 MPa or even higher for advanced grades. In general, when increasing the strength, toughness, ductility and formability are impaired. Multiphase microstructures allow to improve these latter properties. However, with increasing the complexity of the microstructure it is more and more difficult to identify the microstructural features directly related to the mechanical behavior. In the past, simple microstructures such as polygonal ferrite/pearlite, have been adequately characterized through the assessment of grain size, pearlite spacing and colony size. In particular, the effect of microstructure on impact toughness has attracted a great attention during the development of ferrite-pearlite steels. The combination between $R_{p0.2}$ and DBTT is improved if steels manufactured by a quenching and tempering (Q&T) process are considered. 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 [2], mechanical properties [3-4] and weldability [5]. 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.

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 [6]. Investigated steels were selected in order to have various carbon equivalent (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. 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 1 050 °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 build up continuous cooling transformation (CCT) 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.

RESULTS AND DISCUSSION

Mathematical Modeling

Mathematical modeling of Q&T process showed that high yield strength values ($R_{p0.2} > 450$ MPa) after

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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
Min	0,020	0,001	0,001	0,020	0,45
Max	0,030	0,080	0,008	0,035	0,58

Table 2 Steel chemical composition (selected materials) / mass / %

Steel	C	Mn	Cr	Mo	Ni
S0	0,09	1,28	0,22	0,15	0,37
S1	0,10	1,54	0,26	0,23	0,44
S2	0,07	1,70	0,50	0,32	0,51
S3	0,10	1,30	0,51	0,52	0,22

Steel	Nb	Ti	V	Ceq
S0	0,026	0,015	0,001	0,41
S1	0,029	<0,002	0,060	0,49
S2	0,026	0,008	0,040	0,56
S3	0,025	0,008	<0,005	0,54

quenching calls for a microstructure mainly consisting of low-C martensite (> 30%) and bainite.

Additions of manganese, molybdenum, chromium and nickel, with a consequent increase of carbon equivalent (C_{eq}) values and enhanced hardenability, are needed to develop the above martensite amount if fixed AGS and CR are considered. In particular, the metallurgical models gave the following guidelines related to steel chemical composition to be manufactured 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 additions of manganese (1,20 - 1,60 %), chromium (0,20 - 0,55%), nickel (0,20 - 0,50 %), molybdenum (0,15 - 0,52 %), to develop a given martensite (M) and bainite (B) content.
- Microadditions of vanadium to develop precipitation hardening.
- Carbon equivalent ranging 0,45 to 0,58 %, in order to assure high strength together with adequate weldability.

Hardenability

Results from dilatometric curves of selected steels (Table 2) 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} (Figure 1 a, b).

A martensite volume fraction higher than 60% corresponds to an average hardness value higher than 340 HV₁₀, independently of chemical composition (Figure 2).

If chromium and molybdenum contents are increased (Figure 3) a lower critical CR is required in order to reach such hardness value (i.e. martensite volume

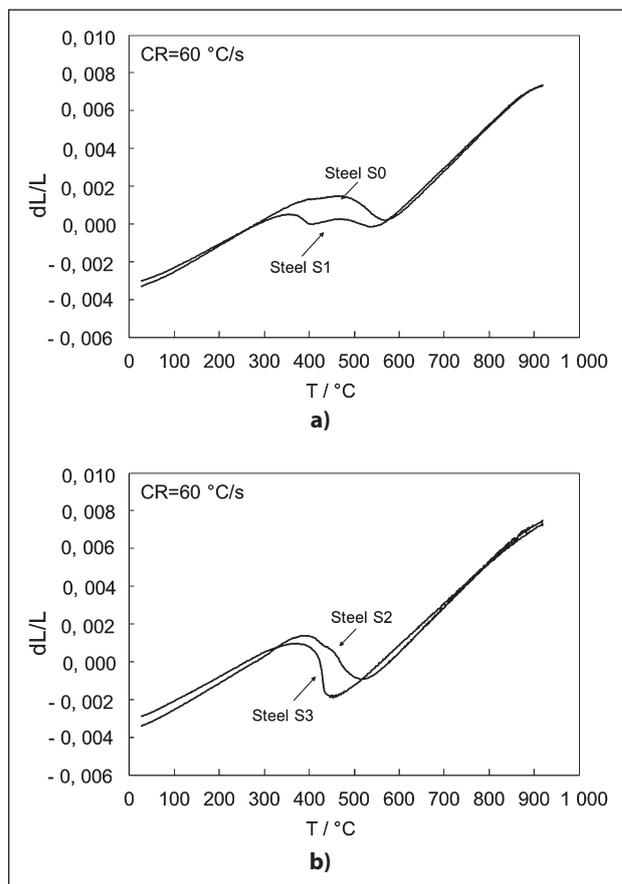


Figure 1 Dilatometric curves of selected steels. CR= 60 °C/s. a) 0,41 - 0,48 % C_{eq} ; b) a) 0,54 - 0,56 % C_{eq} .

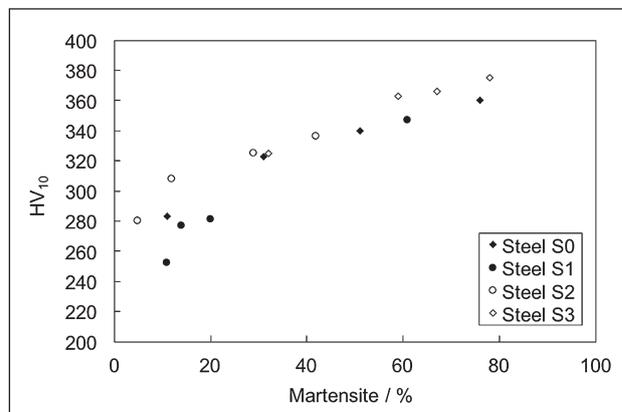


Figure 2 Hardness dependence on martensite volume fraction

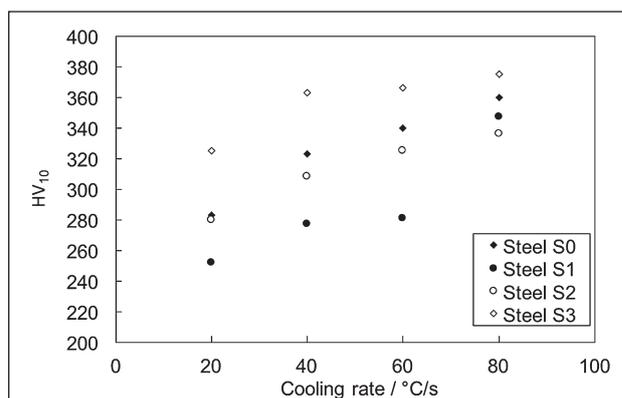


Figure 3 Hardness dependence on cooling rate.

fraction > 60 %). For a given C_{eq} (e.g. 0,54 %), combined Mo and Cr additions are more effective in developing martensite than Manganese addition (see Figure 3, steel S2 versus steel S3).

In order to analyse 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 (Figures 4 and 5 a), b)), with consequently higher hardness values at high cooling rates (Figure 6 a), b)). 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 $CR = 40\text{ }^{\circ}\text{C/s}$ with $AGS = 10\text{ mm}$ was modified to 38 % M - 57 % B - 5 % F in the case of 30 mm AGS.

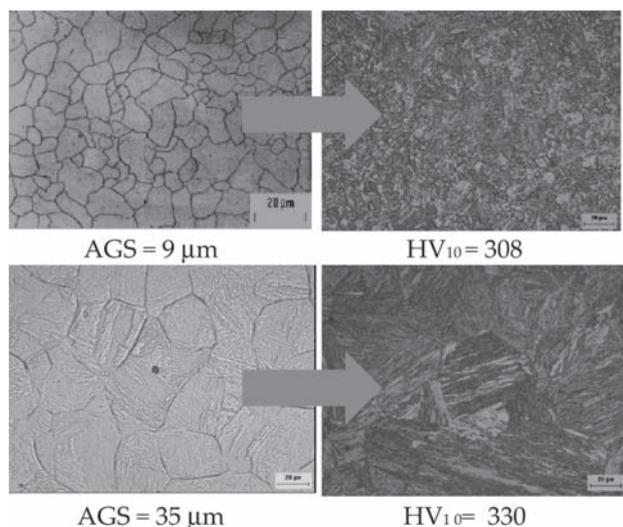


Figure 4 Effect of AGS on microstructure after continuous cooling (steel S3, $CR = 40\text{ }^{\circ}\text{C/s}$).

CONCLUSIONS

Significant progress was achieved in the metallurgical design of high strength steels as a result of an extensive investigations on laboratory steels. Basic aspects were clarified, in particular those concerning microstructure evolution as a function of heat treatment conditions. Various as-quenched materials with microstructures consisting of low carbon (granular) bainitic, mixed bainitic/martensitic and fully martensitic microstructures were reproduced in laboratory and tested by dilatometry. Results show that for a given cooling rate, both an increase of austenite grain size and of molybdenum and chromium contents lowers the transformation temperatures thus favouring martensite formation.

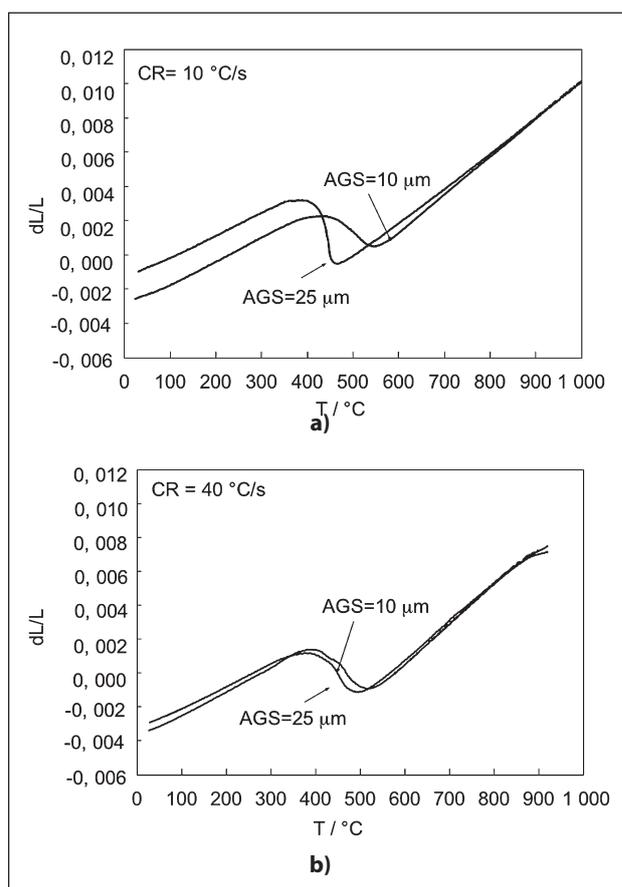


Figure 5 Effect of AGS on length change of dilatometric specimens during continuous cooling: a) cooling rate = $10\text{ }^{\circ}\text{C/s}$; b) cooling rate = $40\text{ }^{\circ}\text{C/s}$ (steel S3).

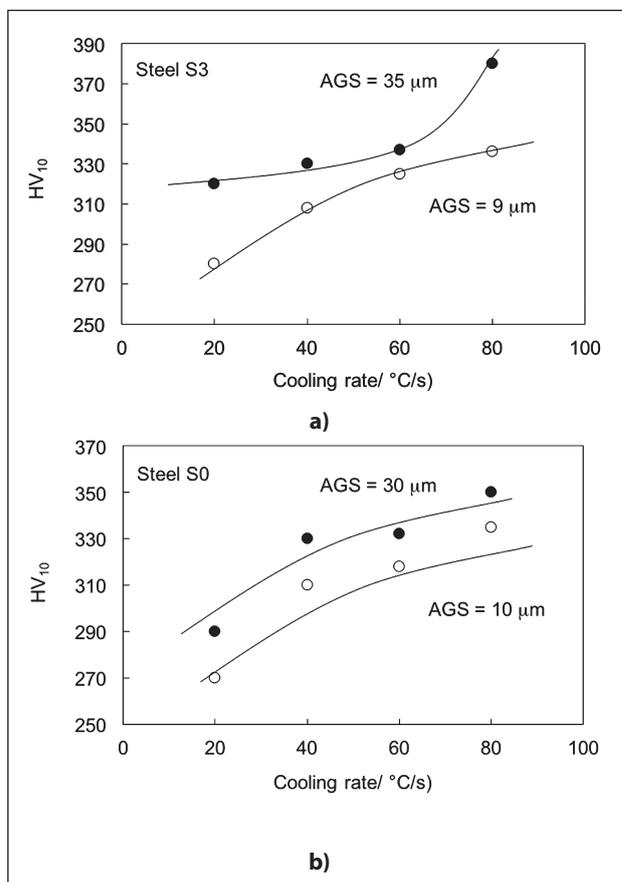


Figure 6 Effect of AGS on hardenability a) Steel S0, b) Steel S3

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