Low temperature kinetics of bainite formation in high carbon steels

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Abstract

This work is concerned with quantifying and discussing the influence of alloying elements on the kinetics of bainite formation at low temperatures (220–250 °C) in high carbon, high silicon steels (100Cr6 and similar grades). In a first step, it is shown that the austenite carbon content is strongly influenced not only by the austenitizing temperature, but also by its duration. A method is thus proposed and validated to estimate this content and ensure that later comparisons are meaningful. In a second step, the influence of Cr, Mn, Mo and Si are evaluated. The relative effects of C, Mn, Cr and Mo are shown to be quantitatively in reasonable agreement with calculated driving forces, with C being by far the strongest retardant of bainite formation. The influences of Mn and Cr are found to be of similar order of magnitude, though with a stronger influence of Mn. Si is shown to continuously slow down bainite kinetics with increasing content, with no threshold content identified and an influence that is stronger than that of Mn or Cr. The role of Si is discussed and the current accepted mechanism is shown to be inconsistent with present and published observations. A new possibility is discussed for how Si influences kinetics in the investigated conditions (carbon content, temperature).
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1. Introduction

Bearing components require specific in-service properties such as high hardness ($\sim$700 HV) and dimensional stability under loading. 100Cr6 grades and variants meet these conditions and therefore are widely used in the bearing industry. Usually, these grades are quenched from a temperature where the material is austenitic, though with a significant fraction of undissolved spheroidized carbides. The resulting martensite is then tempered at low temperatures to allow for decomposition of the retained austenite. This is because decomposition of retained austenite during service would result in dimensional changes that may have strongly detrimental effects on performances.

100Cr6 grades and variants can also be used after bainitic isothermal transformation between 200 and 450 °C [1]. Such "bainitizing" heat treatments offer a number of advantages: reduction of distortion associated with trans-

formation [2], introduction of beneficial compressive residual stresses for larger component [4], and reduction of the amount of retained austenite [1]. Indeed, control of distortion is important for precision machined components. For large bearings in particular, significant distortions are corrected using hard machining, which can significantly impact the overall cost of the component. The benefits of bainitizing hard carbon steels are, however, often cancelled out by the exceedingly long transformation times. There is thus significant interest in shortening the required bainite transformation duration without compromising mechanical properties.

A number of studies have been concerned with modifications of the standard "bainitizing" schedule aiming at shortening the overall heat treatment. These included:

– two-step bainitizing (where the component is held isothermally at a first temperature, then at a second without going through room temperature, both being above the martensite start temperature M_s [3–5];

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– partial bainite formation followed by quenching to room temperature [3–5];
– partial martensite formation before isothermal holding above M_s [3,4,6].

These investigations have shown that, with optimized processes, heat treatment durations could be reduced up to 25% compared to the conventional bainitic heat treatment without reducing fatigue strength, even, in some cases, enhancing the latter. However, such heat treatments introduce additional complexity in material handling and are therefore not easily transferred from the laboratory to the heat-treatment line.

The present investigation is thus concerned with the influence of composition and heat-treatment conditions on bainite formation kinetics in various 1% C steel grades derived from 100Cr6 (AISI 52100). In a first step, the influence of austenitization temperature is investigated, and a method is proposed to derive the actual matrix carbon content. Indeed, the latter depends strongly not only on temperature but also on austenitization duration. In a second step, having ensured identical matrix carbon content, the influence of Si, Mn, Cr and Mo are quantified. Results are compared with thermodynamic calculation of the driving forces.

2. Experimental procedures

2.1. Materials and specimens

Both industrially produced and laboratory cast materials were used in the present study, as identified in Table 1. Industrial materials were cast as 6–7T ingots, soaked at high temperature (1100–1200 °C), hot-rolled to various diameters between 100 and 200 mm and spheroidized. 20 kg ingots were manufactured in a vacuum induction melting furnace, hot-forged to 40 mm diameter bars and spheroidized. Chemical compositions (Table 1) were identified using optical emission spectroscopy (OES), except for carbon and sulphur contents, which were measured using combustion analysis (LECO).

Specimens for dilatometry (12 mm long cylinders of diameter 3 mm) were machined from the spheroidized material, always sampling at the mid-radius of the bars.

2.2. Dilatometry

Dilatometry experiments were carried out on a Baehr 805 quenching dilatometer. This equipment allows for induction heating of the specimens, and controlled cooling using nitrogen or helium. All experiments were carried out using nitrogen for cooling and vacuum for isothermal holding. This ensures that longitudinal gradients in the specimens are minimized. Heat-treatment cycles typically include heating up to the austenitizing temperature at a rate of 1 °C s^{-1}, holding for a duration specified for each experiment, cooling down to the bainitizing temperature

Table 1
Chemical compositions of the steels (wt.%).

	Casts	C	Si	Mn	Cr	Mo
100CrMo7-3	Ind	0.97	0.24	0.64	1.75	0.26
100CrMo7	Ind	0.98	0.29	0.29	1.78	0.16
100CrMnSi6-4	Ind	0.96	0.60	1.18	1.48	0.03
100CrMo7-3 low Si	Lab	0.87	0.07	0.71	1.74	0.26
100CrMo7-3 low Si low Mn	Lab	0.88	0.08	0.32	1.76	0.24
100CrMo7 low Si	Lab	0.91	0.06	0.31	1.77	0.15
100CrMo7-3 medium Si low Mn	Lab	0.89	0.60	0.32	1.74	0.23
100CrMo7-3 high Si low Mn	Lab	0.90	1.20	0.30	1.74	0.27
100CrMo6-3 low Si low Mn	Lab	0.90	0.07	0.32	1.49	0.25

at a rate of 50 °C s^{-1} before isothermal holding for the duration of bainite formation.

Austenitization conditions and bainitization temperature applied are detailed in each section. Kinetics will be presented as a percentage of the bainitic reaction as a function of time. It must be underlined that, even for grades with low Si contents, the end of the bainite reaction does not imply a 100% bainitic structure. Completion of the bainite reaction may lead to a microstructure with, for example, 10% residual austenite and 90% bainite.

2.3. Hardness measurement and retained austenite content

Following heat treatments, specimens were prepared using standard metallography techniques and examined using light optical microscopy. Hardness measurements were carried out using a Vickers indenter and a 30 kg load (indicated values are the average of three indents).

Retained austenite content was determined on electropolished sections of the dilatometry specimens, using X-ray diffraction with energy dispersion from the continuous spectrum of a tungsten anode. This technique uses 15 reflections of α phase (martensite) and 18 reflections of γ phase (austenite) in the energetic domain $12\,keV \leqslant E \leqslant 40\,keV$ with incident beam fixed to $\theta = 18.25°$. This method developed by CETIM is based on reconstitution of theoretical spectra of the different crystalline structures. The high numbers of α and γ phase reflections minimize possible texturing effects.

3. Estimation of austenite carbon content and grain size

3.1. Method for the determination of austenite carbon content

In hypereutectoid steel grades, austenitization is commonly carried out in the AC_1/AC_m domain. As a consequence, the carbon content of the matrix is strongly dependent on the austenization temperature. An additional difficulty comes from the spheroidizing heat treatment that is almost universally used to render the material amenable to machining. Indeed, although it is sometimes assumed that equilibrium is rapidly achieved for cementite dissolution [12], spheroidized microstructures take up to 3 h to