Low temperature bainitic ferrite: Evidence of carbon super-saturation and tetragonality

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Abstract—Experimental evidence indicates that bainitic ferrite formed by transformation at low temperatures (200–350 °C) contains quantities of carbon in solid solution far beyond those expected from para-equilibrium. A change in the conventional symmetry of the bainitic ferrite lattice from cubic to tetragonal explains the abnormal solid solubility detected. This carbon supersaturation was measured by atom probe tomography, and the tetragonality of the bainitic ferrite, was characterized by means of X-ray diffraction analysis and high resolution transmission electron microscopy.
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1. Introduction

Atom probe tomography (APT) was recently used to demonstrate that bainitic ferrite grows with a high supersaturation of carbon when transforming at abnormally low temperatures (200 °C) due to the extremely slow kinetics of nanocrystalline bainitic steel [1–4]. Results indicated that iron and substitutional atoms, such as Mn, Cr and Si, do not diffuse during the bainite transformation, and that the partitioning of carbon into the residual austenite occurs immediately after growth. The bainite reaction ceases well before the austenite carbon content reaches para-equilibrium. All these results were explained in terms of the diffusionless growth of bainite sub-units [1–4].

In addition, APT revealed the presence of a high level of carbon in bainitic ferrite, which was well above that expected from para-equilibrium with austenite once the reaction proceeds to completion. This reluctance of the carbon to partition was first attributed to carbon-trapping at dislocations in the vicinity of the austenite–ferrite interface, Cottrell atmospheres [5], and to the fact that the lower the reaction temperature, the higher the dislocation density of bainitic ferrite [6–8]. However, recent APT work has shown that as the transformation temperature is decreased, higher amounts of carbon remain in defect-free solid solution in the bainitic ferrite after the transformation. In fact, the recorded composition profiles revealed that the carbon content is rather homogeneously distributed within each phase, indicating that carbon had sufficient time to be distributed to a state close to certain kind of equilibrium that is independent of the initial distribution between bainitic ferrite and parent austenite.

The interesting question is what factors have caused the abnormally high carbon solubility in bainitic ferrite. Bhadeshia and co-workers, using first-principles calculations, proposed that the apparent reluctance of the excess carbon to partition from bainitic ferrite, is due to a change in the symmetry of the ferrite unit cell originating from the mechanisms of transformation [9]. In other words, when body centered tetragonal ferrite (BCT) is in "equilibrium" with austenite, it has a much greater solubility for carbon than is the case for body centered cubic ferrite (bcc) in the same circumstances [10].

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In this work, these first principles calculations were validated from APT measurements of the carbon content in bainitic ferrite plates away from any carbon-enriched regions, such as dislocations, boundaries, and carbide particles. A variety of microstructures were studied in two nanostructured bainitic steels after transformation at low temperatures, 200–300 °C. The results are also validated with those obtained as the bainitic transformation progresses at 200 °C, and at different tempering stages. In addition, new experimental evidence is provided on the tetragonality of nanostructured bainitic ferrite, based on X-ray diffraction (XRD) measurements, and high resolution transmission electron microscopy (HRTEM).

2. Materials and experimental procedures

The steels studied exhibit a nanocrystalline bainitic structure, as described elsewhere [11–13] with the chemical composition as stated in Table 1.

A Bahr 805D high-resolution dilatometer was used to perform the heat treatments and to track the isothermal decomposition of austenite into bainitic ferrite on samples that were 5 mm in diameter and 10 mm long. In these experiments, by means of an induction system, samples were heated above the Ac3 and subsequently cooled down to the isothermal temperature. The process parameters, i.e., the austenitisation temperature, cooling rate to the isothermal temperature and the value of this same temperature, were adapted to the alloy chemical composition and to its hardenability, the latter to avoid the formation of ferrite and pearlite prior to bainite transformation. The nanostructured bainite was produced during the isothermal holding at temperatures ranging between 200 and 350 °C. For most of the experiments, the selected isothermal holding times were those strictly necessary to ensure the end of the bainitic transformation. But, some experiments were kept longer than strictly necessary for reasons later described in further detail, those experiments are identified by the '+' sign followed by the amount of extra time after the end of the bainitic transformation. For example for the case of Alloy 2 treated at 220 °C, the '+6d' means that the sample was held for an additional 6 days after the completion of the isothermal transformation taking place after 24 h of heat treatment. For details in the time needed to finish the bainitic transformation at the different isothermal temperatures see Table 1.

After the isothermal heat treatment, samples were Ar quenched to room temperature. It is important to note here that, as austenite (γ) is enriched in carbon relative to the
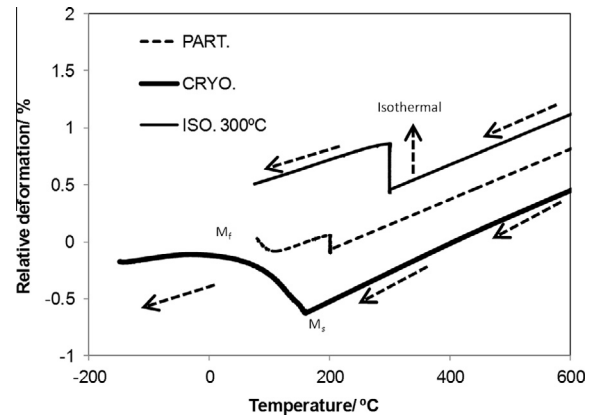

Fig. 1. Alloy 3 dilatometric curves from the austenitisation temperature down to three possible scenarios, as described in the main body of the text.

average composition of the steel, due to the partial partitioning of carbon from the bainitic ferrite (α_b), during quenching to room temperature, no martensite (α') forms, as the martensite start temperature, M_s, of the C enriched retained austenite is well below room temperature. Finally, the microstructure thus achieved consists of fine platelets of bainitic ferrite in a matrix of carbon-enriched residual austenite. Numerous microstructural studies are available elsewhere and are not reproduced here for the sake of brevity [11–13].

The results obtained in this work could be interpreted as suggesting that martensite and nanostructured bainitic ferrite are the same phase. Indeed, they share many common aspects [14], but they are quite separate phases, since the transformation occurs at very different transformation temperature ranges. Thus, for Alloy 3, dilatometric curves from the austenitisation temperature under different scenarios, Fig. 1, illustrates:

- CRYO: The dilatometric curve of a cryogenic test, down to −150 °C, where the full martensitic transformation is visible, beginning (M_s) and end (M_f).
- PART: Partial bainitic transformation at 200 °C, where not enough carbon enrichment has taken place, and during cooling to room temperature, the martensitic transformation takes place from the untransformed retained austenite.
- ISO: Completed bainitic transformation at 300 °C, enough carbon enrichment of austenite has taken place, and therefore, during cooling down to room temperature austenite remains stable.

Table 1. Chemical composition of the alloys studied in wt.% and at.%. T and t_{finish} indicate the bainitic isothermal temperature, in °C, and the time needed to finish the transformation at such temperature.

		C	Si	Mn	Cr	Mo	Co	Al	Ni	V	T	t_{finish}
Alloy 1	wt.%	1.0	1.5	1.9	1.3	0.26				0.1	200	6d
	at.%	4.4	2.8	1.8	1.3	0.1				0.1	300	12 h
Alloy 2	wt.%	0.7	1.4	1.3	1.0	0.24			0.1		220	24 h
											250	14 h
	at.%	3.1	2.7	1.3	1.0	0.1			0.1		300	5 h
											350	4.5
Alloy 3	wt.%	0.8	1.6	2.0	1.0	0.24	4.0	1.7			250	12 h
	at.%	3.5	2.9	1.91	1.0	0.1	3.6	3.3			300	6 h