Available online at ScienceDirect
ScienceDirect
J. Mater. Sci. Technol., 2014, 30(5), 511–516
JMST
www.JMST.org

Phase Transformation under Continuous Cooling Conditions in Medium Carbon Microalloyed Steels

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[Manuscript received September 18, 2013, in revised form December 9, 2013, Available online 1 April 2014]

Several 35CrMo4 and 38MnV7 steels with different additions of Ti and V were manufactured by electroslag remelting. The influence of the alloying and microalloying elements on phase transformation at different cooling rates was studied and the continuous cooling transformation diagrams were plotted. In order to optimize the heat treatment and improve the mechanical properties, the range of cooling rates leading to a fully bainitic microstructure (without ferrite, pearlite and especially without martensite) was determined. Bainite and martensite transformation start temperatures (B_s, M_s) were also established and compared with the values predicted by empirical equations. The important role of precipitates (especially V carbonitride particles) on final microstructure and mechanical properties was assessed.

KEY WORDS: Microalloyed steel; Phase transformation; Precipitation; Dilatometry; Continuous cooling transformation diagram

1. Introduction

Medium carbon steels with 0.30–0.40 wt% C have been used during last decades as high strength steels, especially for automotive parts manufacturing. These steels were used firstly in the quenched and tempered (Q + T) condition, with a good compromise between strength and toughness. Later, medium carbon steels microalloyed with V and/or Ti were developed[1]. These steels suffered a normalizing treatment after hot stamping, in order to obtain a fine microstructure of ferrite + pearlite with similar mechanical properties compared to Q + T steels but at a lower cost. In the last years, microalloyed steels presenting a bainitic microstructure are being studied and introduced in the industrial production. This microstructure offers a better behavior in terms of fracture mechanics, because crack generated in service encounters more obstacles in its propagation through bainitic laths and packets compared to ferrite grains[2].

Whereas ferrite–pearlite microstructure is very well known, a much deeper knowledge about bainite microstructure is needed. Bainitic steels with a wide range of carbon contents (from less than 0.1% to near 1%) are being investigated nowadays[3–10]. Important developments have been achieved, especially on low carbon bainitic steels. However, a deeper research is especially necessary on medium and high carbon steels, as the good values of strength in these steels are usually accompanied by relatively low values of toughness. On this regard, an improved knowledge about the thermal treatments (both under isothermal and continuous cooling conditions) to obtain microstructures with lower, upper or granular bainite will be crucial to enhance toughness values and fracture mechanics behavior.

Austenite–bainite transformation is complex. First of all, it is difficult to obtain fully bainitic microstructures, as usually other phases will appear after cooling. In order to study all these phase transformations, one of the more useful techniques that can be applied is dilatometry. Dilatometry is an experimental technique that lets to situate and follow the solid state phase transformations occurring in different materials, particularly steels. Phase transitions bring about volume changes, and these changes can be recorded studying the length changes of samples with normalized dimensions during their heating or cooling. The variations in the rate and direction of length change vs temperature (dilation/contraction) allow determining the temperatures where phase transformations of steel take place. In steel, dilations and contractions occur as a result of the different crystalline structures of Fe and the phases that can arise during heating or cooling. In a medium carbon microalloyed steel, the main phases that can form are[11–15]: ferrite (δ and α), austenite (γ), cementite (Fe_3C), pearlite (ferrite and cementite), bainite (ferrite and cementite) and martensite, as well as carbides of the microalloying elements. The lattice parameters of the different phases in steel can vary with the content in carbon and other alloying elements. Expressions where the influence of temperature on lattice parameter is taken into account can be found elsewhere[16].

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http://dx.doi.org/10.1016/j.jmst.2014.03.015

Optical microscopy (OM) reveals bainitic packets where plates grow with the same orientation, but the size of individual ferrite plates is usually too small to be observed by this technique. The packet defined by OM can be considered as the “morphological packet”, but it should be taken into account that the microstructural unit controlling crack propagation in a cleavage fracture is the “crystallographic packet”. This packet can be measured by electron back-scattered diffraction (EBSD). Applying a misorientation angle criterion of 15°, the bainite packet size is near one third of the value determined by OM[17].

Martensite is achieved at the highest cooling rates. Carbon atoms are arranged causing a distortion in the crystal structure, and the lattice changes from body-centered cubic structure (bcc) to body-centered tetragonal (bct). Martensite needles also develop in packets with the same direction, but in this case some needles present a high misorientation angle[18]. As will be seen later, the martensitic transformation start temperature (M_s) is a function of austenite carbon content. In all steels with sufficiently high carbon content, the martensitic transformation cannot go to the end so a certain fraction of austenite remains in the structure after cooling as “retained austenite” (γ_R)[19].

Each phase in steel has its own mechanical properties, from soft and ductile ferrite to hard and more brittle martensite. From an industrial point of view, the achievement of a particular microstructure in steel under continuous cooling conditions is generally preferred to the same or similar result obtained under isothermal conditions. In many steels, it is technically important to know the microstructures obtained when cooling rates after thermal treatment close to air-cooling are applied. On the other hand, vanadium is the most important alloying element in medium carbon microalloyed steels. V carbonitride (VCN) particles promote a precipitation strengthening effect in ferrite–pearlite[20] and bainitic microstructures[21]. V additions can be also beneficial to toughness as a result of the preferential intragranular nucleation of acicular ferrite on VCN or VN particles[22,23]. These precipitates can also nucleate on existing TiN particles and oxides to form complex inclusions that serve as nucleation sites for the acicular ferrite, which helps to refine bainitic microstructure[24].

For all the aforementioned reasons, continuous cooling transformation (CCT) diagrams have been determined in this work for five medium carbon steels with different compositions (essentially different Cr, V, Ti and Mn contents). These diagrams provide a useful tool to the design of optimized thermal treatments and to generate the desired microstructures. To determine the CCT diagrams, dilatometry tests at several cooling rates were carried out on the steels studied as described later.

2. Experimental

One reference steel and four medium carbon V/Ti microalloyed steels with different Cr, Mo, Mn and N contents were studied. These steels (whose main application is the automotive parts production) were manufactured by electroslag remelting (ESR) technique. Their compositions are shown in Table 1. These steels may be used in quenched and tempered condition, but they might also be processed under continuous cooling, since Cr, Mo and Mn additions let to obtain bainitic microstructures under a wide range of cooling rates. Steels CR1, CR2 and CR3 correspond to a 35CrMo4 steel with relatively low Mn content. Cr and Mo additions contribute to obtain bainitic microstructure at moderate cooling rates. Steel CR1 is the reference steel and steels CR2 and CR3 have been respectively microalloyed with V and Ti. On the other hand, steels MN4 and MN6 are 35MnV7 steels with two levels of Mn.

In order to analyze the decomposition of austenite and to determine the critical phase transformation temperatures under

Table 1 Chemical composition of the steels studied (wt%)

Steel	C	Si	Mn	Cr	Mo	V	Ti	N
CR1	0.38	0.24	0.82	0.83	0.17			0.0090
CR2	0.38	0.28	0.9	1.01	0.2	0.12		0.0214
CR5	0.36	0.38	0.94	1.16	0.23		0.038	0.0093
MN4	0.38	0.25	1.53	0.19	0.041	0.11		0.0217
MN6	0.38	0.25	2.23	0.16	0.033	0.12		0.0118

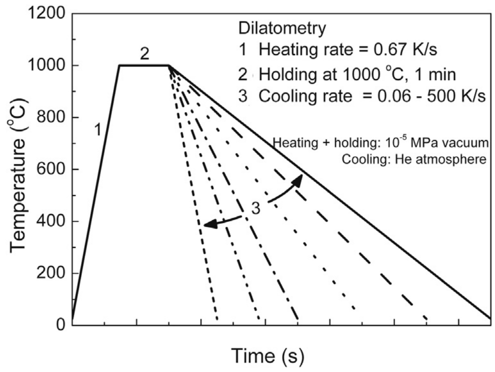

Fig. 1 Experimental conditions for the dilatometry tests.

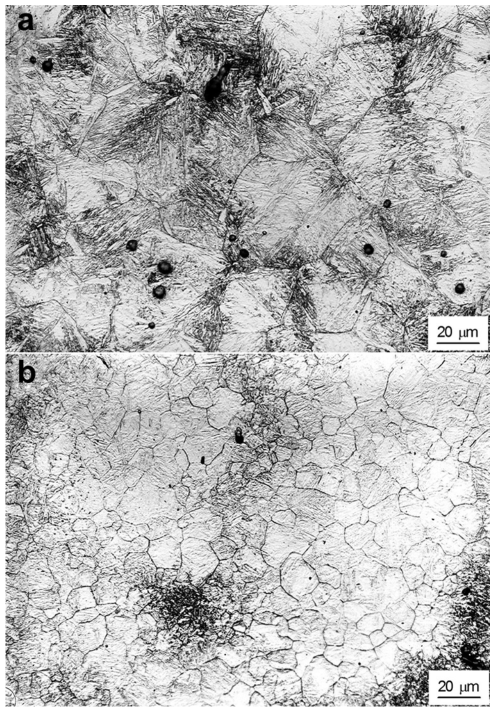

Fig. 2 Microstructure of two dilatometry samples quenched from reheating temperature (1000 °C) after 2 min holding time, etched to reveal prior austenite grain boundaries: (a) steel CR1; (b) steel MN4.