



Study of the temperature dependence of the bainitic transformation rate in a multiphase TRIP-assisted steel

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Abstract

A prerequisite to the development of multiphase TRIP-assisted steels is a good understanding of the bainitic transformation that takes place during the related thermo-mechanical processing. In this framework, the present paper proposes to investigate the formation of bainite when originating from intercritical austenite in a Si bearing steel. The experimental results suggest the contribution of a martensitic type mechanism to the transformation process. Yet, the overall bainitic reaction rates are found to strongly depend on the holding temperature. This original kinetics is correlated with the typical microstructure the steel exhibits after the intercritical annealing stage. To this extent, the crucial role of the adjacent development of bainitic ferrite for the observed temperature dependence is discussed. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

The microstructure of multiphase TRIP-assisted steels typically consists of a fine dispersion of metastable retained austenite islands in a ferritic base matrix. This multiphase microstructure is usually generated by a standard two stage heat-treatment [1]. The material is first intercritically annealed in the ferrite/austenite coexistence domain during which the austenite is created. Next, isothermal holding in the bainite formation domain is performed in order to stabilize the remaining austenite and to permit its presence at room temperature. Since the accomplishment of the last step is crucial for the retention of austenite and, thereby, the control of the mechanical properties, a good understanding of the associated bainitic reaction seems necessary. However, it appears that emphasis has been drawn so far on the study of bainite formation when originating from a fully austenitic microstructure. This appreciably differs from the processing of multiphase

TRIP-assisted steels, for which intercritical annealing leads to an original duplex ferrite/austenite microstructure. The purpose of this work is to contribute to the understanding of the bainite formation originating from intercritical austenite. The investigation was carried out on a Si bearing steel, so that carbide precipitation is substantially retarded and does not interfere with the progress of the bainitic transformation [2]. A strong temperature dependence of the bainitic reaction rate is evidenced and interpreted by means of the microstructural features of multiphase TRIP-assisted steels.

2. Material and experimental procedures

The investigation was carried out on an Fe–0.11C–1.50Si–1.53Mn steel previously hot and cold-rolled down to 0.8mm thickness following classical processing routes. The desired multiphase microstructure is obtained as follows. The cold-rolled material is first intercritically annealed in the ($\alpha + \gamma$) region at 750°C. It was then rapidly cooled and held at an intermediate temperature where upper bainite formation can take place,

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namely between 375 and 450°C. The heat-treatment was eventually interrupted by fast quenching down to room temperature. The thermal simulations were conducted under vacuum in a Theta dilatometer using $15 \times 4 \times 0.8$ mm flat specimens cut out by spark-erosion. The length change of the samples was continuously monitored during the holding stage to study the rate of bainite formation. The microstructural evolution along the isothermal holding was studied on specimens whose treatment was interrupted by quenching. Particular sample preparation [3] was carried out prior to scanning electron microscopy (SEM) observations. Transmission electron microscopy (TEM) examinations were also performed on specimens electropolished by using a solution composed of 80% methanol and 20% perchloric acid. The carbon content of the retained austenite was estimated from the lattice parameter a_0 measured from the (220) γ X-ray diffraction peak, using the base relationship a_0 (Å) = $3.578 + 0.033$ (wt.%C) [4]. Since the steel studied contained Mn and Si, the latter formula was appropriately modified with the respective factors [4,5] to take these elements into account.

3. Results and discussion

Fig. 1 shows the rate at which bainite forms at 375, 416 and 450°C, as determined by dilatometry. It appears clearly that the overall reaction rate of the bainitic transformation is strongly dependent on the holding temperature. Moreover, for the three temperatures under consideration, bainite formation is found to cease well before the whole consumption of austenite, exhibiting thereby a transformation ‘stasis’. At that stage, it is found that the austenite carbon enrichment accompanying the bainite formation is sufficient to

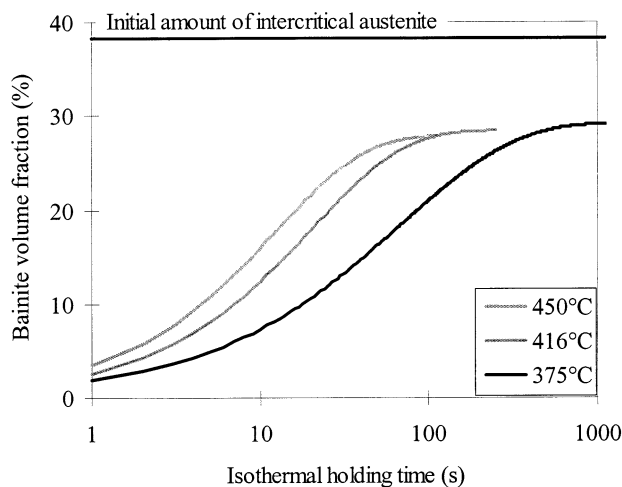


Fig. 1. Kinetics of the bainitic reaction between 375 and 450°C, as determined by dilatometry.

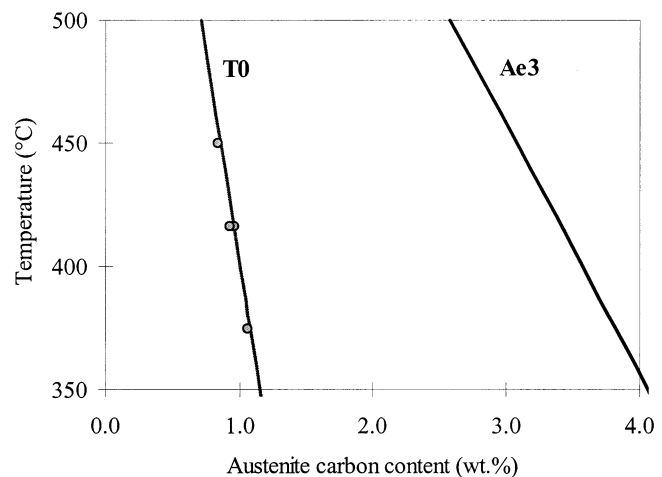


Fig. 2. Comparison of ultimate austenite carbon content (dots) determined by XRD with calculated T_0 and A_{e3} curves (solid lines).

avoid any presence of martensite at room temperature. This means that all the residual austenite is effectively stabilised and thus the carbon content measured at room temperature is also relevant to the state just before cooling.

Fig. 2 shows the austenite carbon content reached at the termination of the bainitic transformation together with the T_0 and the A_{e3} curves. T_0 is the temperature at which austenite and ferrite of identical composition have equal free Gibbs energy, whereas A_{e3} refers to the $\alpha + \gamma/\gamma$ paraequilibrium temperature (i.e. with no substitutional partitioning). The T_0 and the A_{e3} lines were calculated using the PARROT [6] module of the Thermo-Calc [7] data-bank system. In this module it is possible to do a calculation corresponding to the condition that defines respectively the T_0 and A_{e3} temperatures. The experimental values of the carbon content of austenite prove to fall fairly well on the T_0 locus. This suggests the contribution to the investigated bainite growth of a martensitic type mechanism where carbon diffusion is prohibited. Accordingly, the bainitic reaction is observed to proceed until the Gibbs energy of the parent phase (the residual austenite) and the product phase (the supersaturated ferrite) of the same composition are identical. The large gap between the measured values and the T_0 curve on one hand and the A_{e3} locus on the other hand seems to rule out the occurrence of bainite growth under carbon diffusion control. Note finally that the fact that the T_0 temperature is a decreasing function of the carbon concentration is effectively consistent with the increase of the degree of transformation to bainite as temperature is reduced, visible on Fig. 1.

The dilatometric experiments reveal that the overall rate of the bainitic reaction strongly depends on the holding temperature, a trend that has also been recently observed by the present authors in other multiphase

TRIP-assisted steels [8]. It must be emphasised that the manifestation of this temperature dependence is new, given that bainite formation kinetics of austenitized Si bearing steels are usually reported to be hardly dependent on temperature, e.g. Ref. [9]. In order to better understand this new issue, comparative TEM observations were carried out on specimens isothermally transformed until cessation of the bainitic reaction. In accordance with other studies [10,11], Fig. 3 shows that a bainite unit is composed of a set of parallel ferrite laths. However, for the multiphase TRIP-assisted steel studied, the prior austenite grains from which bainite originates are small (i.e. about 1 μm in size) because they were formed in the intercritical domain. Due to these geometrical restrictions, one lath only suffices to cross a parent austenite grain. Therefore, a bainite unit appears to consist of an adjacent pile up of laths, whose typical arrangement can be seen in Fig. 3.

Further microscopy examination showed that the nucleation process of the laths is heterogeneous and, when thermodynamically allowed, favoured at the α/γ boundaries [12]. Since the experimental results presented in Fig. 2 suggest that the growth of bainitic ferrite laths is diffusionless, an interpretation of the kinetics observed is rather to be found in the nucleation process of these laths. After a lath is martensitically formed, the carbon in supersaturation in the product ferrite tends to be rapidly released into the surrounding austenite [13], which leads to the carbon enrichment measured. The development of the following lath will depend to a large extent on the effectiveness of the carbon previously ejected to disperse and uniformly spread in the austenite. The growth of a lath is indeed energetically favoured in a low carbon concentration environment, where the chemical driving force is

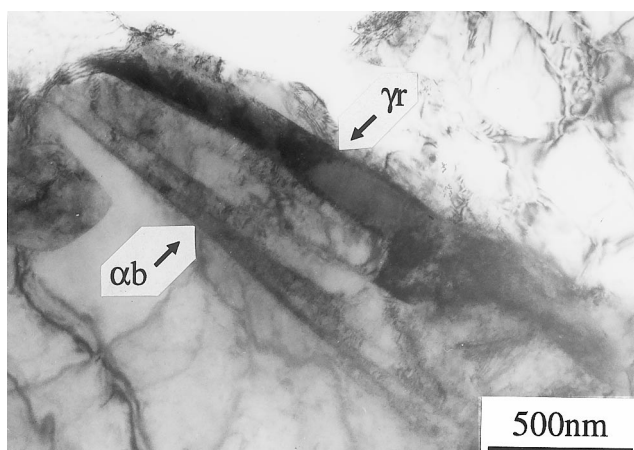


Fig. 3. TEM micrograph of an intercritical austenite grain partly transformed to bainite at 375°C (γ_r , retained austenite; α_b , bainitic ferrite). The bainite unit is clearly composed of an adjacent pile-up of individual ferrite laths. The specimen was isothermally held for 30 min.

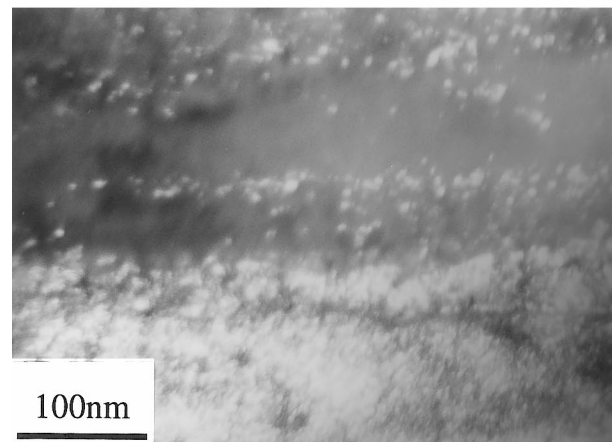
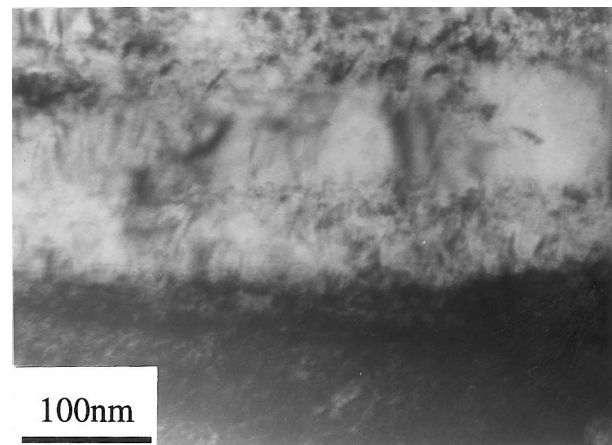


Fig. 4. TEM micrographs of an intercritical austenite grain partly transformed to bainite at 375°C. (a) Bright field image, showing the parent austenite (in black) together with three adjacent bainitic ferrite laths. (b) The corresponding dark field image revealing the presence of residual austenite between the laths. The specimen was isothermally held for 30 min.

higher. It has been shown in the present study that because of the small size of the parent austenite grains, the bainitic ferrite laths can only develop side by side. Yet, the adjacent carbon evacuation through the long edges of a lath is likely to provoke a rapid build-up of carbon concentration in austenite domains near the interface, especially at moderate temperatures. Evidence of this tendency is seen in Fig. 4 which shows the bright (a) and corresponding dark (b) field images of a representative austenite grain partially transformed to bainite at 375°C. It is clear that a large amount of residual austenite (i.e. the illuminated phase in the dark field conditions) is retained between the laths of bainitic ferrite. This austenite retention can only be interpreted by the initial presence of zones highly enriched in carbon, a source of stabilisation. For a transformation temperature of 450°C interlath austenite is almost absent. Substantial carbon heterogeneities are, therefore, observed to emerge in the residual austenite near the long edge of the laths as the holding temperature

decreases. The presence and persistence of the observed domains of high carbon content are believed to substantially increase the delay between the adjacent formation of two successive laths. As a consequence, the overall rate of formation of a bainite unit is markedly reduced at low temperatures, leading to the kinetics of Fig. 1.

In view of the above results, it appears that the observed bainitic transformation kinetics is typical of multiphase TRIP-assisted steels. Thus, due to the small size of the intercritical austenite grains, the development of the bainite laths is constrained to proceed in an adjacent way. The increasing difficulty of carbon to transversally disperse as the temperature decreases accounts for a corresponding slowing in the progress of the reaction. This justification is not inconsistent with the fact that the rate of the bainitic reaction after full austenitisation is reported to hardly depend on the holding temperature. Austenitization indeed gives rise to coarse austenite grains, in which the adjacent development of the laths is no longer required. Consequently, carbon dispersion may take place in a larger volume of diffusion around the laths, so that carbon heterogeneities can be rapidly dissipated and do not significantly affect the transformation kinetics.

4. Conclusions

The present investigation carried out on an intercritically annealed and isothermally held Fe–0.11C–1.50Si–1.53Mn steel showed the following points. (1) The bainitic transformation that takes place during isothermal holding ceases well before the complete consumption of the residual austenite, exhibiting, thereby, an incomplete reaction phenomenon. The carbon concentration of untransformed austenite measured at the cessation of bainite formation proves to correlate fairly well with the calculated T_0 line. This suggests the contribution of a diffusionless mechanism to the considered bainitic transformation. (2) However, the overall rate at which bainite forms is found to depend on the transformation temperature. This is due to the fact that, inside the small intercritical austenite grains, adjacent development of the bainitic ferrite laths is neces-

sary. This transformation process is indeed observed to easily cause a build-up of carbon in the austenite near the interface, which significantly persists at low temperature and hinders the progress of the reaction. (3) Hence, the kinetics of bainite formation that is seen in this study differs from that reported on fully austenitized grades and seems to be typical of multiphase TRIP-assisted steels.

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