Effect of Boron on the Microstructure and Tensile Properties of Dual-Phase Steel

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The effect of boron on the hardenability of austenite during the production of dual-phase steel and on tensile properties has been studied. Increasing boron content from 0.0005 to 0.0029 wt pct decreased the volume fraction of austenite present at constant intercritical annealing temperature but increased the fraction of the austenite which transformed to martensite on cooling. Increasing boron also decreased the sensitivity of martensite content to cooling rate and, therefore, of tensile properties to cooling rate. The lower volume fraction of austenite present at constant intercritical annealing temperature, and the consequentially higher carbon content of the austenite, was in agreement with the known effect of boron on the phase diagram. The previously determined effect of carbon concentration in austenite on the austenite's martensitic hardenability was sufficient to explain the observed effects of increasing boron content. The absence of a direct effect of boron was investigated using particle-tracking autoradiography (PTA) to follow changes in boron segregation. The pattern of segregation to prior austenite grain boundaries in the initial, normalized condition dispersed slightly on holding in the \((\alpha + \gamma)\) phase field, but no evidence was found of resegregation to \(\alpha/\gamma\) interfaces.

I. INTRODUCTION

The microstructure of dual-phase steel is a mixture of ferrite and martensite. Its manufacture requires that at some stage in processing, a prior mixture of ferrite and austenite phases is established. Cooling within an appropriate range of rates then allows a fraction of the austenite to transform to ferrite and another fraction to martensite. Intermediate transformation products, pearlite and bainite, are generally avoided. The fraction of the austenite that transforms to martensite, when expressed as a function of cooling rate, defines the martensitic hardenability of the austenite and depends on the chemical composition and dispersion of the austenite at the time it is cooled. Adequate hardenability is needed to avoid rapid quenching, attendant residual stresses and distortion, and property variations through a section.

Two methods of manufacturing dual-phase steel are controlled thermomechanical processing from the fully austenitized condition and intercritical annealing of a previously rolled product.

A disadvantage of as-rolled dual-phase steel is that for typical products, the range of cooling rates that can be applied at the moment when an appropriate \((\alpha + \gamma)\) mixture has been achieved during thermomechanical processing is somewhat restricted. Thus, alloying elements selected from Mn, Mo, Cr, and V are needed to control the martensitic hardenability of austenite and provide a processing window that matches the range of processing parameters available with the mill equipment. This implies a cost disadvantage compared with simpler steels.

Intercritical annealing has the apparent advantage of being simpler in concept and easier to control, although it bears the cost burden of being an additional heat treatment applied to a finished product. When a low-carbon low-alloy steel is heated into the two-phase \((\alpha + \gamma)\) phase field, the amount of austenite that is formed and its composition are determined at short times and low intercritical temperatures by paraequilibrium, in which carbon but not substitutional alloying elements partition between the phases, or at long times and high temperatures by full equilibrium, in which substitutional alloying elements also partition between ferrite and austenite. Manganese is the principal alloying element used; thus, the carbon and manganese contents of the austenite, and the austenite's martensitic hardenability, depend on the temperature and duration of intercritical annealing.

The dispersion of the austenite at the time it is cooled also has a powerful effect on its hardenability. A particular volume fraction of austenite present as coarse particles yields more martensite than the same volume fraction present as fine particles when both are cooled at the same rate. Thus, the production of finely dispersed martensite particles in a ferrite matrix requires higher cooling rates, or higher alloy contents if slower critical cooling rates are to be practical.

The key to low-cost, fine-grained dual-phase steel production clearly lies in finding a cheap way to control the hardenability of austenite in a two-phase \((\alpha + \gamma)\) mixture. Boron is used as an alloying element in a number of steels; during cooling from the fully austenitized condition (e.g., normalizing), boron increases hardenability. This effect of boron is related to its ability to segregate to austenite grain boundaries and inhibit the grain boundary nucleation of ferrite. Its action, therefore, is to delay the formation of ferrite relative to the formation of lower temperature transformation products. In the production of dual-phase steels, inhibition of ferrite formation would be expected to increase the yield of martensite. However, in contrast to the cooling of fully austenitized steels, where boron delays ferrite nucleation, in dual-phase steels, ferrite forms during cooling from the \((\alpha + \gamma)\) phase field by the growth of existing
ferrite. Nucleation of new ferrite grains, although observed in some instances, does not contribute significantly or generally to the kinetics of ferrite formation during cooling of the \((\alpha + \gamma)\) mixture. Nevertheless, since the energy of the \(\alpha/\gamma\) interface is comparable to that of the \(\gamma/\gamma\) grain boundary, it may be expected that redistribution of boron from prior austenite grain boundaries to \(\alpha/\gamma\) interfaces may occur during intercritical annealing. It may then interfere with the mechanisms of growth of ferrite into austenite during subsequent cooling.

Consequently, the effect of boron additions to a low-carbon manganese steel on the hardenability of austenite present after intercritical annealing has been studied. In addition, the tensile behaviors of the dual-phase steels that were produced were also measured to determine whether the presence of boron was detrimental to mechanical properties.

II. EXPERIMENTAL DETAILS

Three steels with similar base composition but varying boron contents were made by vacuum induction melting. The boron additions were protected by the prior addition of titanium to form TiN in preference to BN. The compositions of the steels are given in Table I.

Ingots approximately 75-mm square were hot-forged to 50-mm square. The forged bars were soaked for 3 hours at 1100 °C and hot-rolled to 15-mm-diameter bar, finishing at approximately 1000 °C. Individual lengths of the bar stock were reheated at 950 °C for 30 minutes and furnace-cooled in order to obtain a uniform starting microstructure of ferrite and pearlite.

Round tensile specimens were machined having 10-mm-diameter shoulders, 5-mm-diameter gage sections, 35-mm gage lengths, and smooth fillets. They were intercritically annealed at temperatures between 770 °C and 870 °C for 20 minutes before being quenched into brine, water, or oil. A servohydraulic testing machine was used for tension tests at an initial strain rate of 0.02/min. Metallographic sections were taken from heat-treated gage lengths. Volume fractions of microstructural constituents were determined by point counting on appropriately etched surfaces. Sufficient points were counted to determine martensite volume fractions to ±1.6 pct at the 95 pct confidence level.

Particle-tracking autoradiography (PTA)[8] was used to study the location of boron in microstructures. A metallographic surface was coated with a cellulose acetate film which acted as a solid detector of \(\alpha\)-particle tracks. The coated specimens were irradiated with thermal neutrons to integrated fluxes of \(10^{13}\) to \(10^{14}\) neutrons/cm\(^2\), during which \(\alpha\) particles released by the fission of boron are tracked in the cellulose acetate film. After development, the films were examined by optical microscopy. The sensitivity of the technique is approximately 1 ppm boron.

Conventional scanning and transmission electron microscopy techniques were also used to examine specimens taken from the gage lengths of tensile test pieces.

III. RESULTS AND DISCUSSION

Representative microstructures of the three steels water-quenched from two intercritical annealing temperatures and etched to reveal martensite are illustrated in Figure 1. Increasing boron content decreased the martensite content after quenching at the two fastest rates from all intercritical temperatures. This is illustrated for water-quenched samples in Figure 2. At sufficiently fast cooling rates, very little of the austenite present at the intercritical annealing temperature transformed back to ferrite during cooling before the temperature fell to the martensite start temperature of the austenite. Thus, the martensite contents revealed in Figures 1 and 2 are slightly less than the austenite contents present at the annealing temperatures, but they do reflect the dependence of austenite volume fraction on intercritical annealing temperature and on boron content.

The clear effect of boron, of reducing the volume fraction of austenite present at the intercritical annealing temperature, arises directly from its effect on the \(\text{Ae}_3\) temperature. Figure 3 shows the effects of small boron additions on the extent of the \(\gamma\) phase field in Fe-C alloys.[8] At constant intercritical temperature, boron decreases the austenite content and increases the carbon concentration present in the austenite of hypoeutectoid steels. Without taking into account the presence of other alloying elements, Figure 3 suggests that the concentration of boron in steel C would place its composition in the three-phase, ferrite + austenite + carbide phase field at temperatures below approximately 800 °C. Similarly, the composition of steel B would be in the ferrite + austenite + carbide phase field at temperatures below approximately 770 °C. The effects of boron in the steels used here, which contain significant concentrations of manganese and silicon, would be expected to be only qualitatively similar to its effects in Fe-C alloys. It should also be noted that the intercritical annealing duration of 20 minutes results in phase volume fractions and compositions nearer to paraequilibrium than to true equilibrium. Therefore, although the effect of boron described in Figure 3 explains its role in reducing the austenite content obtained during intercritical annealing, quantitative predictions of austenite volume fraction and austenite carbon content are not possible.

Figure 4 is a “microstructure” map for the three steels intercritically annealed at 800 °C, in which the volume

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<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>N</th>
<th>Al</th>
<th>Ti</th>
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