Communication

The Effect of Nb Micro-alloying on the Bainitic Phase Transformation Under Strip Casting Conditions

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The effect of Nb concentration on the transformation from austenite to bainitic ferrite has been examined under simulated strip casting conditions. Nb concentration was found to delay the nucleation of bainite, but accelerated its growth. It is suggested that the delay in nucleation increases the driving force for transformation, which results in an increase in the growth rate of the bainite. The bainite/austenite interfaces are proposed to move too quickly to suffer appreciable solute drag.

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Direct strip casting is a method of producing steel sheet from liquid steel by casting it directly into thin sheet.[1] This process eliminates the need for reheating and hot rolling, and this leads to a significant energy saving when compared to conventional processing. For environmental reasons, it is anticipated that direct strip casting will become an increasingly common method of producing steel sheet. However, the strip casting process subjects the material to extremely high cooling rates, and this results in strip cast steels typically developing a mixed microstructure of Widmanstätten, martensitic, and bainitic ferrite morphologies, depending on the steel chemistry.[2-6] The effect of solute elements such as Nb is of particular importance in strip casting because the cooling rate during austenite decomposition is sufficiently high that precipitation of carbides and nitrides cannot occur,[3,7,8] and in the case of a typical high strength low alloy steel chemistry, Nb and C both exist in solid solution above equilibrium concentration. It therefore becomes imperative in this case to understand the mechanism of the phase transformation under these conditions in order to guide future alloy and process design, with particular emphasis on the increased solute content and high cooling rates.

High-strength low-alloy (HSLA) steels that are processed by strip casting form predominantly bainitic microstructures.[3] The bainitic transformation is well studied, *e.g.*, References 9–12 and the effect of Nb has received some attention because of its industrial importance as an alloying element in HSLA steel grades.[3,6,13,14] Chen *et al.*[15,16] have recently shown that concentration spikes in Mn ahead of the interphase interface can retard bainitic growth rates, the so-called transformation stasis, and one would anticipate that Nb may have a similar effect. Indeed, the formations of polygonal ferrite[17] and ferrite formed by the massive transformation[18] have both been shown to suffer from solute drag as a consequence of Nb segregation at the austenite/ferrite interface. But will solute drag have any impact under strip casting conditions? Does this process require a more stringent control of steel chemistry than the conventional slab casting process? To examine these questions, three alloy compositions have been examined to determine explicitly what effect the addition of Nb will have on the microstructural development of low-alloy steels under strip casting conditions. Rather than simply reheating bar stock and examine the microstructure after continuous cooling, we have taken the more experimentally intense route of simulating the strip casting process from liquid through to room temperature. In this way, the other unique features of strip cast material are captured, and these include the large columnar austenite grain size, formation of fine scale sulfides,[7,19] retention of carbon and nitrogen in solid solution,[3] and the micro-segregation of alloying elements to the inter-dendritic regions that develops during solidification.

In order to study the phase transformation over the full thermal cycle from liquid to ferrite, a strip casting simulator was used. The specimens were made by the rapid immersion of a copper substrate into the liquid steel, and the apparatus used in this study has been described in detail elsewhere.[20] R-type thermocouples with high thermal response time were placed on top of the copper substrate to measure the cooling rate of the specimen, and the temperature data were acquired at a rate of 10,000 measurements per second. The compositions chosen for study were based on the commercial HSLA steel alloy class, and are listed in Table I. The only variable in the compositions was the Nb concentration, which was varied from 0 to 0.18 wt pct. All alloys were examined optically, and it was confirmed that the transformation was bainitic in all cases, as shown in Figure 1. A more detailed study of the microstructure of this as-cast steel is provided in Reference 8 and the effect of coiling is the subject of Reference 21.

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There are a significant number of process variables that effect the solidification behavior, heat transfer, and cooling rate under strip casting conditions. Variables include the melt temperature,[20,22] presence of surface active elements such as sulfur,[23] substrate cleanliness,[24] substrate surface,[20,22,24-26] and the substrate temperature.[27] For this reason, all of these variables were carefully controlled in the present set of experiments. The substrate temperature was kept at 65 °C (± 10 °C), the surface was cleaned in between each testing cycle with a wire brush, and the melt temperature was kept at 1552 °C (± 5 °C).

The exothermic phase transformations cause an inflection in the cooling curve, and these inflections were used to determine the transformation start and finish temperatures, as shown in Figure 2. The undercoolings were determined by comparing the measured transformation temperatures with the predicted equilibrium transformation temperatures that were calculated using the commercially available software package Thermocalc (TCFE3 database). The undercooling measured for each of the four alloys is shown as a function of Nb concentration in Figure 3(a). It can be seen that the undercooling is increased as a function of Nb concentration. Since the carbon content is the same for all alloys, the only chemical effect increasing the undercooling is the addition of Nb. This data confirms that under strip casting conditions, where the cooling rate during austenite decomposition is in the order of 10 °C/s,[8] the addition of Nb to the steel results in a delay in the transformation. In such cooling conditions, the Nb remains supersaturated during solidification.[8]

In Figure 3(b), an additional parameter is introduced, the transformation time. This is often not quoted in literature, and in the present case is introduced to interrogate further the transformation behavior. Figure 3(b) shows that alloys with higher Nb concentrations have shorter transformation times, and suggests that the growth rate of the bainite is higher in these alloys (remembering that the cooling rates are similar in all cases). This seems to indicate that the addition of Nb actually increases the growth rate of the bainite. A collation of data from the literature seems to confirm this result, as shown in Figure 3(b). In the present case, it is apparent that the addition of 0.18 pct Nb halves the transformation time from 16 to 8 seconds, effectively doubling the growth rate.

From the data presented in Figure 3, we can now differentiate the effects of Nb on nucleation and on

Table I. Composition of the Alloys Tested in the Present Study All Expressed in Weight Percentage

	C	Nb	Mn	Si	S	P	N	Fe
Alloy 1	0.10	—	0.62	0.16	< 0.001	0.005	0.01	bal
Alloy 2	0.10	0.09	0.62	0.16	< 0.001	0.004	0.01	bal
Alloy 3	0.10	0.18	0.61	0.16	< 0.001	0.006	0.01	bal

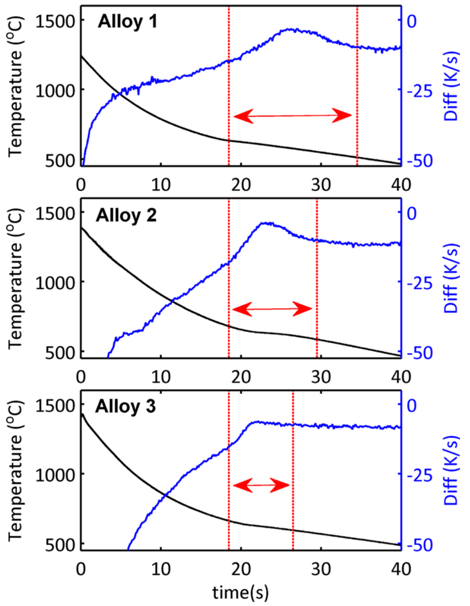

Fig. 2—Typical examples of the measured cooling curves for each of the alloys tested. The derivative of the cooling curve is also shown, as is the measured start and end temperature for the phase transformation.

(a) Alloy 1 (0%Nb) **(b)** Alloy 2 (0.09%Nb) **(c)** Alloy 3 (0.18%Nb)

Fig. 1—Optical micrographs at same magnification of (*a*) alloy 1, (*b*) alloy 2, and (*c*) alloy 3. Specimens were polished by standard methods and then etched in nital. The compositions are detailed in Table I.

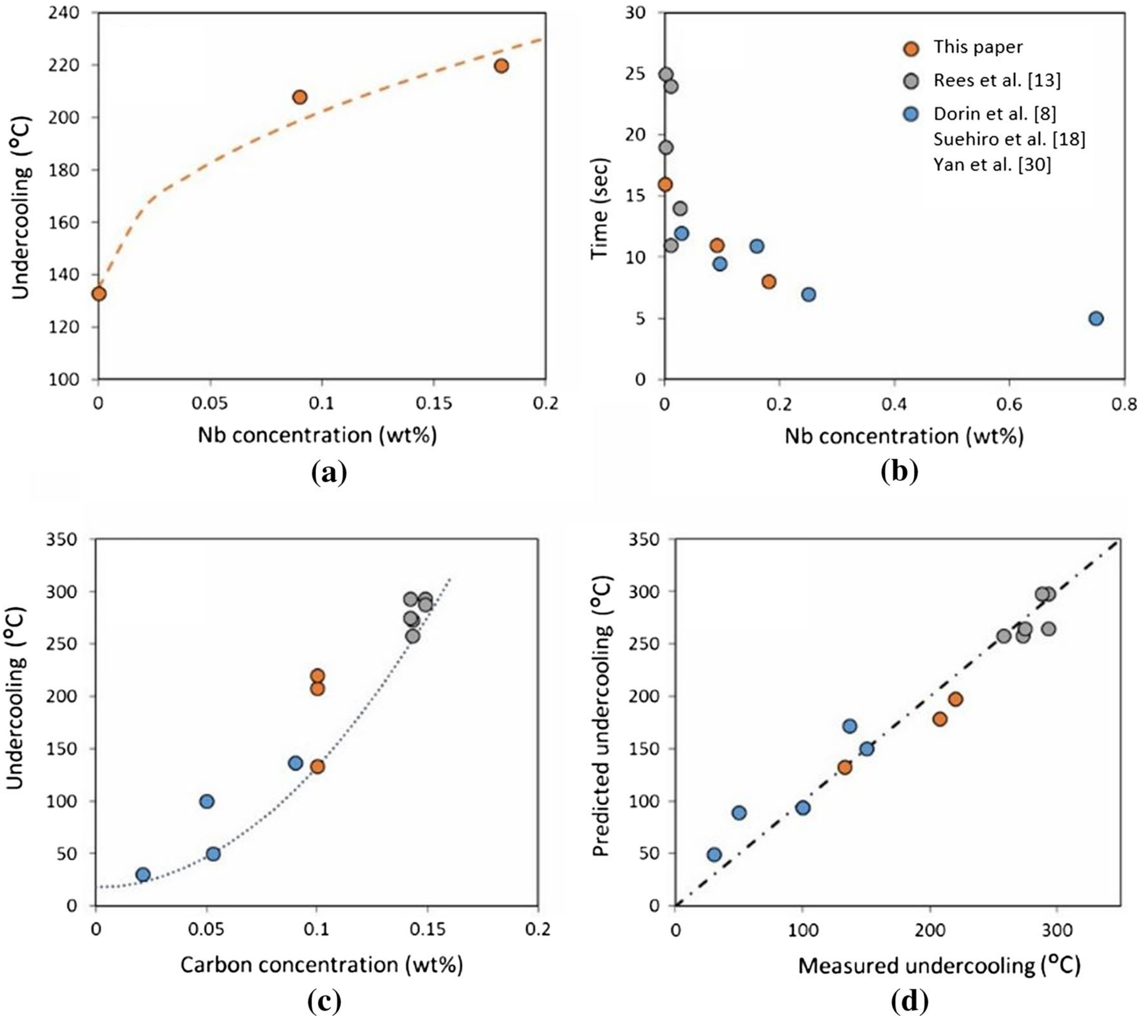

Fig. 3—(*a*) Results from the present experiments showing the effect of Nb on increasing the undercooling. (*b*) Increase in the transformation time for the present data, along with published data. (*c*) Effect of carbon concentration on the undercooling as described in literature. (*d*) Measured and predicted undercoolings, dotted line shows 1:1 fit.

growth. The increase in undercooling with increased Nb concentration indicates that Nb delays nucleation. However, the more concentrated alloys also show shorter transformation times, indicating higher transformation rates. This suggests that the growth of bainite is not inhibited by Nb in solid solution. This increase in growth rate at higher concentrations can be explained by the fact that larger undercoolings increase the driving force for transformation, resulting in faster transformation rates in alloys with higher Nb concentration. Since the alloys that contain Nb are not growth limited, we can conclude that the addition of Nb does not cause appreciable solute drag to the bainite transformation in the present case. This lack of appreciable solute drag agrees with recent research that shows that the growth of bainitic ferrite before stasis is controlled only by carbon diffusion;[15,16] however, it seems inconsistent with the observation of decreased ferrite growth rates in the presence of Nb.[17] Solute drag is a competition between the velocity of the interface and the diffusivity of the solute. Under the extremely fast cooling rates experienced in strip casting it is likely that the interface is moving too quickly to be affected by solute drag. This is therefore another unique feature of the strip casting process, it seems that the cooling rate during austenite decomposition is sufficiently high that the phase transformation does not suffer appreciably from solute drag. This conclusion seems in agreement with site-specific microscopy of strip cast steels[28] that indicate a lack of Nb segregation to the ferrite–ferrite grain boundaries, but these same experiments do reveal some increase in the Nb concentration at the prior austenite boundaries.

The effect of Nb under strip casting conditions therefore seems well described by the present set of experiments. In this case, the carbon concentration was kept constant in order for a clear conclusion to be made about the effect of Nb. However, carbon remains the most important of the alloying elements, and has a dramatic effect on the austenite decomposition. Although the effect of carbon concentration was not examined here experimentally, a collation of literature data for similar compositions shows a strong dependency of the undercooling on the carbon concentration, as shown in Figure 3(c). Note that the data points

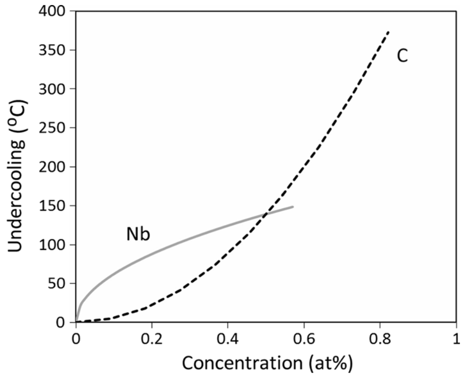

Fig. 4—Predicted effect of Nb and C concentrations on the undercoolings developed during continuous cooling at a rate of ~10 °C/s.

shown in Figure 3(c) are for an approximate cooling rate of 10 °C/s. The strong correlation between carbon concentration and undercooling is in agreement with the work of Quidort and Brechet[29] who show that the nucleation of bainite is limited by the diffusion of carbon at the austenite grain boundaries. Figure 3(c) shows a dotted line which represents a parabolic fit through those data points that were measured on Nb-free specimens, these therefore represent data points that show the effect of carbon (assuming a minimal effect of Si and Mn on the undercooling). Using this as a first approximation, a simple regression analysis has been carried out on these approximations to deduce empirically the effect of C and Nb on the undercooling assuming a simple rule of mixtures:

$$T = T_{\mathrm{C}} + T_{\mathrm{Nb}}$$

$$T_{\mathrm{C}} = 11500[\mathrm{C}]^2 + 18$$

$$T_{\mathrm{Nb}} = 152[\mathrm{Nb}]^{0.5},$$

where [C] and [Nb] are the concentration of carbon and niobium in weight percent. The measured and predicted undercoolings are shown in Figure 3(d). A reasonable agreement can be seen from this empirical analysis. Extrapolating now some general trends, we can compare the relative effects of Nb and C on the undercoolings that develop at the cooling rates which are experienced during strip casting, as shown in Figure 4. Figure 4 is plotted as atomic percentage, rather than weight percentage, and it can be seen that at low concentrations, Nb has a large impact on the undercooling. However, at higher concentrations the effect of Nb plateaus, and the effect of carbon becomes more prominent. In the concentrations typically used for HSLA steel grades, typically less than 0.05 wt pct C (0.23 at. pct) and around 0.02 wt pct Nb (0.01 at. pct) both of these elements show a similar contribution to the undercooling that develops during continuous cooling. If the carbon concentrations were increased to concentrations higher than those shown in Figure 4, it is conceivable that even higher undercoolings may be achieved. If undercoolings in the order of 400 to 500 °C were experienced, these could potentially be high enough for the microstructure to bypass bainite and transform into martensite. This would not be desirable for most applications, so there may be an upper carbon concentration above which strip casting is not feasible, and this will be the topic of a forthcoming publication.

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