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Empirical Equations for the No-Recrystallization Temperature in Hot Rolled Steel Plates

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Abstract

To properly plan rolling schedules, steel plate producers must be able to accurately determine critical temperatures, such as the no-recrystallization temperature (T_{NR}). Several empirical equations have been developed to predict the T_{NR}. However, each of these equations has certain limitations that constrain its applicability. This study examined six laboratory-grade low-carbon microalloyed steels with varying amounts of V, Nb, and Ti. Double-hit deformation tests were conducted to determine the experimental values of the T_{NR}. All samples were reaustenitized at 1250 °C, cooled between 1200 and 750 °C, and compressed twice, to a strain of 0.2 at a strain rate of 5 s^{-1}. The experimental values of the T_{NR} were compared with predicted values of the T_{NR} from four equations given in the literature. The Bai equation appears to be a reasonable estimator for the $T_{NR,}$ as it makes the fewest assumptions and fits well the experimental data. An equation by Fletcher also makes reasonable predictions for the T_{NR}. The Boratto equation ignores the effects of N and consistently predicted high values of the T_{NR} for the steels investigated.

Introduction

Microalloying with multiple alloy elements is widely used in low-carbon high strength low alloy (HSLA) steels. Typical applications of HSLA microalloyed plate steels include marine applications, pipeline steels, construction steels, and machinery steels [1], [2].

Microalloyed steels have small additions of alloying elements, such as V, Ti, and Nb, to improve mechanical properties through grain size control and precipitation strengthening [1]. For example, microalloying is used in API X-70 and X-80 line pipe steels to modify ferrite-pearlite or bainite steels to improve strength and toughness [3].

The present study focuses on the influence of V and Ti on the T_{NR} of Nb-bearing microalloyed steels. If processed correctly, the steels should meet the requirements of API X-70 grade [4]. The primary purpose of this study is to characterize and understand high temperature properties during rolling. The focus of the current study does not encompass mechanical properties at room temperature, but considers mechanical behavior and properties during hot rolling.

The T_{NR} can be determined through many methods. From the literature, the T_{NR} can be estimated through laboratory methods and empirical calculations. The laboratory methods to determine the T_{NR} include [4–13] double-hit deformation testing, multistep hot torsion testing, stress relaxation testing, tension-compression testing, laboratory rolling, and mathematical modeling. The most commonly used methods to obtain an experimental value for the T_{NR} are double-hit deformation testing and multistep hot torsion testing.

The Boratto equation [14–17] is arguably the most known empirical formula to estimate the T_{NR} and is given by:

$$T_{NR} = 887 + 464C + \left(6445Nb - 644\sqrt{Nb}\right) + \left(732V - 230\sqrt{V}\right) + 890Ti + 363Al - 357Si \qquad (1)$$

where C, Nb, V, Ti, Al, and Si are the elements in wt pct of the steel. It should be noted that the Boratto equation does not include N, which is most often involved with precipitation, even though N is almost always present in low-carbon commercial steels [18]. Zaky [19] has found discrepancies with the Boratto equation at low levels of Nb and V (0.01 and 0.10 wt pct, respectively) and high levels of C (above 0.17 wt pct) [19].

A simplified equation by Bai et al. [4], [20] has been shown to produce reasonable T_{NR} estimates when the Boratto equation differs from experimental results. The Bai equation is given by

$$T_{NR} = 174 \log\left[Nb\left(C + \frac{12}{14}N\right)\right] + 1444 \qquad (2)$$

where Nb and C are the elements in wt pct of the steel, and N is the free N remaining after TiN precipitation.

Another T_{NR} equation developed by Fletcher [21] used a database of 59 different T_{NR} values for 17 alloy steels. A stepwise regression was based on the Boratto equation and pass strain was ignored to determine

$$T_{NR} = 849 - 349C + 676\sqrt{Nb} + 337V \; (R^2 = 0.72) \qquad (3)$$

where C, Nb, and¸ V are the elements in wt pct.

Fletcher also developed a T_{NR} model based on pass strain and alloy content using a similar regression model [21]

$$T_{NR} = 203 - 310C - 149\sqrt{V} + 657\sqrt{Nb} + 683e^{-0.36\varepsilon} \qquad (4)$$

where C, V, and Nb are the elements in wt pct, and ε is the pass strain.

Although deformation is known to influence the T_{NR}, the current study was designed to examine only the effects of alloy content on the value of the T_{NR}.

Experimental Procedures

Material for this study was laboratory-produced hot-rolled microalloyed plate steel. The laboratory heats were Nb-microalloyed plate steel to meet API X-70 specifications if processed correctly. Table I gives the chemical composition of the six alloys that were produced.

Table I – Chemical Compositions of Laboratory Nb-Bearing Microalloyed Steels in wt pct

Material ID	C	Mn	Si	Ti	Nb	V	Al	N	S	P
Lo-V	0.065	1.46	0.016	0.005	0.060	0.021	0.030	0.0046	0.0017	0.012
Hi-V	0.068	1.46	0.017	0.005	0.061	0.056	0.029	0.0040	0.0017	0.012
Lo-Nb	0.063	1.47	0.019	0.006	0.027	<0.001	0.030	0.0041	0.0017	0.012
Hi-Nb	0.066	1.46	0.020	0.007	0.060	<0.001	0.028	0.0039	0.0017	0.011
Lo-Ti	0.062	1.48	0.018	0.028	0.060	<0.001	0.032	0.0050	0.0018	0.011
Hi-Ti	0.065	1.48	0.019	0.099	0.059	<0.001	0.030	0.0040	0.0019	0.011

Double-hit deformation tests use cylindrical specimens in an axisymmetric compression test. The test involves reheating to ensure that most precipitates dissolve back into solution, cooling to deformation temperature (T_{def}), compressing with given strain and strain rate, holding for an interpass time (t_{ip}), deforming the specimen again while holding everything else constant, and measuring the percentage recrystallized or fraction of softening (FS) [5], [13], [22–26].

The following testing procedure was used:

- Heat to austenitizing temperature of 1250 °C at 10 °C/s.
- Soak at 1250 °C for 10 minutes to ensure that most precipitates have gone into solution.
- Cool to a single deformation temperature in the range of 1200 °C 750 °C at 50 °C decrements at a rate of 1.25 °C/s.
- Deform with strain (ε) of 0.2, a strain rate ($\dot{\varepsilon}$) of 5 s^{-1} followed by a hold time (t_{ip}) of 5 s.
- Deform again with same parameters of ε of 0.2 and $\dot{\varepsilon}$ of 5 s^{-1}.
- Air cool the sample to room temperature.

The 5 % true strain method [27] was used to determine the FS. The values of FS were determined for each of the six alloys at each testing temperature. The T_{NR} was the temperature where the FS equaled 20 %. All softening greater than 20 % was attributed to static recrystallization [13], [22], [23].

Results and Discussion

The T_{NR} values were found through a sigmoidal fit of the FS values as a function of temperature from the double-hit deformation tests. Figure 1 shows the experimental T_{NR} values (i.e. temperatures where FS = 20%) for each of the six alloys. The experimental T_{NR} is listed above each bar in °C.

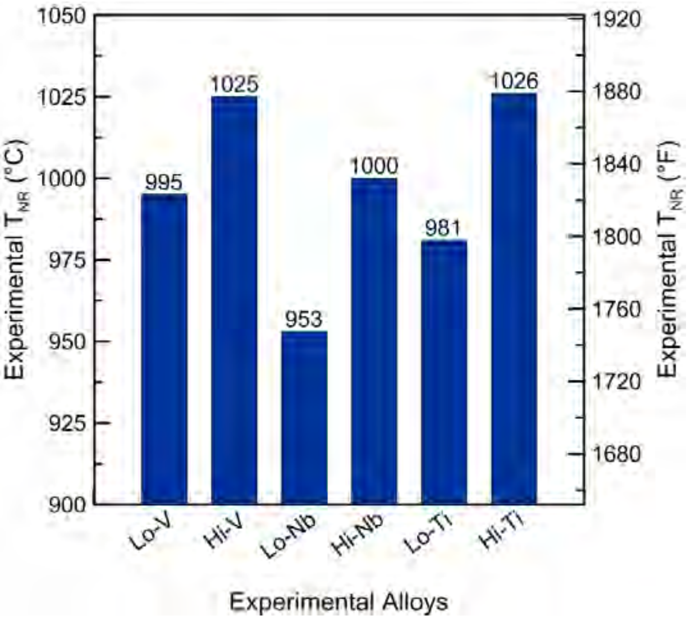
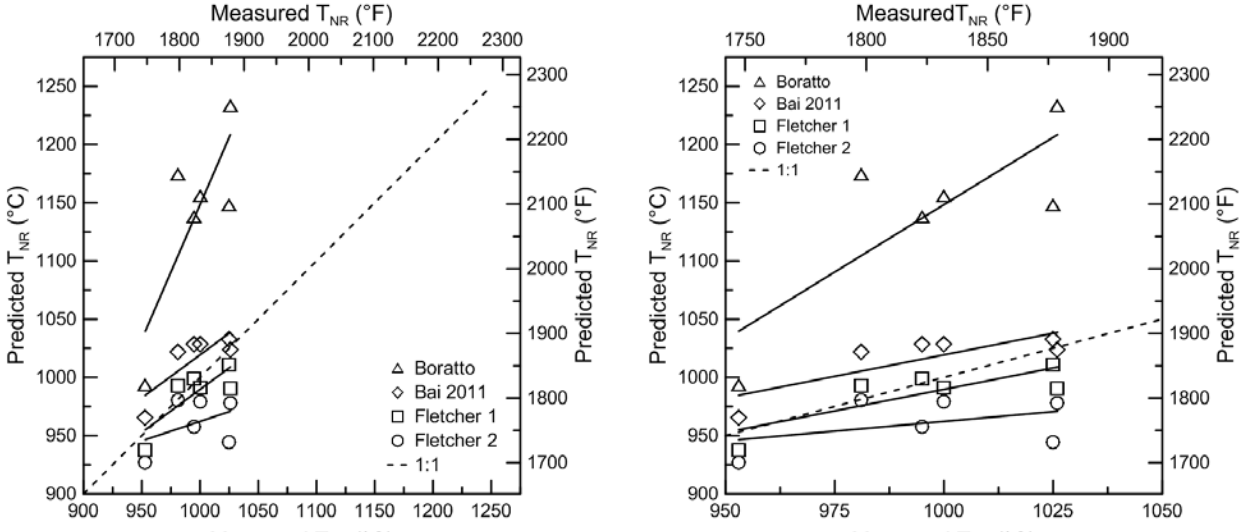


Figure 1 Bar graph showing the experimental T_{NR} for the six alloys.

Table II compares the experimentally-found T_{NR} with the predicted T_{NR} from the literature. Figure 2 shows the comparison graphically (a) with the scale on both axes the same, and (b) with the measured axis showing a smaller temperature range, to more easily see the comparison. It can be seen that the Boratto equation does not accurately predict the T_{NR} for the experimental steels. The Bai equation more closely matched the measured T_{NR}, being only slightly higher for all tested alloys. The Fletcher 1 equation predicts a lower T_{NR} than the experimental results, but the spread is similar to the Bai equation, with a maximum difference of 35 °C (64 °F). The Fletcher 2 equation predicts a T_{NR} that is much lower than the current experimental results. It should be kept in mind that while models are useful, they usually do not explain the actual physical phenomena that occur in testing, and may also be applicable under different conditions.

Table II – Comparison of the T_{NR} Predictions from the Empirical Equations from the Literature and the Temperature Range for T_{NR} Based on the Data Collected

Material ID	Experimental T_{NR} (°C)	Boratto [15] Eq (1)	Bai [20] Eq (2)	Fletcher 1 [21] Eq (3)	Fletcher 2 [21] Eq (4)
Lo-V	995	1138	1029	999	958
Hi-V	1025	1148	1033	1011	944
Lo-Nb	953	994	965	938	922
Hi-Nb	1000	1156	1029	992	979
Lo-Ti	981	1175	1022	993	980
Hi-Ti	1026	1233	1024	991	978



(a) (b)

Figure 2 Empirical T_{NR} equation predictions plotted against experimentally measured values of T_{NR} for the ten alloys of interest in this study showing (a) the fits with similar scales and (b) the fits with the experimental scale covering a smaller range in temperatures. The dotted line is a 1:1 line showing a perfect fit between the predicted empirical T_{NR} values and the experimental T_{NR} values.

Looking at the Boratto equation, the prediction for the Lo-Nb steel is the closest prediction of 994 °C (1821 °F), with the measured T_{NR} of 953 °C (1747 °F). Using the Boratto equation, the predicted T_{NR} for all other alloys are exceptionally high. These discrepancies are believed to occur due to the Boratto equation's lack of accounting for nitrogen. Nitrogen is a known precipitate former and nitrides respond differently than the dissolved compounds. Niobium is known for its strong influence on the T_{NR}, and the Boratto equation shows that niobium has a coefficient that is an order of magnitude higher than that of the other microalloyed elements. It appears this value is slightly exaggerated as the T_{NR} for the alloy with the least Nb was most closely predicted.

The composition of the steels used in the current study fall within the range used to determine the Boratto equation, except for silicon's coefficient being an order of magnitude lower. Silicon is also a major contributor to the Boratto equation and has a rather large negative effect. The V content for all alloys in this study is lower than the necessary 0.1V wt pct V to overcome the negative effects of the radical in the equation. These smaller values for V mean the calculated T_{NR} would be higher due to the V, not lower. When V is absent, the calculated T_{NR} is higher.

In the Bai equation, the nitrogen content is the effective free nitrogen remaining after subtracting nitrogen that is combined with Ti from the total nitrogen from the experimental steels studied by Bai et al. [28]. In their study, the Ti was held constant at 0.015 wt pct. The Ti content in this study ranges from 0.005-0.110 wt pct. Interestingly, the alloy with the closest Ti content to Bai et al.'s steels—the Lo-Ti alloy with 0.028 wt pct Ti—did not have the closest predicted value of the T_{NR}. The Hi-Ti alloy was most closely predicted within 2 °C (4 °F). Overall, the Bai equation is a fairly good estimator of T_{NR}. Ideally the equation would include V and Ti, along with carbide and nitride formation for the V and Ti. However, since Nb has the strongest influence in retarding the T_{NR}, the equation is able to accurately predict the T_{NR} without including the other microalloyed elements.

The Fletcher 1 equation includes C, Nb, and V; it still lacks Ti and N. Both Ti and N play a role in retarding the T_{NR}. This equation consistently predicted a lower T_{NR} than the experimental values, but the difference in the T_{NR} values was not extremely significant, all being within 35 °C (64 °F).

The Fletcher 2 equation is consistent in predicting lower T_{NR} values than the experimental values. Ironically, the Hi-V alloy was found to have the highest experimental T_{NR} value, even though the Fletcher 2 equation predicted that it would have the lowest value.

It is clearly apparent that the Boratto equation is not sufficient to predict the T_{NR} values for the alloys in this study. Neither is the Fletcher 2 equation adequate to predict T_{NR}, even though the equation includes multiple MA elements and strain. The Fletcher 1 equation and the Bai equation do a reasonably good job of predicting the values for T_{NR} for the steels in the current study.

Summary

The Bai equation is a good predictor of T_{NR} for the steels used in the current study. While the model does not have a direct input for Ti, the N content is post-TiN formation, thus indirectly taking Ti into account. The V levels in this study were fairly low. With the strong influence of Nb on T_{NR}, the Nb overpowered most of the effects to which V may have contributed. The Fletcher 1 equation also predicted reasonable T_{NR} values for the experimental steels, but were consistently low. The Fletcher 1 equation included Nb and V, but did not include N and Ti, which both influence the T_{NR}. The Boratto equation was a poor predictor of the T_{NR} for the six experimental steels. Some reasons for the discrepancies may be due to the higher levels of Si used by Boratto et al., the extremely high coefficient on the Nb term, and/or the square root term for V.

Acknowledgements

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