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Strain Hardening Behavior and Cold Reducibility of Boron-added Low-carbon Steel

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Addition of boron in low carbon (0.06% max) hot rolled steel has improved its formability. A unique combination of properties with low strain hardening exponent (*n*) and high total elongation has resulted into higher percentage of cold reducibility of hot rolled coils.

Keywords boron, carbon/alloy steels, cold reducibility, strain hardening exponent

Low-carbon (C 0.06% max, Mn 0.25% max) hot-rolled coils are extensively produced for a variety of cold-reducing applications. Cold reducibility of hot-rolled coils is primarily dependant on low yield strength, high ductility, and low hardness, which in turn is adversely affected by C, Mn, S, P, and dissolved nitrogen in steel. Boron-added low-carbon hot-rolled steel has been recommended in recent past for automotive parts because of its improved formability (Ref 1, 2). Boron being a strong nitride former combines aggressively with dissolved nitrogen in steel and thus increases total elongation and lowers yield strength. It also leads to coarse grain structure partially forming large Boron Nitride (BN) in place of fine Aluminum Nitride (AlN). However, the effect of boron addition in low-carbon steel on cold reducibility has not been explained.

In the present study, the relationship between strain hardening exponent (*n*) and cold reducibility has been investigated in low-carbon aluminum-killed steel and both uniform and postuniform elongation values have been correlated with the presence of boron. The chemical composition of steels used for this study is shown in Table 1.

Both the steels were continuously cast to 210 mm thick slabs and were hot rolled to 2.8 mm thickness. The hot-rolled bands were finish rolled at 880 ± 10 °C and coiled at 620 ± 10 °C. Properties of boron-added steel showed significant improvement compared to steel without boron (Table 2). This has been quantified in terms of lower YS (243-250 MPa), lower UTS (328-335 MPa), and higher total elongation (43-45%). Boron-added steel has lower hardness (44-48 HR_B) in hot-rolled condition as compared to steel without boron (47-54 HR_B). Lower YS, UTS, and hardness value with higher total elongation in boron-added steel can be attributed to the reduced solute nitrogen and carbon contents (Ref 3).

The assessment of cold reducibility required an accurate description of strain hardening behavior. This is because cold reducibility is closely related to the ability of the material to distribute strain uniformly and to resist necking, thereby permitting higher percentage of cold reduction without strip breakage (Ref 4, 5). Stress-strain relations obtained in the uniaxial tensile test commonly represent material hardening data.

The conventional engineering approach has been to fit the uniaxial tensile data in the region of uniform plastic deformation to preselected equations. In the present study, following Holloman equation (Ref 6) has been used as shown in Fig. 1.

$$\sigma = K\varepsilon^n \qquad \text{(Eq 1)}$$

where σ and ε are true stress and true strain, respectively; *K* and *n* (strain hardening exponent) are material constants. Strain hardening exponent has been generally used for estimation of uniform elongation. A high value of regression constant confirms that both the grades follow Holloman equation. It has been found that boron-added steel has low strain hardening coefficient (0.20) as compared to boron-free steel (0.24).

Such a combination of properties in boron-added steel with lower *n* and higher total elongation leading to improved cold reducibility is considered to be a unique feature and to the authors' knowledge is reported for the first time. Lowering of *n* value as a result of boron addition in steel has also been reported by Funukawa et al. (Ref 3) and Hosoya et al. (Ref 7) in a continuously annealed cold-rolled steel. It has been reported in their work that *n* value decreases significantly when C in solution is less than 20×10^{-4}. The reason for this has been explained in terms of morphological changes of carbides in matrix and grain boundary. In the presence of boron, the preferable carbide precipitation site changes from grain boundary to matrix, which ultimately results in higher postuniform elongation and thereby increased total elongation. In an yet another recent work of Antoine et al. (Ref 8), relationship between *n* and yield strength of titanium added IF grade has been analyzed and it is reported that *n* value is controlled by dislocation precipitates and dislocation-grain boundary interactions. It has been found in their study as well that lower amount of dissolved C and N atoms reduce the efficiency of the grain boundary to block dislocations and thus decreases *n* value.

In line with the results of above-mentioned work, the reason for low *n*, high total elongation, and high cold reducibility in boron-containing steel can be attributed to lower amount of C and N in solution.

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Table 1 Chemical composition of steels (wt.%)

Steel	C	Mn	S	P	Si	Al	B	N
Without boron	0.053	0.22	0.013	0.032	0.034	0.029	···	0.0047
With boron	0.047	0.20	0.014	0.016	0.028	0.032	0.0023	0.0038

Table 2 Mechanical properties of steels

Steel	YS, MPa	UTS, MPa	% Total El	% Uniform El	Hardness, HR_B	Grain size, µm
Without B	260-265	357-362	40-42	24-25	47-54	16-18
With B	243-250	328-335	43-45	20-21	44-48	20-22

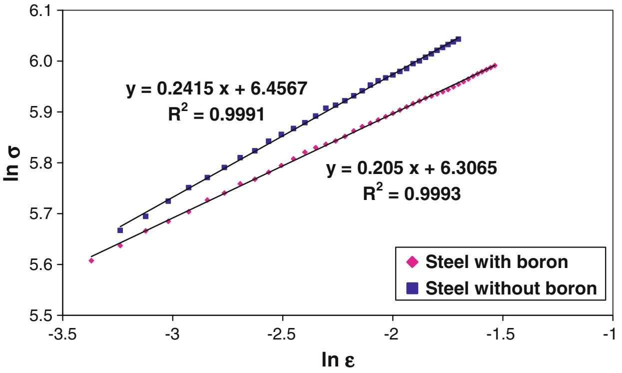

Fig. 1 Calculation of *n* value for low-carbon steel (with & without boron)

Indirect evidence of lowering of C and N in solution as a result of boron addition has been found in the present work as well, where SAI for boron-containing steel is significantly lower (11%) compared to that in steel without boron (16%), which indicates that boron has effectively brought out carbon and nitrogen from solution.

The unique combination of low *n* and high total elongation has been a responsible factor in obtaining higher percentage of cold reducibility, varying from 92 to 93.4% without overloading the mill. In comparison, similar steel without boron could undergo cold reducibility to the extent of 85 to 88%. The stress-strain plot up to necking for low-carbon steel (with & without boron) is shown in Fig. 2. At a strain of 10% the stress is 310 MPa for steel with boron while for the steel without boron, it is 330 MPa. At any given strain, the rate of increase in stress per unit of strain is less in steel with boron. This has resulted into less hardness pickup and thereby lower load during cold rolling of hot-rolled steel.

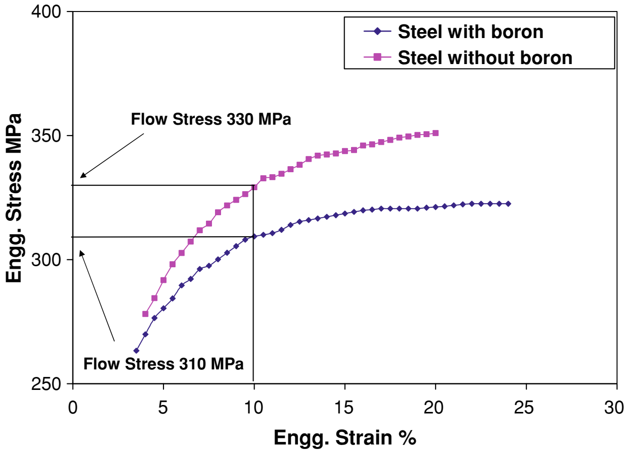

Fig. 2 Stress-strain plot up to necking for low-carbon steel (with & without boron)

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