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The effect of boron addition on the tensile properties of control-rolled and normalized C–Mn steels

M. I. HAQ
PCSIR Labs, Complex-Lahore 16, Pakistan
NAZMA IKRAM
Centre for Solid State Physics, University of the Punjab, Lahore 20, Pakistan

Control-rolled and normalized C–Mn steels with and without boron alloying at two finish rolling temperatures of 800 °C and 1000 °C were studied with respect to their tensile properties in order to investigate the role of boron in enhancing the strength of these materials. It was found that in boron steels ultimate tensile strength increased and impact transition temperature decreased owing to a decrease in grain size and an increase in pearlite fraction at both the finish rolling temperatures.

1. Introduction

Mechanical properties of ferrous metals are markedly improved by small additions of alloying elements such as C, N, Al, Si, Mo, Ni, Cr, Ti, V, Mn and Nb. Systematic development of these steels depends on the optimization of alloying elements and the study of those microstructural factors which control their important mechanical and chemical properties, such as grain refinement and precipitation hardening [1–2]. In this paper we present the effect of boron addition on the mechanical properties of low alloy steels.

The effect of boron alloying on the microstructure of alloys other than steel, such as nickel base alloys, has been reported by various authors [3]. It was found that boron-containing nickel alloys were less vulnerable to environmental degradation of mechanical properties by grain boundary attack. It was further observed that small additions of boron and carbon in polycrystalline nickel base super alloys improved their high temperature mechanical properties by inhibiting grain boundary sliding. However, the mechanism by which boron additions improved high temperature mechanical properties was less clear. While excessive boron additions improved intergranular fracture ductility at the expense of creep strength, lower amounts of boron produced creep strengthening by reducing the rate of void formation on those grain boundaries which were transverse to the applied stress.

The importance of small additions of boron in low alloy steels have long been recognized, especially with respect to high strength and hardenability of heat treatable steels. A few p.p.m. of boron alloying not only increases hardenability in quenched and tempered steels, but also controls grain size and increases elevated temperature strength [4]. The main problem with microstructural studies of boron steels lies in the detection of this element and its state, whether in solid solution, segregated or combined in various phases or precipitates. This difficulty arises from the low concentration of boron used in low alloy steels. Further, the boron hardenability is affected as carbon and other alloying substances increase [5]. Therefore, an increased understanding of the interaction of boron with other alloying elements is required in order to improve the mechanical properties of low alloy boron steels. The present research work was undertaken in order to see the effect of small additions of boron with other alloying elements such as Si, S, P and N at two different finish rolling temperatures of control-rolled and normalized samples of C–Mn steels on their final structure and such mechanical properties as yield strength, impact transition temperature (for brittle fracture), grain size and strain ageing.

2. Experimental procedure

In order to investigate the effect of boron alloying, two steel samples, with and without boron addition, were prepared with chemical compositions shown in Table I. These steels were melted in a high frequency induction furnace as 27.3 Kg ingots. Next, they were hot rolled into 1.27 cm thick plates at two finish rolling temperatures of about 800 °C and 1000 °C (Table II). This was achieved by soaking these steels for 2 h at 1260 °C. Before rolling to 800 °C, they were held for approximately 4 min, while in the case of rolling to 1000 °C, the holding time was 1.5 min. The materials were then cooled in air. In this way, two samples A and B of each steel were prepared. They are referred to as control-rolled samples in this paper.

Mechanical properties of the material were determined through tensile and Charpy impact tests.

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TABLE I Chemical composition of steels (wt %)

Steel no.	C	Si	Mn	S	P	N	B
1	0.14	0.23	1.23	0.021	0.01	0.0033	
2	0.15	0.22	1.25	0.021	0.011	0.0035	0.003

TABLE II Finish rolling temperatures (FRT)

Steel no.	FRT (°C)	
	A	B
1	995	800
2	1000	805

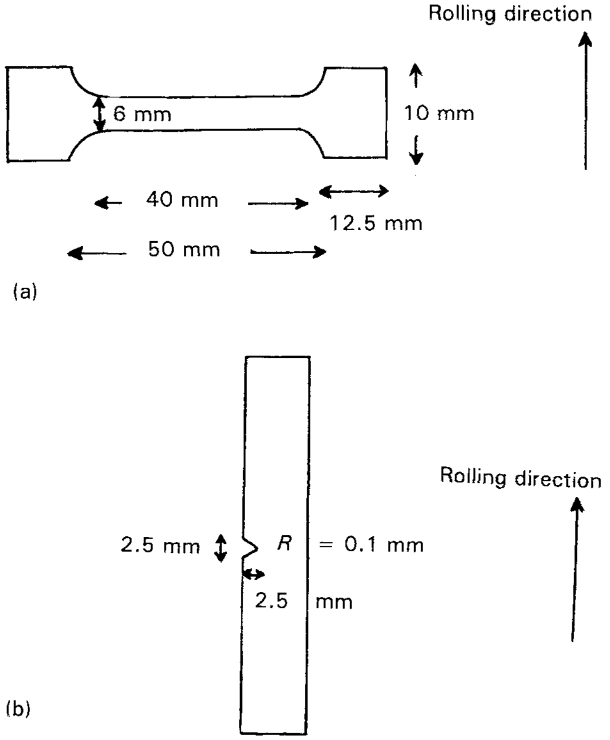

Figure 1 Shape and dimensions of specimens used. (a) Tensile specimen. (b) Charpy V-notch specimen. $R = 0.1$ mm is the radius at the root of the notch.

Tensile specimens of control-rolled material were machined from 1.27 cm thick plates in a direction transverse to the rolling direction (Fig. 1a) and Charpy V-notched specimens were machined in a direction parallel to the rolling direction so that the fracture could occur transversely during testing (Fig. 1b). The plain of symmetry of the notch was kept perpendicular to the longitudinal axis of the test specimen and at right angles to the face in which it was cut. The purpose of making the transverse tensile specimens and longitudinal Charpy V-notched specimens was to eliminate the effect of rolling direction on the observation of mechanical properties. Some of the tensile and Charpy V-notched specimens were normalized at 900 °C for 1 h in a Wild–Bar field tube furnace. Normalizing was carried out in an argon atmosphere with 0.5% oxygen in argon. Decarburization of the specimens was assumed to be negligible owing to the short heating time. Specimens were furnace cooled with a cooling rate of 4–5 °C min^{-1}. Next, for the study of Hall–Petch's relationship, tensile specimens prepared at the lower finishing temperature for both the steels were heat treated in batches at the following temperatures and timings in the same furnace and under the same conditions:

(i) at 900 °C for 1 h;
(ii) at 1100 °C for 2 h;
(iii) at 1200 ° for 2 h.

In the first batch two attempts were made such that in the second attempt, instead of furnace cooling, specimens were air cooled. The need arose because of the coarse grain size in furnace-cooled specimens. A finer grain size was obtained by air cooling.

Tensile testing of control-rolled and normalized tensile specimens was carried out on a servo-hydraulic Mayes tensile testing machine having a full load of 100 kN. Each tensile specimen was pulled isothermally at a load rate of 5 kN min^{-1} and the load elongation was recorded at a chart speed of 20 mm min^{-1} until the final fracture occurred. The lower yield point was determined from the recorded load elongation curve. Next, for all control-rolled and normalized steels, strain ageing was performed by giving each specimen an extension of 10% and ageing at 100 °C for 0.5 h. After ageing, tensile tests were repeated. Next, metallographic observations for both the control-rolled and normalized specimens were carried out in order to find their pearlite fraction, P_f, and the ferrite grain size d. For this purpose, a Vickers 55 optical microscope was used at a magnification of × 700. Pearlite fraction was determined on the basis of point counting, on a 22 × 108 mm screen, giving a total of 1600 points. Pearlite fraction was counted as follows:

$$P_f = \text{number of points observed on pearlite} \times 100/1600.$$

In order to find the ferrite grain size, each specimen was etched with 2% nital and was observed through the same microscope at the same magnification. A screen with three circles having a total circumference length of 200 mm was used and the intercepts of these circular lines with the ferrite grain boundary were counted taking forty fields for each specimen. In this way, the total distance accounted for was 40 × 200 = 8000 mm. Then, the grain size was calculated using the relation

$$d^{-1/2} = [A(1 - P_f)]^{-1/2}$$

where $A = 800/(\text{number of intercepts} \times \text{magnification})$.

Metallographic results for control-rolled and normalized steels are given in Tables III and V, respectively, along with the corresponding values of yield stress σ_y and strain ageing parameter Δy for transversely rolled specimens, and are the average of two observations.

Longitudinal Charpy V-notched impact test specimens of control-rolled and normalized materials were tested in the temperature range − 80–100 °C on a Lausenhausen impact testing machine and are given in Tables IV and VI, respectively. At subzero temperatures, dry ice and acetone were used. At still lower temperatures liquid nitrogen and ether mixtures were used. For above room temperature, specimens were placed in hot water. In each case, the period of immersion of the specimen was 10 min and every specimen was broken within 6 s from the time of removal from the bath. The ductile to brittle transition temperatures were recorded as those at which 27 J and 54 J energies were absorbed.

3. Results and discussion

In order to study the effect of a small addition of boron on the mechanical properties of C–Mn steels, two samples, steel 1 and steel 2, without and with boron alloying, respectively, were prepared (Table I). Each of these steels was control-rolled at two finish rolling temperatures (FRT) of about 1000 °C and 800 °C (Table II) giving two types, A and B, of each steel. Next, tensile test specimens and Charpy V-notched impact test specimens were prepared from these steels. Half of these control-rolled specimens were normalized, rendering two sets of specimens, control-rolled and normalized, for each of the four steel samples. For each specimen, yield strength of σ_y, ferrite grain size d, pearlite fraction P_f, strain ageing index Δy and impact transition temperature ITT were observed and were mutually compared in order to see the effect of boron on their mechanical properties.

In Table III, yield strength σ_y and ferrite grain size parameter $d^{-1/2}$ for control-rolled steels is presented

TABLE III Yield and structural properties of control-rolled steels

Steel no.	σ_y (N mm^{-2})	$\Delta\sigma_y$ (N mm^{-2})	$\Delta_{FRT}\sigma_y$ (N mm^{-2})	$d^{-1/2}$ (mm^{-1})	P_f	Δy (N mm^{-2})	$\Delta(\Delta y)$ (N mm^{-2})	$\Delta_{FRT}(\Delta y)$ (N mm^{-2})
1A	301.5			8.23	21.62	49.5		
2A	308.0	6.5		8.56	30.35	37.6	11.9	
1B	326.0		24.5	9.41	21.85	56.9		7.4
2B	328.0	2.0	20.0	10.62	33.25	33.2	23.7	− 4.4

$\Delta\sigma_y$ and $\Delta(\Delta y)$ represent the change in yield stress σ_y and strain ageing parameter Δy caused by the addition of boron at the same FRT. $\Delta_{FRT}\sigma_y$ and $\Delta_{FRT}(\Delta y)$ represent the changes in σ_y and Δy caused by different FRT for the same type of steel.

TABLE IV Impact transition temperature (ITT) (°C) for control-rolled steels

Steel no.	At 27 J			At 54 J		
	ITT	$\Delta(ITT)$	$\Delta_{FRT}(ITT)$	ITT	$\Delta(ITT)$	$\Delta_{FRT}(ITT)$
1A	− 50			− 36		
2A	− 60	− 10		− 46	− 10	
1B	− 60		− 10	− 50		− 14
2B	− 70	− 10	− 10	− 57	− 7	− 11

$\Delta(ITT)$ represents the change in ITT caused by boron alloying at the same FRT and $\Delta_{FRT}(ITT)$ represents the change in ITT caused by different FRT for the same type of steel.

TABLE V Yield and structural properties of normalized steels

Steel no.	$(\sigma_y)_N$ (N mm^{-2})	$(\Delta\sigma_y)_N$ (N mm^{-2})	$(\Delta_{FRT}\sigma_y)_N$ (N mm^{-2})	$d^{-1/2}$ (mm^{-1})	P_f	$(\Delta y)_N$ (N mm^{-2})	$\Delta(\Delta y)_N$ (N mm^{-2})	$\Delta_{FRT}(\Delta y)_N$ (N mm^{-2})
1A	283.7			8.19	24.63	51.58		
2A	281.8	− 1.9		8.39	25.50	42.69	8.89	
1B	290.3		6.6	9.09	24.50	55.50		3.92
2B	291.3	1.0	9.5	8.97	29.44	42.84	12.66	0.15

TABLE VI Impact transition temperature (ITT) (°C) for normalized steels

Steel no.	At 27 J			At 54 J		
	ITT	$\Delta(ITT)_N$	$\Delta_{FRT}(ITT)_N$	ITT	$\Delta(ITT)_N$	$\Delta_{FRT}(ITT)_N$
1A	− 52.0			− 50		
2A	− 80.5	− 28.5		− 77	− 27.0	
1B	− 59.0		− 7.0	− 54.5		− 4.5
2B	− 56.0	3.0	24.5	− 52.5	2.5	24.5

along with the pearlite fraction P_f and strain ageing index Δy, whereas their impact transition temperatures are given in Table IV. When the microstructure at the two finish rolling temperatures in steel 1 was compared, it was found (Table III) that the ferrite grain size in steel 1B was smaller than that in steel 1A, implying that the steel at lower FRT was stronger and tougher. The same was true about steel 2. Next, the ferrite grain size of steel 2 was compared with that of steel 1 and it was found that the grain size was reduced to 8.56 mm^{-1} in steel 2A and 10.62 mm^{-1} in steel 2B from 8.23 mm^{-1} in steel 1A and 9.41 mm^{-1} in steel 1B, respectively. Further, there was an increase in the percentage volume of pearlite fraction P_f in steel 2 at both FRT as compared to that in steel 1. Both the decrease in ferrite grain size and the increase in pearlite fraction depict an increase in the hardenability of the material due to boron alloying. Next, the yield strength σ_y was measured for steel 1 and steel 2 at both the finish rolling temperatures and an insignificantly small increase in σ_y was noticed due to boron alloying, i.e. from 301.5 N mm^{-2} in steel 1A and 326 N mm^{-2} in steel 1B to 308 N mm^{-2} in steel 2A and 328 N mm^{-2} in steel 2B. It is argued that though boron has a high affinity for nitrogen, making boron nitride precipitates and hence increasing the yield strength, this effect seemed to be offset by an increase in hardenability in steel 2. It was further noticed that the change in yield strength due to a change in the finish rolling temperature $\Delta_{\text{FRT}}\sigma_y$ was reduced from 24.5 N mm^{-2} in steel 1 to 20 N mm^{-2} in steel 2. Thus, due to boron alloying, the mechanical properties in steel 2 were converged at the two FRT as compared to those in steel 1.

Table III also shows the strain ageing parameter, Δy, for the two steels at both the finish rolling temperatures. Δy is a measure of the difference in the lower yield points with and without the absorption of free nitrogen available in the material. In the absence of boron (steel 1) Δy was found to be high, whereas after boron alloying (steel 2) nitrogen was picked up by boron to form boron nitride and a very small amount of free nitrogen was left behind in the material, thereby reducing the strain ageing index and making it less prone to ageing. Further, in steel 1 the difference in strain ageing parameter $\Delta_{\text{FRT}}(\Delta y)$ due to the two FRT was 7.4 N mm^{-2} in favour of lower FRT steel, whereas in steel 2 $\Delta_{\text{FRT}}(\Delta y)$ was reduced to 4.4 N mm^{-2} in favour of the higher FRT, again showing that in boron steels there was a lesser amount of free nitrogen available. In Table IV the results of Charpy V-notched tests are presented. It was observed that the addition of boron had decreased the impact transition temperature (ITT) at both the finish rolling temperatures. This was due to a decrease in ferrite grain size and a consequent increase in the toughness of the material. Further, the difference in impact transition temperature between two FRT $\Delta_{\text{FRT}}(ITT)$ was constant for both the steels, but on the tougher side in boron steels.

In Table V the yield strength, ferrite grain size, pearlite fraction and strain ageing index for normalized steels are presented and their impact transition temperatures are given in Table VI. It was observed that in steel 1 ferrite grain size and pearlite fraction were about the same at both the finish rolling temperatures, as expected, since normalization at 900 °C had released the residual stresses and removed the FRT effect. Even in steel 2, boron alloying did not bring any appreciable change in these microstructural parameters owing to the fact that austenization of boron steels in the temperature range 850–950 °C results in loss of hardenability due to an increased boron concentration on the austenite grain boundaries [6]. However, in comparison with as-rolled steels, $d^{-1/2}$ showed a decrease indicating grain coarsening in normalized steels. This was because normalized steels were furnace cooled at a rate of 4–5 $^\circ\text{C min}^{-1}$, therefore the tendency to smaller grain size in normalized conditions seemed to be offset by such a slow rate of cooling. The yield strength of both the steels after normalizing showed the same effect as in the case of control-rolled steels. The value of $(\sigma_y)_N$ for normalized steels (Table V) was found to be less than those of control-rolled steels (Table III), due to an increase in grain size in the former case. There was no significant change in the value of $(\sigma_y)_N$ due to boron alloying. Table V also shows the strain ageing index $(\Delta y)_N$ for normalized steels. In normalized steel 2 $(\Delta y)_N$ was found to be 42.69 N mm^{-2} and 42.84 N mm^{-2} at the upper and lower FRT, respectively. Though these values were considerably less than those in normalized steel 1, they were fairly high as compared to those for control-rolled steel 2. It seemed as if in normalized boron steel boron nitride was dissociated and the effect of boron as found in the control-rolled steels was nullified. Due to boron alloying, the impact transition temperatures in normalized steels were also affected (Table VI). For example, in steel 2A there was a marked decrease in the values of ITT as compared to the corresponding values in steel 1A. This was due to

TABLE VII Results regarding the Hall-Petch's relationship for air-cooled (AC) and furnace-cooled (FC) samples

Steel no.	σ_y (N mm^{-2})				$d^{-1/2}$ ($\text{mm}^{-1/2}$)				P_f			
	900 °C for 1 h		1100 °C for 2 h	1200 °C for 2 h	900 °C for 1 h		1100 °C for 2 h	1200 °C for 2 h	900 °C for 1 h		1100 °C for 2 h	1200 °C for 2 h
	FC	AC	FC	FC	FC	AC	FC	FC	FC	AC	FC	FC
1B	260.9	354.7	233.4	218.4	5.93	12.63	5.16	5.25	25.3	28.94	26.69	25.75
2B	260.9	402.8	235.9	215.8	6.77	12.80	5.07	5.23	27.32	30.50	23.94	31.13

the free nitrogen in steel 2A having combined with boron, hence causing a distinct drop in the values of ITT.

Boron steel was autoradiographed at 130 × 500 magnification. The photomicrograph revealed a uniform distribution of boron with no apparent correlation with any phase structure. In fact, the distribution was so uniform that it was difficult to pinpoint the tracks.

Next, the Hall–Petch relationship ($\sigma_y = \sigma_0 + Kyd^{-1/2}$) was established for both the steels. For this purpose steel 1B and steel 2B tensile specimens were heat treated at 900 °C, 1100 °C and 1200 °C, as discussed in section 2, and their microstructures and yield strengths were recorded (Table VII). Then σ_y was plotted as a function of $d^{-1/2}$ (Fig. 2) and a line of maximum fit was drawn through the points for each steel. Since a small number of observations were taken, the value of σ_y at $d^{-1/2} = 0$ was regarded as a rough estimate for the friction stress σ_0, and it was 117 N mm^{-2} and 106 N mm^{-2} for steel 1 and steel 2, respectively.

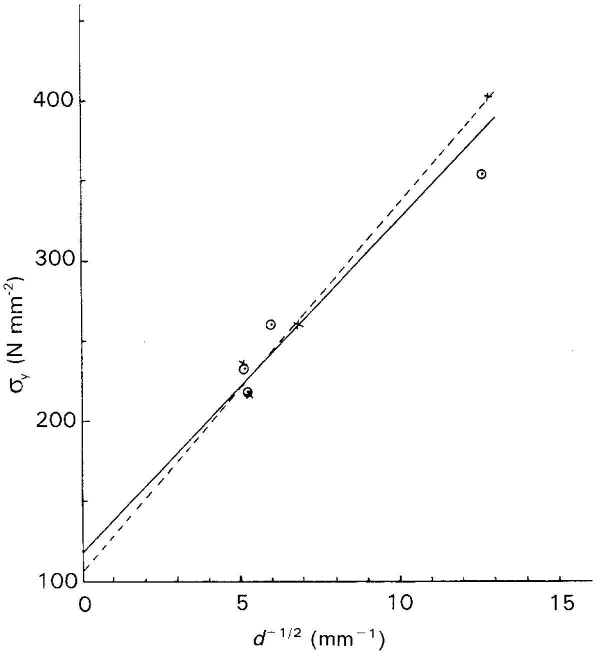

Figure 2 The Hall–Petch relationship. Steel 1 —⊙—; Steel 2 ---×---.

4. Conclusion

Mechanical properties of a material depend, among other factors, on the thermomechanical conditions and the alloying composition. In this paper the influence of small additions of boron on the structure of C–Mn steels was studied. For this purpose, control-rolled and normalized C–Mn steel samples were prepared at two finish rolling temperatures of 800 °C and 1000 °C with two alloying compositions, one having 0.003% by weight boron in it and the other without it. By comparing the mechanical and microstructural properties of these alloys the following conclusions were drawn about boron alloying of C–Mn steels.

(i) Boron decreased the ferrite grain size.

(ii) Boron increased the pearlite fraction due to an increase in hardenability on rolling, but not so on normalizing.

(iii) In control-rolled steels the addition of boron caused a slight increase in yield strength. Further, in normalized steels boron reduced the yield strength with respect to the control-rolled steels.

(iv) Boron reduced the strain ageing index by consuming the free nitrogen available in the material and decreased the transition temperature.

(v) Boron alloying reduced the difference in the mechanical properties of the material with respect to the change in finish rolling temperatures.

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