International Journal of Metallurgical Engineering 2012, 1(1): 1-6
DOI: 10.5923/j.ijmee.20120101.01

Effect of Austenitising Temperature and Cooling Condition on Mechanical Properties of Low Carbon Boron Containing Steel

Anjana Deva[1,*], N.K. Jha[2], B. K. Jha[1]

[1]Research and Development Centre for Iron and Steel, Steel authority of India Limited, Ranchi, 834002, India
[2]IISCO Steel Plant, Steel authority of India Limited, Burnpur, 713325, India

Abstract The hardening behaviour of boron free and boron added low carbon aluminium killed steel was studied through heat treatment experiments by varying the austenitising temperatures and cooling condition. These parameters have been found to significantly influence the segregation and precipitation of boron and thereby final mechanical properties of steel. Strong dependence of cooling condition on effectiveness of boron as hardener is noticed; rather below a critical cooling rate boron has softened the steel. Strain hardening exponent (n) has been correlated with hardening / softening behaviour of boron.

Keywords Boron, Hardenability, Austenitising Temperature, Cooling Condition, Strain Hardening Exponent

1. Introduction

It is well established[1-2] that boron increases hardenability of steels by retarding the heterogeneous nucleation of ferrite at the austenite grain surfaces. It is probable that this effect is due to the reduction in interfacial energy as the boron segregates to the grain boundaries. This in turn makes grain boundary less effective as heterogeneous sites. However, boron effect is entirely different in low and high carbon steel, plain and alloyed steel, with low and high soaking temperature, and more significantly with low and high cooling condition. In recent thermo-mechanical simulation study[3-4], the effectiveness of boron on hardenability has been found to be strongly dependant on soaking temperature and cooling condition, rather below a critical cooling rate boron has soften the low carbon aluminium killed steel. In order to validate these results, a series of heat treatment schedule was designed to carry out influence of austenitising temperature and cooling rate on the mechanical properties.

2. Experimental

Heat treatment cycles were carried out in a muffle furnace using hot rolled samples with and without boron. The rolled strips processed industrially through continuous casting – Ladle refining – Hot strip mill route. The chemical samples for this experiment were prepared from the hot chemical composition of boron free and boron added steel are shown in Table 1.

Samples were heated at different austenitising temperatures one falling in $\alpha + \lambda$ range (850°C), another closer to Ac_3 temperature and third one well above Ac_3, the calculated Ac_3 temperatures for the steel is ~ 890°C. After proper soaking, samples were subjected to air cooling (AC), oil quenching (OQ) and water quenching (WQ). Schematic representation of the heat treatment cycle is shown in figure 1. After heat treatment the samples were analyzed in terms of its mechanical properties.

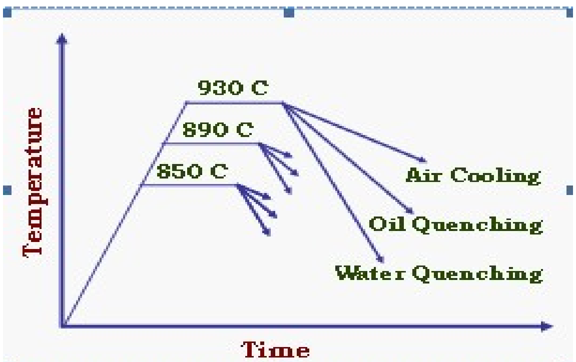


Figure 1. Schematic representation of heat treatment cycle for with and without boron steel

3. Results and Discussion

Effect of boron on yield and tensile strength

Figure 2 (a-f) depict yield strength (YS) and ultimate ten-

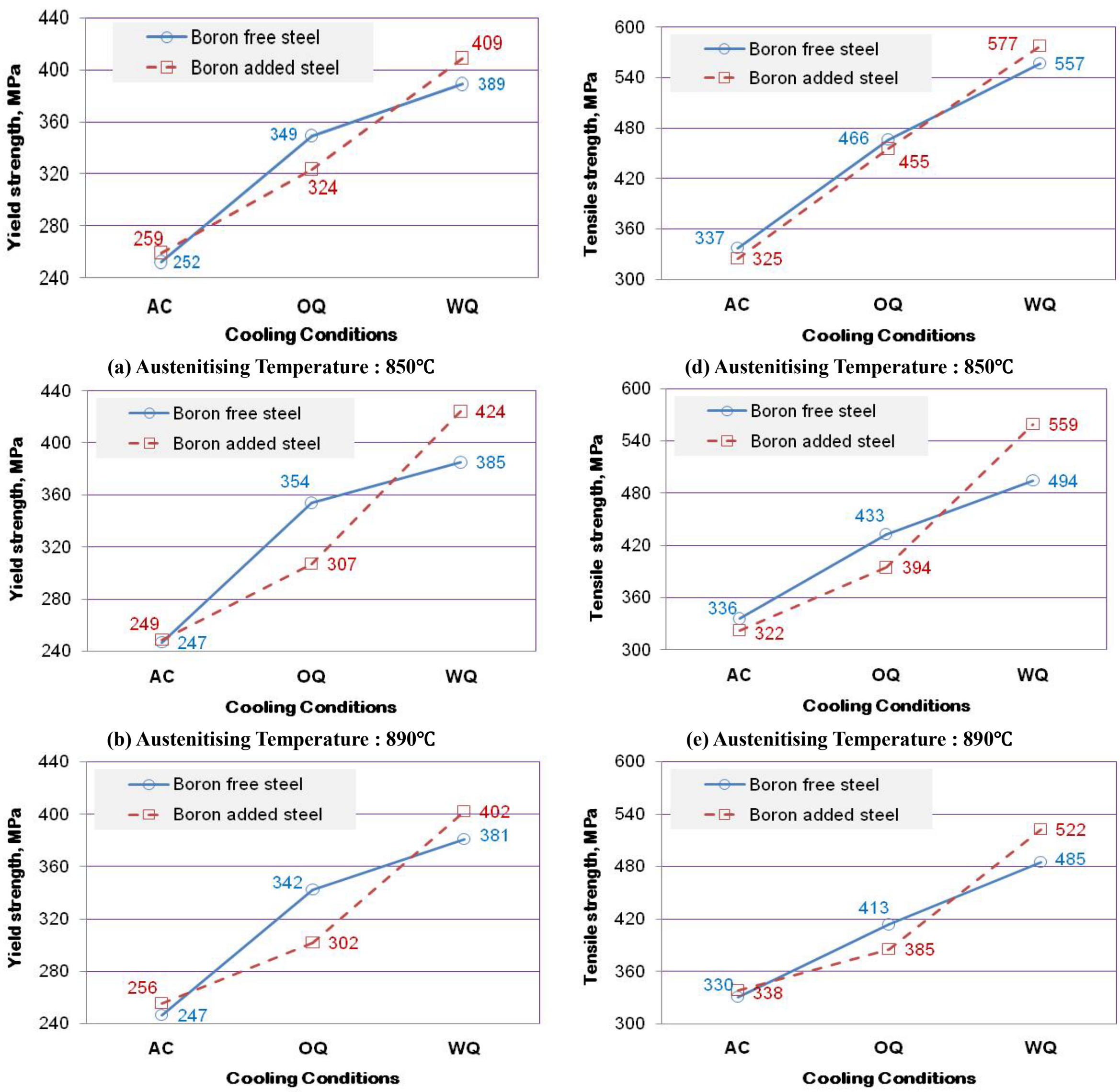
* Corresponding author:
bkjha@sail-rdcis.com (Anjana Deva)
Published online at http://journal.sapub.org/ijmee

sile strength (UTS) of the low carbon aluminium killed steels viz. boron free and boron added, heat treated with three austenitising temperatures, viz. 850°C, 890°C and 930°C followed by three varying cooling conditions achieved through air cooling (AC), oil quenching (OQ) and water quenching (WQ). YS values are almost similar for both the steels under AC condition at 850°C (Figure 2a). Under oil quenching (OQ) condition, there is less increases in YS in case of boron added steel as compared to that in boron free steel. With further increase in cooling rate as in case of water quenching (WQ) condition, increase in YS is more in case of boron added steel than that observed in boron free steel, which led to higher YS value of 409 MPa in boron added steel as compared to 389 MPa of boron free steel.

When austenitising temperature is raised to 890°C & 930°C, trend of increase in YS with increase in cooling rate is found to be the same as observed at 850°C. The dissimilarity is found with respect to the difference in YS value on oil quenching and water quenching (Figure 2 b & c). The difference in YS is observed to be higher (47 MPa on oil quenching and 39 MPa on water quenching) when austenitising temperature is kept at 890°C, as compared to the corresponding values of 25 MPa and 10 MPa when austenitised at 850°C. With further increase in austenitising temperature to 930°C, difference in YS value is found to be 40 MPa on oil quenching and 23 MPa on water quenching (Figure 2 a-c).

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



(a) Austenitising Temperature : 850°C

(d) Austenitising Temperature : 850°C

(b) Austenitising Temperature : 890°C

(e) Austenitising Temperature : 890°C

(c) Austenitising Temperature : 930°C

(f) Austenitising Temperature : 930°C

Effect on YS

Effect on UTS

Figure 2. Effect of boron on YS and UTS with varying cooling rate when cooled from austenititising temperature of (a) 850°C, (b) 890°C and (c) 930°C

When plots were generated relating to UTS values with increasing cooling rate and austenitising at 850°C, 890°C and 930°C (Figure 2 d -f), it is found that trend is same as was observed in case of change in YS. UTS value is similar for both the steels with and without boron, when cooling rate is very slow (AC) at all austenitising temperatures. It increases less in case of steel with boron as compared to that in steel without boron on OQ at 890°C. With further increase in cooling rate to WQ, increase is found to be more in case of steel with boron than that observed with steel without boron. It reaches to 559 MPa in boron added steel as compared to 494 MPa in boron free steel. The trend for both the steel with increase in cooling rate is same when subjected at 930°C. It is interesting to note that YS & UTS both for the boron added steel is substantially higher for sample austenitised at 890°C than that of 930°C.

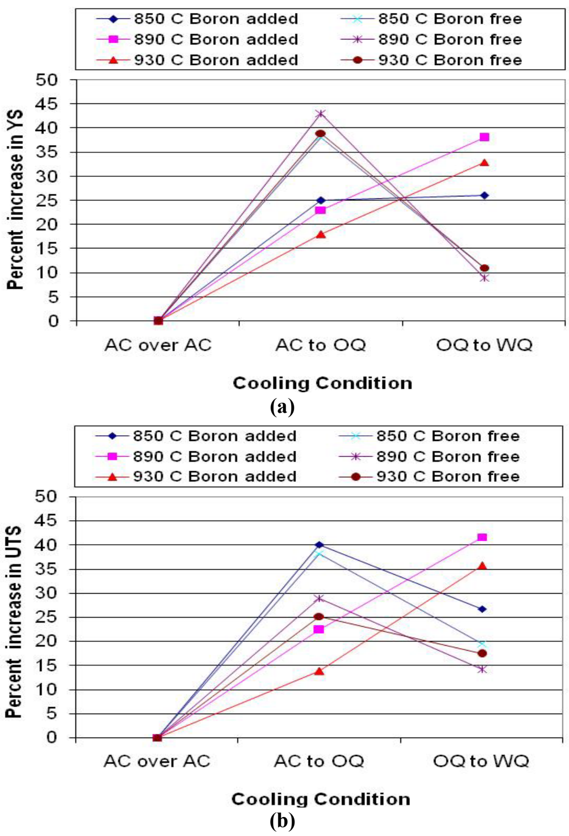


Figure 3. Percent increase in YS and UTS with respect to cooling condition

The influence of boron addition can be better understood by plotting percentage increase in YS and UTS with respect to cooling rate rather than the absolute changes in these values. Figure 3 a & b show the percentage increase for YS and UTS for boron added and boron free steel with cooling rate on x axis. It clearly shows that in general, with increase in cooling rate, trend for percentage increase in YS and TS is upward for boron added steel when austenitised at 890°C and 930°C, particularly for change in cooling condition from OQ to WQ. For example percentage increase in UTS in boron added steel is 41 and 35.5 % compared to that of boron free steel i.e 14 and 17 % only at austenitising temperature of 890 and 930°C. Whereas the trend is downward for boron free steel from OQ to WQ for all austeninitising temperatures and even for boron added steel austenitised at 850°C.

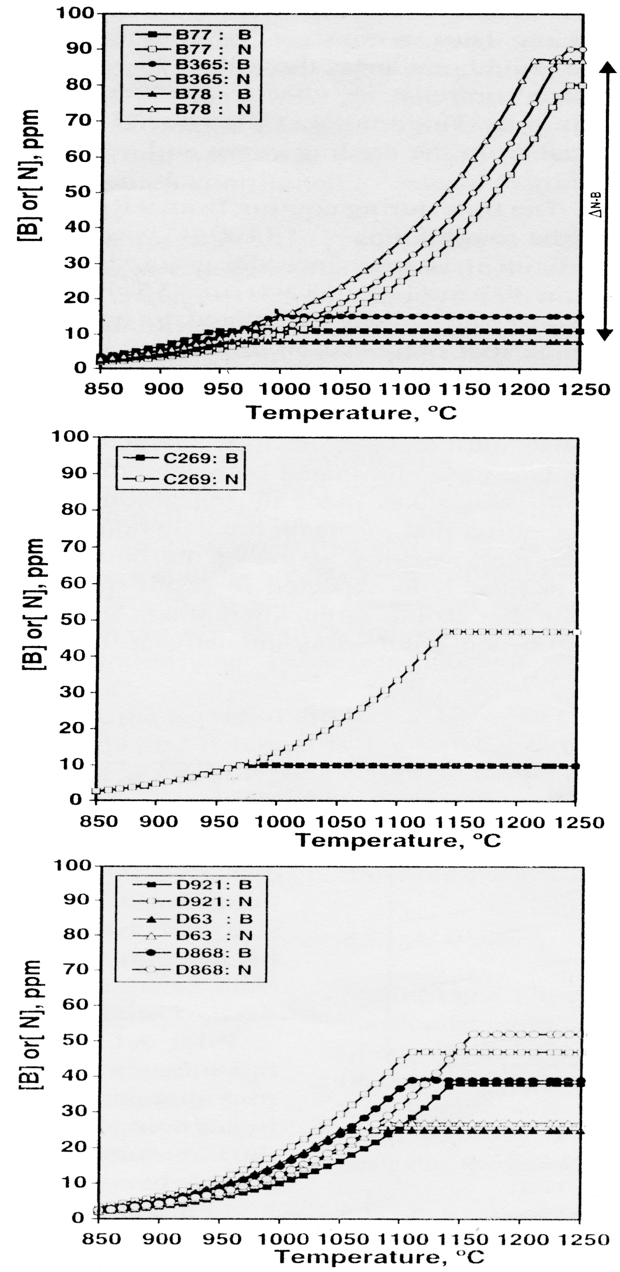


Figure 4. Calculated equilibrium [B] and [N] contents

The above results can be explained based on precipitation behavior of boron as a result of increasing austenitising behavior and cooling condition. In the recent study by Kevin Banks et al the solute B and N contents in the Al-B-N system have been calculated for low carbon unalloyed steel using mass balance and solubility data[5]**.** Neglecting the small Ti presence of only 0.001-0.002 % the nitrogen in solution [N] can be expressed in terms of AlN and BN[6.] The accuracy of solubility model depends largely on the solubility data particularly that of Al/N with varies considerably in the literature[7.] The calculated equilibrium [B] and [N] contents for the various steel as a function of temperature is shown in Figure

4[5] and it was found that soluble boron content increases with increasing temperature , It reaches its maximum value at different temperatures depending on boron (0-50 ppm) and nitrogen (40-90 ppm) content of steel.

Since the solubility of boron in austenite is very high as compared to that of ferrite, below austenite to ferrite temperature, its amount will be negligible in solution. That is reason, in all the calculated equilibrium plots, temperature less than 850°C has not been considered while calculating amount of boron in solution.

On the basis of above mentioned results, it is expected that at austenitising temperature of 850°C, amount of boron in solution will be almost nil. As the samples used for this heat treatment study have been collected from hot rolled coils, boron nitride must be present as precipitates at 850°C, which is reflected from the results also, wherein steel austenitised at 850°C, with and without boron, behaves in almost similar way, irrespective of the cooling rate. With increase in austenitising temperature amount of boron in solution increases and its effectiveness is more with enhanced cooling rate.

However, an interesting result has appeared in the present study, i.e. in spite of the higher amount of boron in solution at 930°C, YS and UTS reached its maximum values at 890°C in water quenched condition for boron added steel, through not much difference is observed in these values for boron free steel. It can be explained based on the segregation of boron to grain boundary. Hardenability is dominated mainly by the grain boundary concentration of boron atoms. It is established that when boron segregates to austenite grain boundary, austenite to transformation is retarded; when coagulates (or precipitates) on the other hand, its retarding effect is decreased. So, the segregated boron is effective but the coagulated or precipitated boron is ineffective in suppressing the transformation. Hence it is reasonable to define the boron which has been segregated at austenite just before the transformation as “effective boron”. Furthermore, the effective boron content depends on the thermal hysteresis in austenite range[11]**.** Austenising temperature of 890°C is just close to Ac_3 temperature in the present study and based on the above theory, effective boron to contribute towards increase in hardenability is more at this temperature compared to that of 930°C.

Dilation Tests

The dilation tests experiments carried out in Gleeble-3500, thermo-mechanical simulator, for understanding the effect of boron on austenite to ferrite transformation temperature. Figure 5[3] shows the variation in Ar_3 temperature with cooling rate for different austenitising temperatures, ranging from 950°C to 1200°C. The results show that increase in cooling rate resulted in significant decrease in Ar_3 temperature at higher austenitising temperatures (>1000°C) and the effect was more prominent at 1200°C.

It can be also concluded that at very slow cooling rate of 1°C/sec, Ar_3 temperature was found to be almost similar, irrespective of variation in austenitising temperature, rather boron will soften the steel as a result of bringing down nitrogen from solution and forming BN. The drop in Ar_3 temperature was more pronounce with the increase in austenitising temperature and cooling rate. The plot clearly depicts that effect of addition of boron in lowering of Ar_3 temperature was observed when cooling rate exceeded 20°C/sec.

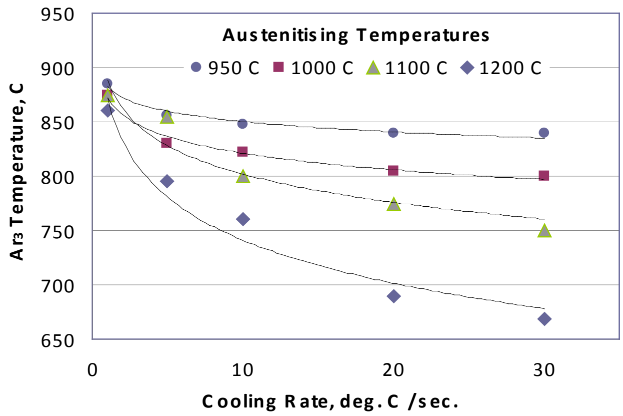


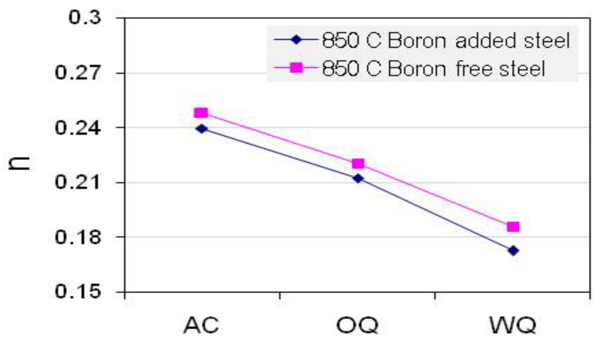
Figure 5. Variation in Ar_3 temperature with cooling rate for different austenitising temperatures

The results obtained through heat treatment study vary with that obtained through thermo-mechanical simulation study, because, in case for heat treatment study, the starting hot rolled material have pre-existed precipitates and some amount of which is present even at higher temperature of 930°C. whereas in gleeble, the samples were soaked upto 1200°C (well above the solutionising temperature), where all boron in solution at higher temperature.

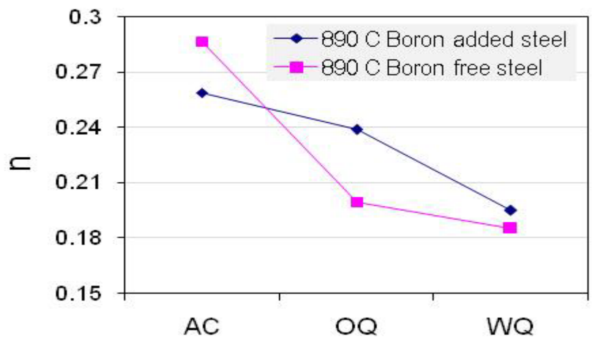
In the present study, maximum temperature at which the hot rolled samples were soaked is 930°C, which is lower than the lowest temperature for thermo mechanical study i.e 950°C and even at that temperature no effect on lowering of transformation temperature is observed upto 20°C/sec. In the heat treatment study the critical cooling rate appears to between OQ and WQ, above which contribution of boron as hardener is more prominently observed, commonly used in quenched and tempered grades.

Addition of boron in presence of C-Mn-Mo-Cr increases the hardenability by many fold compared to that of unalloyed steel. Importance of critical cooling rate above which hardenability effect of boron decreases has been highlighted by Dong Jun Mun et al[9]. The authors have observed that in low alloyed boron containing C-Mn-Ni-Mo-Ti steel with high Mn (2%) and Si (0.5 %), a critical cooling rate (10-20°C) exists for the maximum segregation of boron at grain boundary. A cooling rate higher than this may result in decreasing hardenability of steel as a result of boron not getting sufficient time to segregate to the boundary. The present study focuses on the unalloyed low carbon steel wherein, this critical cooling rate is likely to be very high (may be between OQ & WQ, Fig. 2). Exceeding the cooling rate beyond the critical one result in insufficient time for boron to segregate to the boundary and part of it remains in matrix. That is precisely the reason that in WQ samples with boron austenitised at 930°C has lower UTS compared to that of austenised at 890°C where boron in solution is through more, effective boron at grain boundary is more for samples austenised at 890°C.

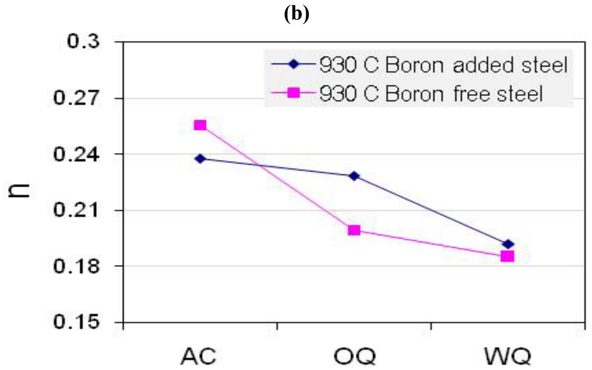
Another interesting feature of the present study is emergence of continuous yielding in samples austenitised at 850°C followed by WQ for both the steels (with or without boron) and sample austenitised at 890°C followed by WQ in steel with boron only. The appearance of continuous yielding samples austenitised at 850°C is a result of temperature falling in α + γ region. The volume fraction of austenite at this temperature is rich is carbon and transforms to martensite and gives rise to continuous yielding with low YS and high UTS values as typically observed in dual phase steels. The role of boron at this temperature is minimal. However sample treated at 890°C followed by water quenching continuous yielding is observed only in boron containing steel. It further authenticates the role of boron for the sample austenitised at 890°C (near (Ac_3) in improving hardenability followed by WQ good combination of properties suited for forming application i.e. continuous yielding with YS (424 MPa), uts (559 MPa) and YS/UTS (0.76) compared to discontinuous yielding with YS (385 MPa), UTS (494 MPa) and YS/UTS (0.78) for steel without boron.



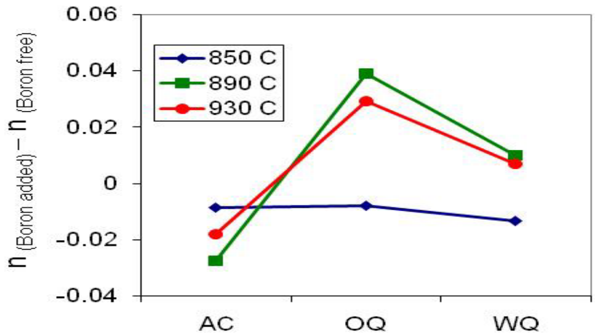
(a)



(b)



(c)



(d)

Figure 6 (a-d). Effect of different cooling rate with varying austenitising temperatures on strain hardening behaviour in steel with and without boron

Strain Hardening Behaviour

As strain hardening exponent (n) is an important parameter to assess the deformation characteristics of steel, the effect of austenitising temperature and cooling condition on ‘n’ was also examined. Figure 6 a-c show the trend in strain hardening behavior for steel with and without boron subjected at different austenitising temperatures of 850°C, 890°C and 930°C with varying cooling rate. n value decreases with increase in cooling rate for all the conditions. It is observed that with austenitising temperature of 850°C, not much difference in n value at AC, OQ and WQ states are observed between the steel with and without boron.

A detailed study on n value of low carbon hot rolled boron added steel has been carried out[10], wherein lowering of n in boron added steel low carbon unalloyed steel has been attributed to changes in carbide precipitation site and its morphology. In presence of boron in low carbon unalloyed steel, the preferable carbide precipitate changes from grain boundary to matrix and fine carbide precipitation in matrix deteriorates ‘n’. However, this precipitation behaviour and absence of cementite on grain boundary results in improved post uniform ductility. The authors have further shown that lower ‘n’ and lower hardness in boron containing hot rolled steel results increases cold reducibility behaviour of steel. The strain hardening behaviour has been studied on the hot rolled industrially processed steel where cooling rate on runout table is in the range of 8-10°C / sec., which is closer to air cooling and the same reason holds true for lowering of n in air cooled sample. With increase in austenitising temperature to 890°C and 930°C and cooling rate n values for steel with boron is not always lower.

In fact the extent of softening or hardening as a result of boron addition can be related to difference in ‘n’ value (n value of boron containing steel – n value of steel without boron) and has been termed as n effective in present context. ‘n’ effective is plotted (Figure 6d) against cooling rate and it is found that it is always negative when austenitised at 850°C, i.e. it is always lower in case of boron added steel when compared with that in boron free steel . When austenitised at 890°C, it is negative on air cooling, but with increasing cooling rate it suddenly moves towards positive value and reaches maximum. With further increase in cooling rate, it drops drastically. Similar trend is observed when austenitising temperature is 930°C. Positive values can be seen only in four cases, when austeitised at 890°C & 930°C with oil and water quenching. As discussed earlier (Figure 4) similar trend is observed while correlating, rate of increase in YS and UTS with respect to cooling rate. The trend for rate of increase in YS and TS is upward for boron containing steel when austenitised at 890°C and 930°C, particularly for change in cooling condition from OQ to WQ. The decrease in 'n' effective form OQ to WQ can be related to the critical cooling rate concept discussed above. The effective 'n' can therefore be a measure of hardening or softening behaviour of boron in low carbon unalloyed steel.

4. Conclusions

- Both austenitising temperature and cooling rate are critical in influencing the mechanical properties of boron containing low carbon steel.
- With increase in austentising temperature the relative increase in YS & UTS as a result of cooling is high in boron containing steel compared to that of without boron which has been attributed to boron present in solution at the austenitising temperature and its segregation behaviour during cooling.
- Even in low carbon unalloyed steel presence of boron leads to an attractive combination of forming properties i.e. continuous yielding with high YS (425 MPa), high UTS (560 MPa) and low YS/UTS ratio (0.75) when austenised at 890°C followed by water quenching.
- The extent of softening or hardening as a result of boron addition has been correlated with 'n' effective (n in boron containing steel – n is steel without boron).

ACKNOWLEDGMENTS

The authors thankfully acknowledge the help and support extended by the management of Research and Development Centre for Iron and Steel, Ranchi.

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