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# Effect of Boron-to-nitrogen Ratio and Quenching Media on the Properties of Low Carbon Low Manganese Unalloyed Steel

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**Abstract** The present work was carried out to understand effect of boron to nitrogen ratio and the different quenching media in low carbon low manganese unalloyed steel. Tensile samples of hot rolled sheets were heat treated in laboratory muffle furnace to 890°C and quenched in oil and water. Mechanical properties and microstructure of quenched samples were analysed. A decreasing trend of YS/UTS ratio observed after quenching irrespective of the quenching media. It has been observed that boron and cooling rate in combination improves the hardenability and increase the UTS value. Boron played an important role in contributing microstructure evolution with different quenching media and thereby resulted excellent combination of properties in cost effective low carbon unalloyed steel. Good combination of properties observed in water quenched as well as oil quenched steel samples with low B/N ratio. Quenched samples were further normalized at 920°C and properties were compared with as rolled boron free steel and results shows improvement in properties in terms of lower YS/UTS value with boron addition. The reason behind may be formation of contributing phases which are retained in the microstructure even after normalizing. Drop in strength values when compared with properties of low carbon boron added hot rolled steel revealed more drop in case of water quenching than that of oil quenching.

**Keywords** Low carbon boron added steel, Quenching, Normalizing, Drawability

## 1. Introduction

Significant progress has been made towards the development of new steel products with improved attributes by addition of micro-alloying elements in the past [1-3]. The properties attained in the final product depend on presence of small additions of niobium (Nb), vanadium (V), titanium (Ti) or boron (B), which by precipitating in the form of carbide and carbo-nitride, can give precipitation hardening and / or inhibition of grain growth. Out of these elements boron is a unique one, which can increase or decrease the hardness of steel depending on presence of titanium or zirconium (Zr), nitrogen (N) content and process conditions i.e. austenitising temperature, cooling rate etc. [4-11].

Carbon and low/high alloyed steels are quenched in water, oil or other medium to increase its hardenability. This process comprises soaking of a material at a high temperature, above the recrystallization phase, followed by a rapid cooling process to obtain certain desirable material properties associated with a crystalline structure or phase distribution. Although boron as a cost effective hardenability agent for low alloyed quenched and tempered steel has long been recognized [12, 13], amount of boron, carbon and other alloying elements alongwith heat treatment parameter has significant role to play in deciding the various end product purposes [14, 15]. The consensus has been that only a small amount of dissolved boron would be effective to increase the hardenability of steel and its effectiveness depends on the form of boron retained in the steel being influenced by the presence of other elements present in steel.

In view of above, present work was carried out to understand effect of boron to nitrogen ratio and the different quenching media in low carbon low manganese unalloyed steel.

## 2. Experimental

Tensile samples were prepared from the heats of composition with different B/N stochiometric ratio (shown in Table 1). These heats were industrially produced in LD converter and processed through ladle refining unit. Continuous cast slabs of 200 mm thickness were reheated and subjected to roughing and subsequently to finishing strands for achieving ~ 3 mm thickness in hot strip. Finishing temperature & coiling temperature maintained were 880°C and 570°C respectively. For comparative study, samples were also prepared from steel without boron, made and

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processed through same route.

**Table 1.** Chemical Composition (Wt %)

| C (%) | Mn (%) | S (%) | P (%) | Si (%) | Al (%) | B (ppm) | N (ppm) | B/N |
|---|---|---|---|---|---|---|---|---|
| 0.034 | 0.173 | 0.005 | 0.015 | 0.030 | 0.030 | 12 | 84 | 0.185 |
| 0.033 | 0.172 | 0.009 | 0.014 | 0.032 | 0.041 | 45 | 67 | 0.87 |

**Note:** B/N is atomic ratio

### 2.1. Quenching of Low Carbon Boron Added Steel

Tensile samples of hot rolled sheets were heated in laboratory muffle furnace at austenitising temperature (890°C) soaked and then quenched in oil and water medium. Mechanical properties and microstructure were analyzed of quenched samples.

### 2.2. Normalizing of Quenched Samples

Quenched samples were further normalized at 920°C and properties were compared with as rolled boron free steel.

## 3. Results & Discussions

There are two variables in this study to which material responded differently. These are boron content of steel and quenching media, i.e., cooling rate. Steel properties has also been further, analyzed and compared after normalizing with as rolled boron free steels to see the extent to which properties of steel regained.

### 3.1. Effect of Quenching on Low C Boron Added Steel

Hardenability of boron-steel is affected by the precipitation behaviour of boron. In the work of Watanabe and Ohtani [16] with different kinds of precipitates of boron, which change their state depending on the heating temperature before rolling and quenching temperature during heat treatment of Al-B treated steels, they found that when the steels are furnace cooled (cooling rate of 0.67 C/min.) after hot rolling, AlN grows radially from BN which precipitated before the nucleation of AlN. AlN formed on BN during furnace cooling is dendritic. Al, B and N dissolve into solid solution during reheating of slab at 1300°C. On subsequent hot rolling and post cooling, aided by high diffusivity of B and N over Al, concentration of B and N atoms increases at grain boundaries to the extent that even solubility product is exceeded while Al atoms remain distributed homogeneously and do not prevent BN to precipitate. Thus, due to high diffusion velocity, BN precipitates on austenite grain boundaries. Under the situation, the effect of boron on the hardenability almost disappears. This situation corresponds to non equilibrium state of Al-B-N-Fe system. Habu et.al [17] showed by calculating B content in solid solution in the equilibrium state of Al-B-N-Fe system, that Al protects B from precipitating as BN by fixing N as AlN, which ensures presence of B in solid solution, needed for hardenability. The competitive precipitation of AlN and BN has been studied by several authors [18, 19]. It has been found that AlN can form at the expense of BN during equilibrium treatments in low alloy steels. In Figure 1a, UTS trend is first increasing as B/N ratio increased to 0.185 and then decreased at 0.87 B/N ratio for both media whereas, YS showing a downward trend as shown in Figure 1b. It is well known that YS is always governed by grain size whereas, UTS value depends upon factors like presence of secondary phases, distribution & size of phases, dislocation density, grain-size, etc. At lower B/N ratio i.e. 0.185, there plays role of higher AlN precipitates led finer grain size due to higher aluminium and absolute nitrogen, see Table 1 and also the available free boron which increased the hardenability. These two factors impart higher UTS value at 0.185 B/N ratio whereas, at higher B/N ratio (0.87), since there is higher concentration of B and lesser absolute nitrogen content, Al wasn't found able to prevent B from precipitating as BN thereby, plays the combined effect of AlN and BN to reduce YS and UTS.

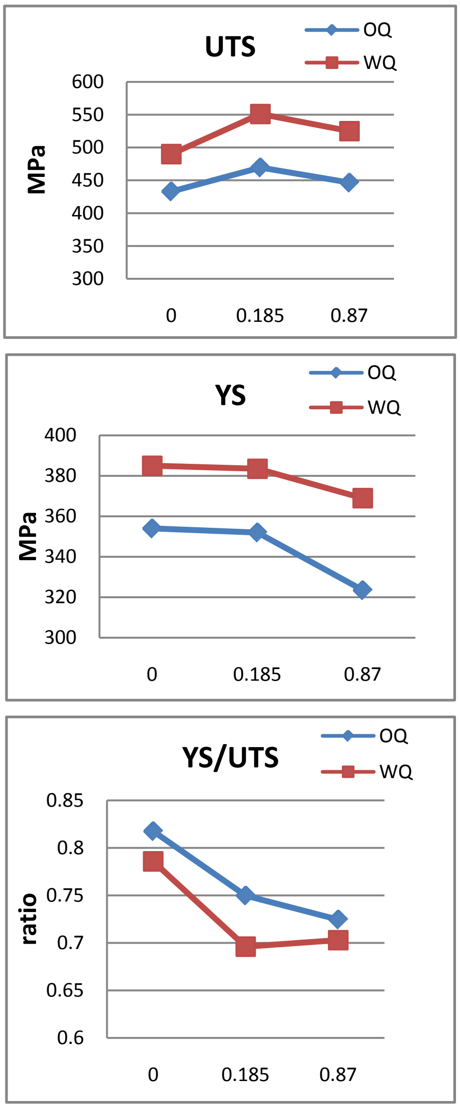



**Figure 1.** Effect of quenching on mechanical properties of low C boron added steel (a) UTS (b) YS (c) YS/UTS

Also, strength of water quenched samples was found to be always higher as compared to oil quenched samples with lower YS/UTS values with different B/N ratio, see two lowest points in Figure 1c. The curve is steeper and then became almost constant in case of water quenching. Low YS/UTS value is always associated with continuous yielding, which is due to mobile dislocations caused by austenite to martensite transformation as cooling rate is too high in water quenching. Stress-strain curve of oil-quenched & water quenched samples for experimental B/N ratio is shown in Fig. 2 & 3 respectively**.** The dislocations which are understood to be the causes of plastic deformation are pinned and hence become immobile, whereas it is mobile in case of water quenched samples. There are many preferentially yielding zones around the harder phases, and initial yielding begins simultaneously from these zones under a very low applied stress compared to the normal yield strength of the ferrite because the internal stress assist the initial yielding. Thus the steels yield continuously. Instead, in case of oil quenching, no continuous yielding is there due to combined effect of boron and slow cooling rate comparatively due to which hardenability didn't improved much. Also, yield-point elongation is almost similar in oil quenched samples for 0.185 B/N and 0.87 B/N ratios. % Elongation was found to be higher (22%) for oil quenched sample with lower B/N ratio (0.185) as compared to 15-19 % in other conditions.

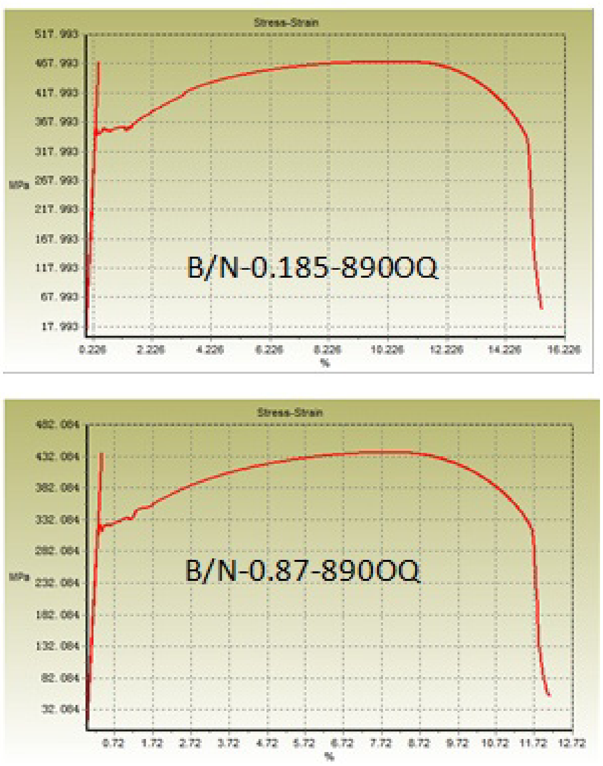



**Figure 2.** Stress-strain curve of oil-quenched samples

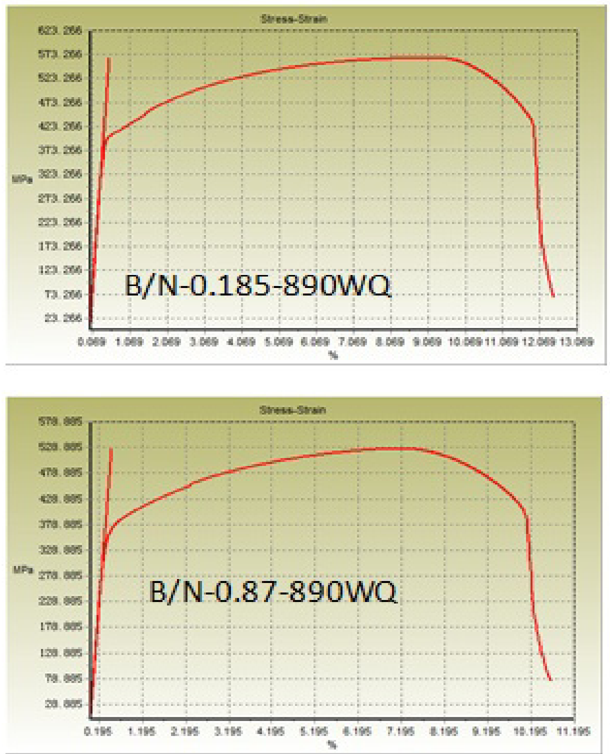
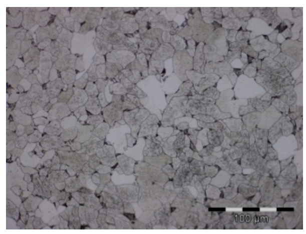
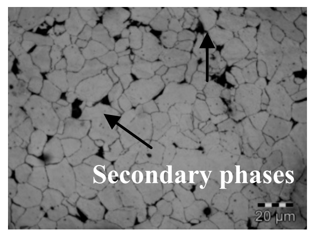


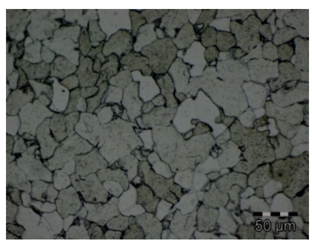

**Figure 3.** Stress-strain curve of water-quenched samples. (**Note:** X-axis showing strain % based on elongation of total length of the sample.)



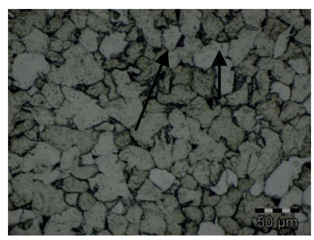
OQ-0B/N -15.87μm



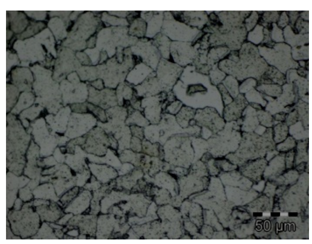

WQ-0B/N-11μm




OQ-0.185B/N-25μm




WQ-0.185B/N-17μm




OQ-0.87B/N-23μm


WQ-0.87B/N-20μm

**Figure 4.** Microstructure of quenched and normalized samples

Microstructure shown in Figure 4 revealed a secondary phase in between ferrite boundaries which is pearlite for boron free water quenched steels which gets transformed to harder and semi-harder phases like martensite and bainite for boron added steels having B/N 0.185 and 0.87 ratios. Volume fraction of these phases is higher for 0.185 B/N ratio. Density of these harder phases hasn't increased in case of oil quenched samples lead to absence of continuous yielding. Water quenched steel having 0.185 B/N ratio is also having uniform finer grain size due to AlN which enabled higher strength as well as formability to steel.

### 3.2. Effect of Normalizing of Quenched Samples

From Figure 5a & b, it can be seen that normalizing improves properties in terms of YS and UTS for lower B/N ratio i.e., 0.185 for oil quenched samples but UTS increased similar to as rolled boron free steels for 0.87 B/N ratio water quenched steels. On the other hand, normalizing enabled lower YS/UTS value with boron addition to 0.87 B/N ratio. It varied from 0.74 to 0.65 in case of normalized oil quenched samples and to 0.69 in case of normalized water quenched samples. Although, with normalizing harder phases generally gets degenerated, but in some of conditions discussed earlier in this section, higher strength may be due to formation of contributing phases which gets retained in the microstructure even after normalizing [6-10]. Grain size effect should also be taken into account for the variation in yield strength as shown in Figure 6.

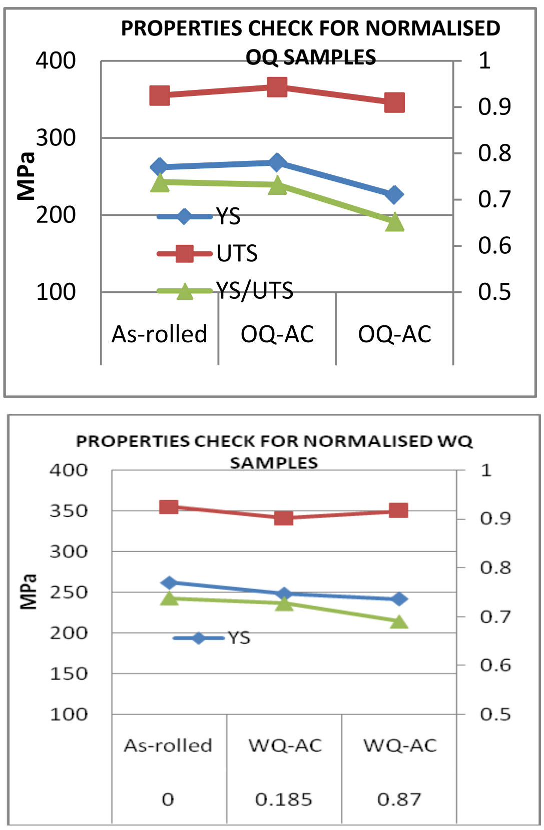



**Figure 5.** Normalizing effect on (a) oil-quenched samples (b) water quenched samples

With the advantages of grain uniformity and grain refinement, it is obvious that on air cooling at lower B/N ratio, restricted grain coarsening tends grain size almost comparable to as rolled state. In case of higher B/N ratio presence of lesser aluminium nitride precipitates causes grain coarsening on normalizing. That is why YS is showing a decreasing trend in oil quenching as well as water quenching at 0.87B/N ratio. Pinning of grains at 0.185 B/N ratio didn't allow grains to grow. Harder phases although degenerated on air cooling still some are get retained caused higher strength.

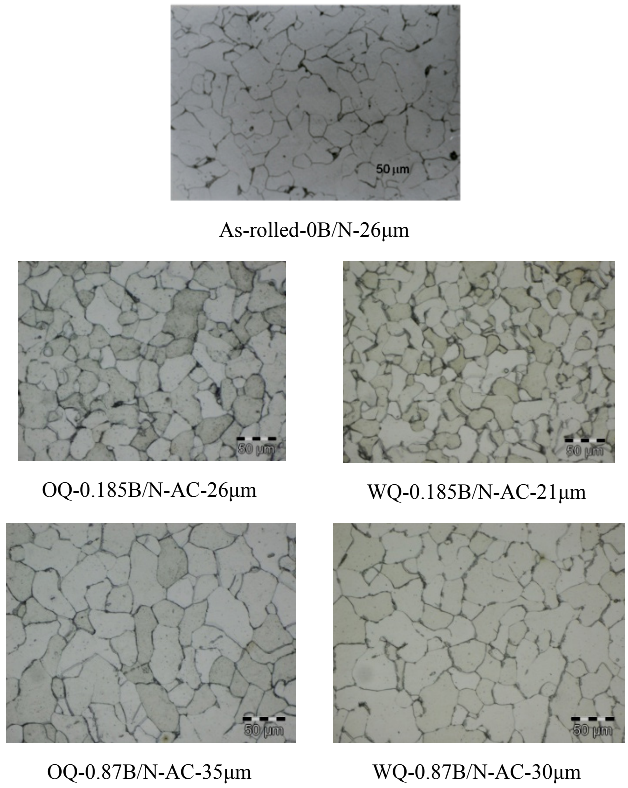



**Figure 6.** Microstructure of normalized samples compared with as-rolled samples

Individual stress-strain curve for normalized samples depicts speculating results as shown in Figure 7 a, b which reveals higher yield point elongation in case of low B/N ratio (0.185) containing steel. Also, yield point elongation was slightly higher for normalized oil quenched samples at lower B/N ratio (0.185) whether it was slightly higher for normalized water quenched samples at higher B/N ratio (0.87).

Drop in strength values has been compared with properties of low carbon boron added hot rolled steel as shown in Figure 8. Higher drop revealed in case of water quenching than that of oil quenching as second phase got degenerated. Also, drop in UTS is more than the drop in YS as the drop in YS is only governed by grain size and UTS value gets retained to some extent due to presence of some harder phases and their distribution.

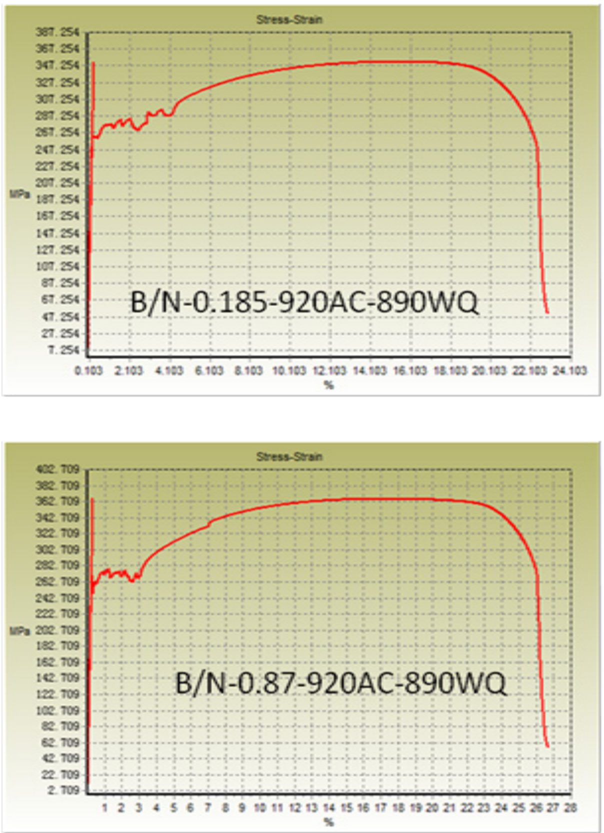



**Figure 7a.** Stress-strain curve of normalized samples (water quenching)

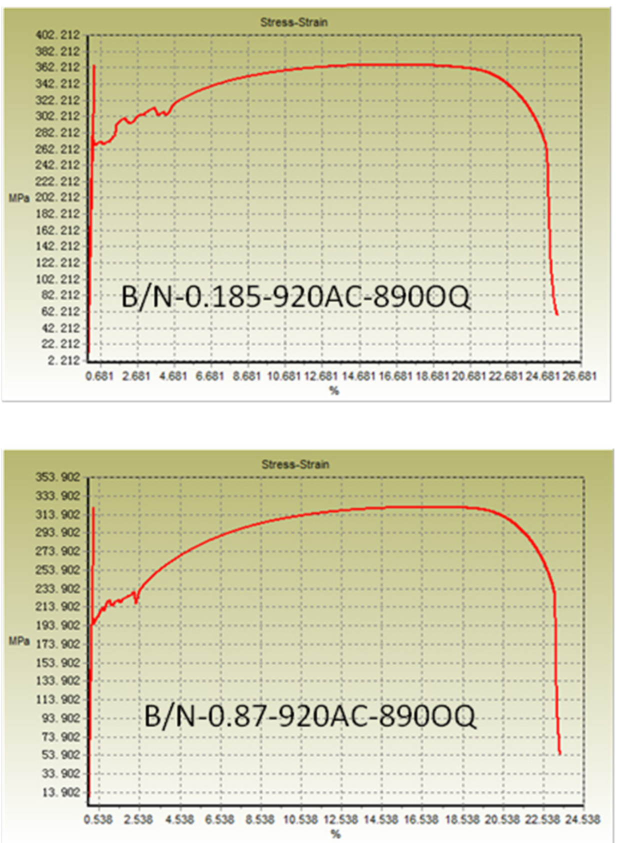



**Figure 7b.** Stress-strain curve of normalized samples (oil quenched)

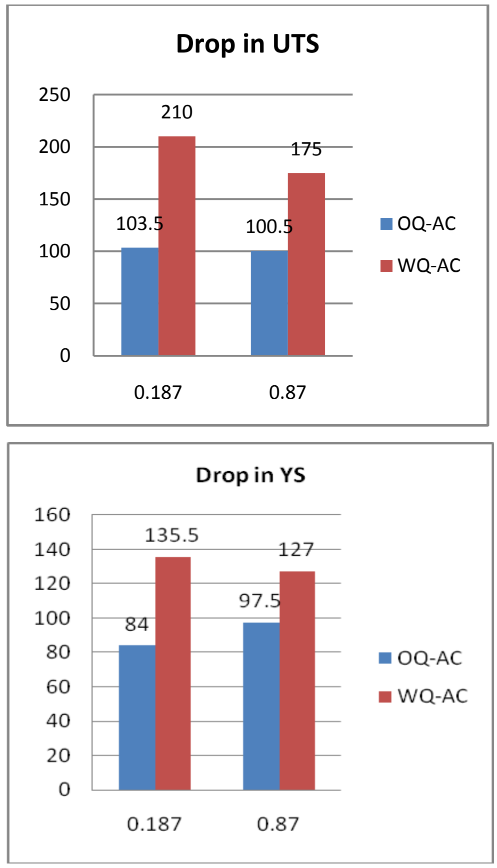



**Figure 8.** Drop in strength after normalizing

# 4. Conclusions

a) It was observed that on water quenching YS varied from 385-369MPa, UTS from 490-525MPa and YS/UTS from 0.79 to 0.70 as the B/N ratio increased whereas in case of oil quenching, YS varied from 350-323MPa, UTS from 433-446MPa and YS/UTS from 0.82 to 0.72, respectively due to combined effect of boron as a hardenability agent, its content controlling the AlN precipitation in microstructure and the cooling rate which if faster causes continuous yielding.

b) Good combination of properties observed in water quenched steel (YS-384MPa, UTS-551MPa, YS/UTS-0.69) with low B/N ratio (0.187) and oil quenched steel (YS-326MPa, UTS-447MPa, YS/UTS-0.73) with high B/N ratio (0.87). Also, with water quenching media, although lower YS/UTS value observed with boron addition, but it didn't improve further as B/N ratio goes up from 0.185 to 0.87.

c) Comparing further normalized quenched samples with as rolled boron free steel shows improvement in properties in terms of lower YS/UTS value with boron addition. It varied from 0.74 to 0.65 in case of normalized oil quenched samples and to 0.69 in case of normalized water quenched samples. Boron played an important role in contributing microstructure evolution with different quenching media and thereby resulted in better combination of properties in cost effective low carbon unalloyed steel.

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