GLOBAL JOURNAL OF ENGINEERING RESEARCH VOL. 2, NO. 1 & 2, 2003: 41 - 47

THE EFFECTS OF ALLOYING ELEMENTS ON STRENGTH, HARDENABILITY, AND INTERCHANGEABILITY IN DUAL PHASE STEELS

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(Receivd 6 January 2003; Revision accepted 26 June 2003

ABSTRACT

The effects of alloying elements (Nb, V, Mo) on dual phase steels have been studied in relation to ultimate tensile strength (U.T.S.) ductility and hardenability. C-Mn, Nb-Mo, Nb and Nb-V steels were hot rolled from 25mm to 4.5mm finishing at temperatures in the range 780°C – 950°C. They were then air cooled before being cold rolled to ~0.9mm and annealed. Dual phase heat treatment was carried out at 755°C followed by quenching in water. Tensile and hardenability tests were carried out. Results showed that alloying elements in steel increased strength in the dual phase steels by amounts ranging from 150 MPa for Nb-V steel to 226 MPa for Nb steel. Strain hardening exponent, n, was also increased from ~0.22 for annealed to 0.35 in the dual phase steels. Using the multiplying factor principle, increase in hardenability recorded ranged from 1.1 times for Nb-V to 1.37 times for Nb-Mo steels over alloy free steels. Possible interchangeability between Nb and V alloys was also observed.

Key words : Alloying elements, Ultimate tensile strength, Hardenability, Interchangeability.

INTRODUCTION

Dual phase steels are a new class of high strength, low alloy steels characterized by a micro-structure consisting of a dispersion of hard martensite particles in a soft, ductile ferrite matrix. They are currently being used in the automobile industry and other numerous applications, because of the several important advantages they offer over conventional steels. These advantages are continuous yielding behaviour at the initial straining region, a high ultimate tensile strength, high total uniform elongation values, high strain hardening rate in the work hardening region and reduction in weight of materials used without loss of strength. Dual phase microstructure can be produced on virtually all steel sheets provided that appropriate cooling conditions are used following an intercritical heat treatment(Repas,1978).

The development of a dual phase microstructure per se does not guarantee the development of excellent strength and ductility. The composite microstructure derives its properties from the individual properties of the ferrite phase and those of the martensite phase (as well as the volume fraction and the size and distribution of the phases), and the amount of alloying elements present in solid solution during intercritical annealing and the manner in which these alloys, either dissolve in austenite or ferrite, or remain as undissolved carbides.

Attention to these individual factors is necessary to produce optimum strength-ductility combinations. In the annealed state; alloy elements in steels tend to either dissolve wholly in the ferrite phase or combine as carbides(Paxton et al, 1975). Those that favour dissolution in ferrite include silicon, copper, cobalt, nickel and aluminium. Those that find their way into the carbide state include chromium, molybdenum, vanadium, tungsten, tantalium, columbium, zirconium and titanium. During dual phase intercritical annealing, alloys in carbide form tend to dissolve into the austenite phase in large amounts thereby creating coarse, homogenous grains of austenite, hence increased hardenability of austenite and steel. For example, steels containing vanadium and Nb interact strongly with carbon and nitrogen in the annealed state to form fine dispersion of VCN or NbCN precipitate. Upon intercritical dual phase annealing (α + γ region), this dispersion dissolved as the austenite phase grows into the ferrite(Geils et al,1980).

Silicon also is observed to widen the α and γ phase field thus permitting a wider range of intercritical temperatures to be used. Virtually unlimited amounts of alloying elements can be

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dissolved into the austenite phase from carbide phase. Alloying elements exert a strong hardening effect on the austenite when the carbon content is low and when the cooling rate is high.

In dual phase steels, alloying elements in general decrease the rates of transformation of austenite at sub-critical temperatures thereby facilitating the attainment of low temperature transformation to martensite without prior transformation to 'unwanted higher temperature products'(McGannon,1964). Functions of alloying elements could be evaluated and expressed in terms of hardenability using the multiplying factor principle(Grossman,1966). Since strength and toughness are characteristics of the micro-structure rather than the composite of the steel, alloy steels of equal hardenabilities but utilizing different combinations of alloying elements are generally interchangeable for heat treatment to produce the same desired micro-structure. This principle permits an intelligent choice of alloying elements combinations which, for reasons of economy or availability are best suited for particular applications. This principle was widely used in the past(McGannon,1964) to develop substitute compositions utilizing the alloying elements most suitable at the time, thereby conserving the scarcer alloying elements. Grossman(1966), further found that the cumulative effects of alloying elements on hardenability could be evaluated by multiplying the base hardenability of the iron-carbon alloy progressively by the multiplying factors for these elements. Thus the hardenability of any given alloy combination could be evaluated. The multiplying factor principle is of importance as a means of predicting the approximate hardenability of a steel from its composition. It also shows that in general, the addition of relatively small amounts of several alloying elements is more effective in increasing hardenability than the addition of a relatively large amount of a single element.

EXPERIMENTATION

Material and Initial Hot Processing

The four types of steels used were of the compositions listed in Table 1 below. They were received in the form of 25mm thick hot-rolled slabs from British steel company. These were rolled down to 4.5mm thickness in four passes (without reheating) from initial temperature of 1200°C to finishing temperature of 800°C. Specimens required for tensile testing were then air-cooled before being further cold rolled down to 0.8-0.9mm thickness (80% reduction), and annealed for 6 hours at 700°C in argon.

Heat Treatment

Steel specimens were then intercritically annealed in the dual phase ($\alpha + \gamma$) region at a temperature of 755°C in argon for 10 minutes followed by water quenching.

Metallography

Metallographic samples were hot mounted in plastic, ground under water on successively finer emery paper, and polished on velvet covered wheels impregnated with diamond paste. Generally, microstructures were observed on longitudinal transverse sections after etching with nital.

Mechanical Testing

Standard longitudinal and transverse sheet tensile specimens with gauge lengths of 20mm, thickness 0.8-0.9mm and width 4.81mm, were stamped out of cold rolled and annealed strips before dual phase heat treatment and quenching. Tensile tests were carried out using Instron Universal testing machine of 5 tonne capacity, at a nominal longitudinal strain rate of $3.8 \times 10^{-3}s^{-1}$. The tensile test pieces were pulled to failure at room temperature. From the general stress-strain equation $\sigma = K\,\varepsilon^n$ where σ is stress, ε the natural strain, K a constant and n the strain hardening exponent,

$$d\sigma/\,d\varepsilon = n\,K\varepsilon^{n-1} = n\sigma/\varepsilon$$

From $\sigma \sim \varepsilon$ curve, values of $d\sigma/d\varepsilon$ (slope), ε and σ at 0.2% proof stress position
(standard practice in industry), were inserted into equation and hence values of n used in the paper has been obtained for each specimen at 0.2% proof stress.

Hardenability Measurements

Hardenability refers to the depth of hardening and not the maximum hardness that can be obtained in a given steel. Maximum hardness is almost entirely dependent upon the carbon content, while hardenability is dependent upon the alloy content and the grain size of the austenite. Hardenability is expressed in terms of the ideal quench diameter D_i. From hardenability tests, the critical diameter, D, corresponding to the diameter where 50% martensitic transformation has taken place, is obtained for each steel. Since all the quenching in the present tests were done in water, with no agitation, the severity of quench coefficient, H, is 1.0. The measure of hardenability (D_i) is then obtained from the D-H-D_i chart given on page 1051(McGannon,1964). The increase in hardenability is then obtained from comparison between the ideal quench diameters of the alloy steels and the alloy free C-Mn steel. Cylindrical specimens of 7cm diameter and 30cm length

Table 1: Steel Compositions

TYPE OF STEEL	COMPOSITIONS (WEIGHT - %)											
	C	Mn	Si	S	P	Al	Nb	V	Mo	Cr	N_1	N_2
(C-Mn)	0.1	1.44	0.35	0.006	0.006	0.035	-	-	0.02	0.02	0.02	0.008
(Nb)	0.1	0.35	0.35	0.006	0.006	0.015	0.1	-	0.02	0.02	0.02	0.008
(Nb – V)	0.1	0.29	0.29	0.006	0.006	0.030	0.045	0.08	0.02	0.02	0.02	0.014
(Nb – Mo)	0.08	1.33	0.005	0.006	0.006	0.042	0.048	-	0.35	0.02	0.02	0.008

were prepared for each steel (from the as received steel slabs) and quenched in water after dual phase annealing at 755°C for 10 mins. They were then sectioned and etched. Values of critical diameters (D) for the different steels were taken. These were then converted to ideal quench diameters (D_i) using severity of quench H coefficient of 1.0 for water(McGannon,1964).

RESULTS AND DISCUSSIONS

Dual Phase Heat Treatment

Metallographic observation indicated that negligible decarborization occurred during heat treatment. As shown in the series of sample micrographs Figures 1 – 4, the initial processing stages of hot rolling, cold rolling and annealing resulted in a fine-grained ferritic microstructure containing a distribution of cementite particles. Precipitation hardening by microalloy nitrocarbides probably contributed to strength in Nb, Nb-Mo and Nb-V steels. Dual phase heat treatment consisted of heating to a temperature in the intercritical range to convert cementite and part of the ferrite to a relatively high-carbon austenite, followed by rapid cooling to convert that austenite to martensite. Based on Speichs(1981) and relying on the general practice of many researchers(Repas(1978), Geils(1980) Messien(1981), Priestner(1995)), a standard time of 10 minutes was selected for the duration for which specimens were held at the intercritical temperature before quenching. After this length of time, it is known that further transformation and changes in austenite composition proceed very slowly. However, because of the short annealing time, it was assumed that only carbon redistribution occurred between the phases because substitutional Mn diffuses much more slowly than interstitial carbon(Hultgren,1947). Examples of microstructures after dual phase heat treatment are shown in Figure 5 – 6, and the dependence of martensite content on intercritical

Fig. 1 C-Mn steel. Received Condition. 650X.

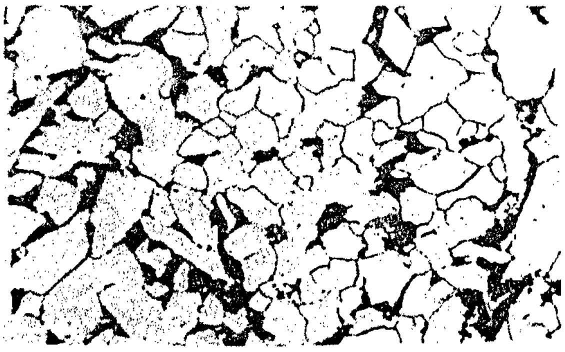

Fig. 2 C-Mn steel. Hot rolled and Air cooled. 80% Reduction. 650X

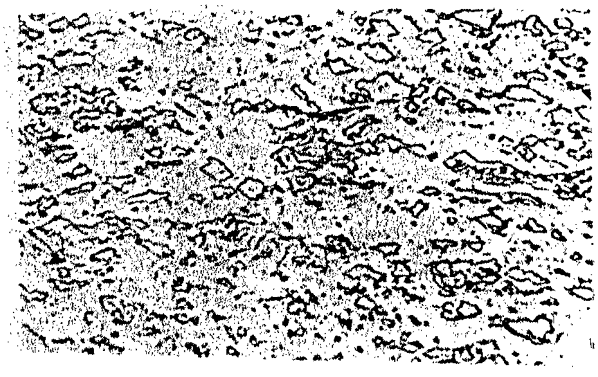

Fig. 3 C-Mn steel. As fig. 2 and cold rolled. 80% Reduction. 650X

heat treatment temperatures (after preliminary heat treatment) is shown in Figure 7. For each steel, the martensite content increased with intercritical temperature, from a value corresponding approximately to the equilibrium amount predicted by the lever rule at the eutectoid temperature. For the final temperature selected (755°C) for heat treatment of tensile specimens, the amount of martensite present in each steel after quenching are listed in Figure 8.

Effect Of Micro-Alloying Elements On Strength And Ductility After Dual Phase Heat Treatment

Results of mechanical tests performed on tensile specimens in both annealed and dual phased conditions are presented in Figures 9 and 10. In the annealed state, carbide forming tendencies place the elements in the following order of increasing intensity – Nb, Mo, and V; hence, varying strength levels in the annealed state (Figures 9a and b).

During dual phase heat treatment, austenite nucleates instantaneously at pearlite or grain boundary cementite and then grows rapidly to dissolve the carbide phase that was present in the annealed condition. Austenite then continues to grow very slowly into ferrite at a rate controlled by carbide diffusion in austenite and Mn diffusion in ferrite(Umemoto,1996). So micro-alloying elements present in the carbide phase (Nb, Mo and V) find their way into austenite thereby strengthening it, in accordance with their carbide forming tendencies and volume fraction (Figures 10a and b). In the dual phase condition, 0.1% Nb addition produced an increase in U.T.S. of 126 MPa over plain carbon steel (C – Mn). For Nb – V steel, addition of Nb(0.045%) and V(0.08%), an increase of 50 MPa is recorded. For Nb – Mo, Nb (0.048%) and Mo (0.36%), a rise of 76 MPa is recorded. Values of n and uniform elongation remained fairly constant for all dual phase steels at 0.35 and 0.19 respectively (Figure 10b). However, in relation to annealed steels (Figure 9b), dual phase heat treatment significantly increased n from 0.22 to 0.35. Strength levels were also significantly increased in all dual phase heat treated steels over the annealed steels ranging from an increase of 60 MPa for Nb – Mo steel to 198 MPa for Nb steel. Values of work hardening rates (d□/d□) were also increased. Values of average uniform elongation however remained approximately constant after dual phase heat treatment (Figures 9 and 10). Tanaka et. al(1979), have shown that both chromium and molybdenum increased hardenability of dual phase steels by about 60 MPa per 1% alloy inclusion for 0.35% C steel after dual phase heat treatment. Also, Repas(1978) and Konopleva et al(1995), has found that vanadium increases strength by about 35 MPa over vanadium free steels for every 1% vanadium addition in 0.11% C steels. He also found that Si similarly increased hardenability by 83 MPa per 1% Si addition.

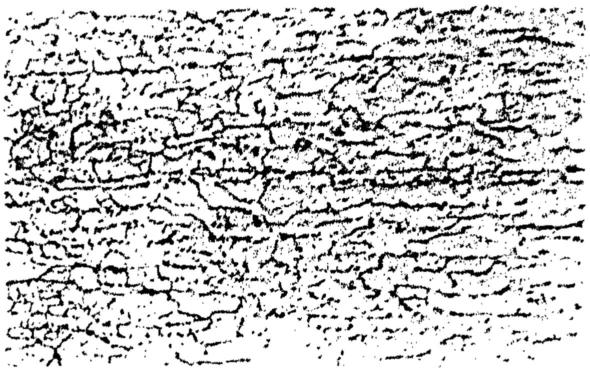

Fig. 4 C-Mn steel. As fig 3 and Annealed 700 °C for 6 HOurs. 650X

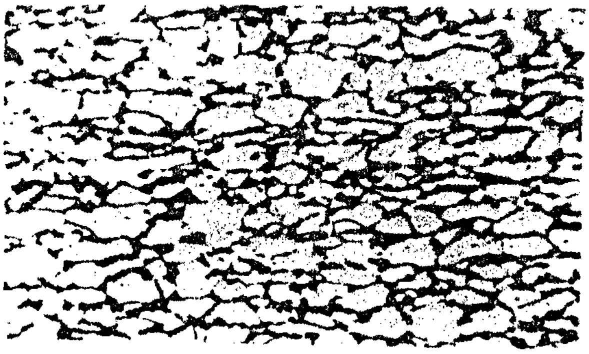

*Fig. 5 C-Mn steel. As fig 4 and dual phased 755 °C for 10 minutes.
Tempered 160 °C for 4 hours.
24% Martensite. 650X*

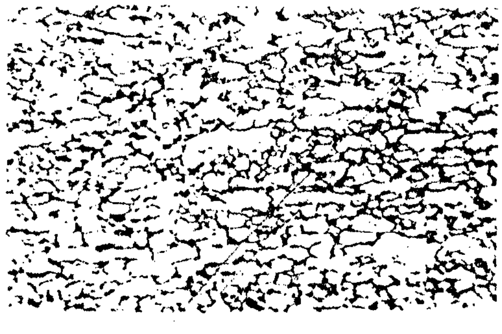

*Fig. 6 Nb steel Dual phase 755 °C for 10 minutes. Tempered 160 °C for 4 hours.
29% Martensite. 650X*

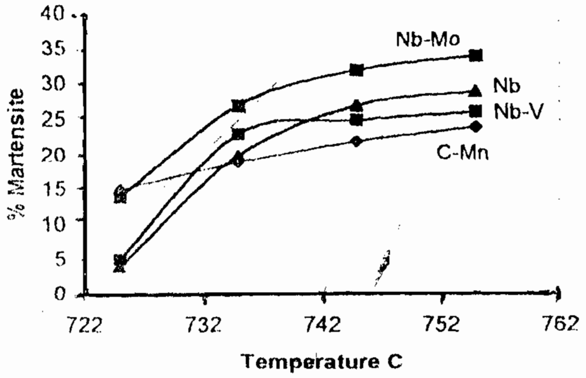

Fig.7 Dependence of martensite content on intercritical temperature of dual phase heat treatment.

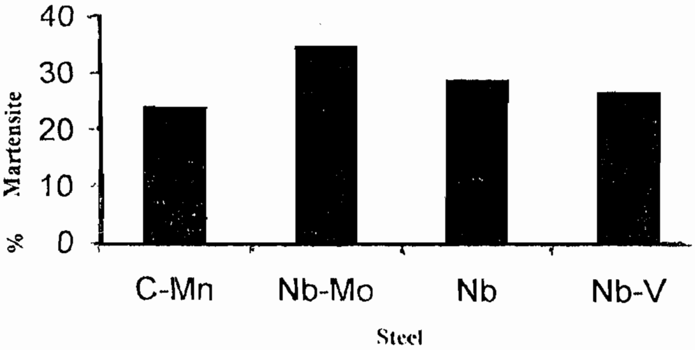

Fig.8 % Martensite in each steel after dual phase heat treatment(755C)

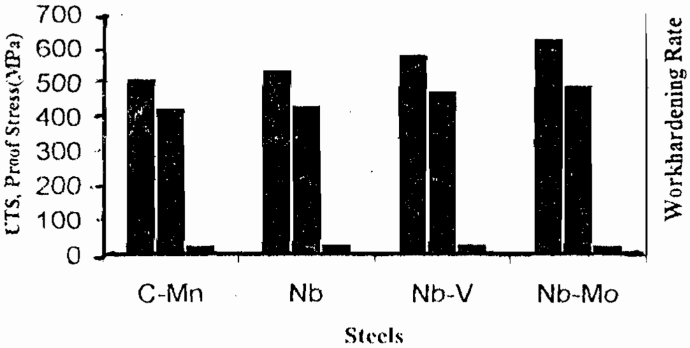

Fig.9a Mechanical Properties(Ultimate Tensile Strength(UTS),Proof Stress,and Workhardening Rate) of steels in the annealed condition

Hardenability in dual phase steels: Multiplying factor principle

Values of critical diameters and hardenability values (D_i) obtained are outlined in Figure 11. The increase in hardenability of Mo (0.36%), V(0.08%), Nb(0.045%) steels over alloy free steels(McGannon,1964) are respectively 1.29, 1.04 and 1.06. Using the multiplying factor principle, increase in hardenability of Nb – V steel over alloy free steel is 1.06 x 1.04 = 1.1 times. Similarly, for Nb – Mo steel, increment in hardenability is 1.29 x 1.06 = 1.37 times and hardenability of Nb steel was found to increase by 1.13 times. Results suggest that additions of smaller amounts of alloying elements (2 or more) to steel is more effective in increasing hardenability than addition of a relatively large amount of one alloying element (Figure 11).

CONCLUSIONS

1. Microalloy additions generally increased the strength levels of steel after dual phase heat treatment over micro alloy free steels. Values ranging from 150 MPa for Nb – V steel to 226 MPa for Nb steel were obtained.

2. Hardenability values were also increased by microalloy additions ranging from 1.1 X for Nb – V to 1.37 X for Nb – Mo steel over alloy free steels.

3. The multiplying factor principle proved that additions of small amounts of Nb, V and Mo in combination increased the hardenability of steel more than addition of a relatively large amount of one alloy (Figure 11).

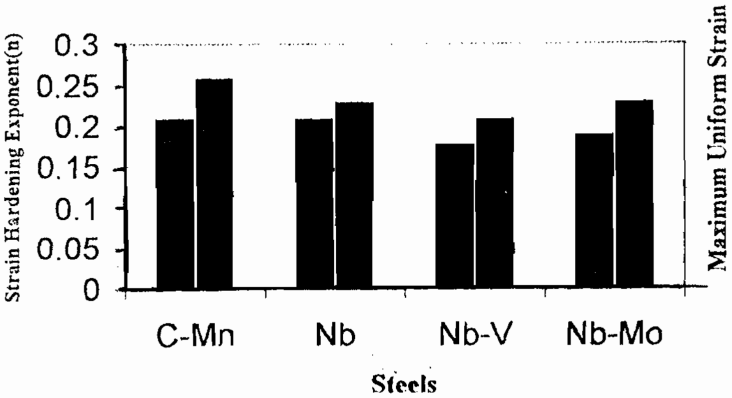

Fig.9b Mechanical Properties(Strain Hardening Exponent(n), Maximum Uniform Strain) of steels in the annealed condition

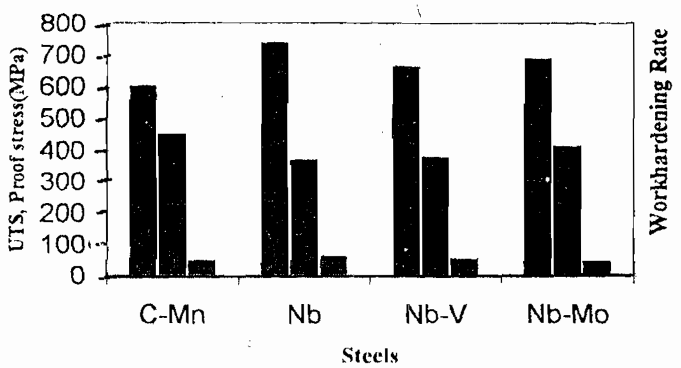

Fig.10a Mechanical Properties(Ultimate Tensile Strength(UTS),Proof Stress, Workhardening Rate) of steels after dual phase heat treatment

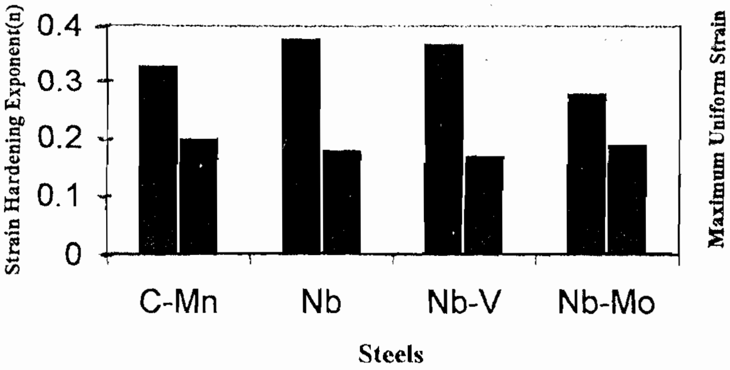

Fig.10b Mechanical properties(Strain Hardening Exponent(n), Maximum Uniform Strain) of steels after dual phase heat treatment

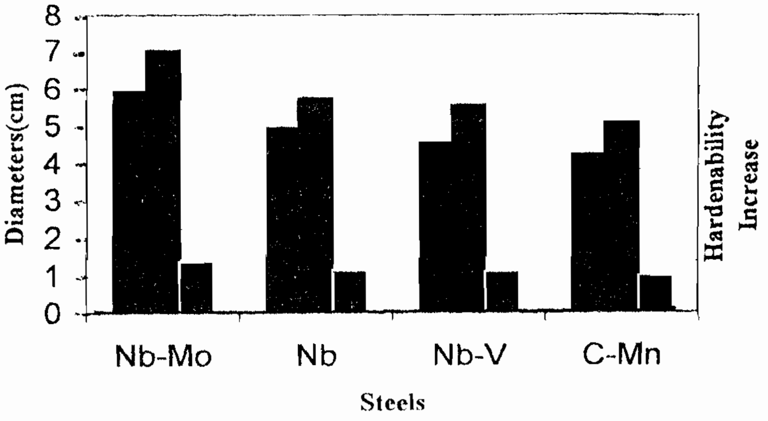

Fig.11 Critical Diameter, Ideal Quench Diameter(Di), Increase in Hardenability(Xtimes) for steels.

4. It may be possible to interchange Nb (0.045%) and V (0.08%) for the purposes of dual phase heat treatment, hence obtaining similar microstructure and mechanical properties.

5. Dual phase steels display better mechanical properties over conventional steels.

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