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Economically attractive high strength steel bars using single microaddition of titanium or vanadium

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Abstract: In this study, single microaddition of either titanium or vanadium was investigated to study its effect on the mechanical properties and microstructure of hot deformed steels. Comparing with non-microalloyed steels, increments of up to 428 and 392 M Pa in the yield and ultimate tensile strengths can be attained by using either V- or Ti-microalloying technique. Microaddition flow carbon steel (0.23% C) with 0.2% Ti is effective to obtain steel with yield and ultimate tensile strengths of 637 and 733M Pa, respectively. Whereas microaddition of 0.2% Vintosteel with higher C-content (0.32%C) results in higher yield and ultimate tensile strengths of 799 and 957M Pa, respectively. These high strength levels are accompanied with good elongation of 18–22%. The strengthening effect of V-or Ti-microadditions is due to grain refinement and precipitation strengthening. V-microalloyed steel exhibits higher precipitation strengthening, whereas Ti-microalloyed steel exerts greater grain refinement effect. Vanadium-or titanium-microalloyed steel can be substituted for commonly used carbon steel in the production of high strength reinforcing steel bars. It is evident that the substitution is economically attractive for both the producer and user. However, producing Ti-microalloyed steel bars seems to be more profit than V-microalloyed steel bars for the steelmaker.

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Keyword: Microalloyed steels, vanadium microaddition, titanium microaddition, strength, ductility, grain refinement, precipitation strengthening.

1. Introduction

The high strength of steel is the principal reason for its wide application as engineering material. The strength of conventional carbon steels depends on their carbon: the higher the carb on content, the higher the strength. Strengthening of steel by means of carbon addition is the cheapest, mosteconomical way of increasing the yield and tensile strength properties. High strength however, though desirable, is only one of many properties required of an engineering material. In addition to strength, the steel must have good ductility to facilitate fabrication by bending or cold forming. It must be resistant to impact or chock loading by having high toughness especially at low temperatures. Since joining by welding involves melting and rapid cooling, the steel must exhibit good weld ability and retain its original properties. Unfortunately, these important engineering properties: ductility, toughness and weld ability, deteriorate rapidly as the carbon content of the steel is increased. Consequently, to maintain a balanced combination of properties, the carbon content, and thus the strength of steel must be reduced.

In recent years, microalloying has been attracted great attention and gained an importance to attain steels with attractive properties. Improvements in the mechanical properties of low carbon steels have been achieved by microaddition of strong carbide- forming elements such as Nb, V or Ti (1-20).

Since the addition of these elements is usually less than one tenth of one percent (0.1%), the term microalloying is frequently applied to this class of steels. Unlike trace elements which are usually undesirable, microalloying elements are added intentionally to improve steel properties. Besides the obvious difference in the magnitude of the alloy content between alloying and microalloying elements, also their different metallurgical effects are usually characteristic. Whilst alloying elements predominately affect the matrix of steel, microalloying elements nearly always influence the microstructure via the precipitation of a second phase besides a solute drag effect. (5)

The newly developed microalloyed steels seem to be capable of combining excellent balance of high strength with other desirable engineering properties. In recent years, there is a growing awareness of the necessity to reduce the weight of products made of steel. Weight reduction is essential in mobile equipment, to reduce the energy consumption.

Compared to low-density materials (aluminum and plastic), the use of high strength steels offers a most effective way to reduce weight. Further, utilization of high strength reinforcing bars instead of the conventional low strength carbon steels, permits lighter construction to be made with thinner sections, reducing substantially the tonnage requirements and transportations cost (1).

In addition, the many earthquakes, with complete collapse of many structures, occurred in the last years in different regions of the world necessitate special requirements for reinforcing steel used for concrete structures. The modern approach to building design is to accept the fact that seismic shocks will produced a mage but to ensure that loss of life is avoided by preventing the complete collapse of a structure. Apart from careful attention to engineering design it is essential that the steels used fore in for cement should be capable of accepting a significant amount of plastic yielding and should not fail by brittle failure. Therefore, conventional steels with high carbon content and consequently low ductility and low impact resistance are unacceptable **(7)**.

This study aims to investigate the effect of V-and Ti-microadditions on the strength and ductility of the hot deformed steels with different carbon contents.

2. Experimental

Three series of non-microalloyed, V-microalloyed and Ti-microalloyed steels were selected to investigate the effect of V-and Ti-microadditions on the strength and ductility of the hot deformed steels with different carbon contents.

Four non-microalloyed steels, four V-microalloyed steels and eight Ti-microalloyed steels with total of sixteen steels were chosen to this investigation. The investigated non-microalloyed steels have different carbon contents in the range of 0.094 to 0.395%. In the two series of V- and Ti-microalloyed steels, V or Ti was varied up to 0.2% in combination with different carbon contents.

All investigated steels were produced as hot rolled air cooled bars with diameter of19mm using the same conventional electric arc furnace (EAF) production route and the conventional hot rolling practice with the same reheating and finishing conditions, 1200ºC and 900ºC for reheating and finish-rolling temperatures, respectively. The reheating temperature of 1200°C was chosen to have significant amounts of microalloying elements solved, necessary to allow for a considerable precipitation strengthening during cooling. The finish-rolling temperature of 900°C was chosen to ensure finishing in the austenite phase. After hot rolling, all steel bars were normal air cooled to room temperature.

Samples from each bar of all investigated steels were taken and subjected to complete chemical analysis. Tensile specimens were machined from the as-hot rolled bars in the rolling direction. The tensile properties were measured at room temperature at a rateof1mm/min and yield strength (YS), ultimate tensile strength (UTS) and elongation (El.%) were determined on duplicate specimens. The test was performed on a Zwick\roell Z100 testing machine.

Other samples of the hot-rolled steel bars were prepared for measuring the hardness measurements. The Vickers hardness was measured and the average of five readings was calculated.

Light microscopic observations were carried out on specimens of hot-rolled bars after polishing and etching in 2% natal solution. The ferrite grain diameter was calculated from the number of bound Aries intersecting a line of known length at a known magnification. A total of about 300 grains was averaged.

Table (1): Chemical composition of the investigated non-microalloyed, V-microalloyed and Ti microalloyed steels

Steel No	Chemical composition, wt%									
	C	Mn	Si	P	S	Cu	Mo	Al	V	Ti
X1	0.094	0.63	0.18	0.035	0.035	0.172	0.018	0.002	--	--
X2	0.214	0.94	0.26	0.011	0.042	0.112	0.01	0.005	--	--
X3	0.304	0.79	0.2	0.013	0.038	0.186	0.011	0.003	--	--
X4	0.395	0.72	0.14	0.011	0.042	0.194	0.017	0.003	--	--
V1	0.21	1	0.28	0.031	0.033	0.122	0.001	0.003	0.12	--
V2	0.195	1.27	0.32	0.012	0.008	0.053	0.001	0.004	0.22	--
V3	0.3	1.03	0.37	0.023	0.024	0.111	0.001	0.005	0.08	--
V4	0.32	0.97	0.35	0.037	0.029	0.242	0.006	0.0001	0.2	--
T1	0.23	0.68	0.2	0.022	0.033	0.163	0.012	0.003	--	0.037
T2	0.23	1.61	0.14	0.007	0.019	0.103	0.01	0.072	--	0.029
T3	0.25	0.87	0.71	0.034	0.026	0.169	0.01	0.046	--	0.058
T4	0.22	1.27	0.36	0.025	0.018	0.089	0.005	0.073	--	0.062
T5	0.3	1.16	0.31	0.025	0.02	0.13	0.001	0.112	--	0.068
T6	0.136	1.08	0.5	0.022	0.023	0.08	0.01	0.12	--	0.1
T7	0.214	1.02	0.28	0.022	0.04	0.138	0.087	0.047	--	0.12
T8	0.23	0.98	0.37	0.04	0.02	0.1	0.01	0.1	--	0.2

Table (2): Mechanical properties and grain size of the investigated non-microalloyed, V-microalloyed and Ti-microalloyed steels

Steel No	Mechanical properties			Hardness (HV)	Grain Size (d) (μm)	d-1/2 (mm-1/2)
	YS (M Pa)	UTS (M Pa)	El. (%)			
X1	322	440	26.1	150	12.4	8.98
X2	393	562	24.4	178	6.8	12.1
X3	371	565	23.2	189	8.6	10.8
X4	371	566	22.7	190	7.9	11.3
V1	559	697	23	207	6.2	12.7
V2	637	770	21	244	4.7	14.6
V3	611	793	23	231	5.9	13.0
V4	799	957	18	272	4.3	15.2
T1	429	577	29	171	5.7	13.2
T2	543	650	27	195	3.4	17.1
T3	456	651	29	197	6	12.9
T4	468	645	25	195	5.4	13.6
T5	557	745	24	214	4.1	15.6
T6	520	598	29	195	4.8	14.4
T7	559	697	25	205	4.2	15.4
T8	637	733	22	236	3.9	16.0

3. Results and Discussion

The chemical analysis, tensile properties, hardness and grain size measurements of the different investigated on-microalloyed, V-microalloyed and Ti-microalloyed steels are listed in **Tables 1 and 2**.

2.1 Effect of carbon content on the mechanical properties

The effect of carbon content, at constant V or Ti contents, on the mechanical properties is shown in **Figures 1 and 2**. Both yield and ultimate tensile strengths increase with increasing carbon content, **Figure 1**. Like the yield and ultimate tensile strengths, **Figure 2** also illustrates increasing the hardness as carbon content increases. On the other carbon content up to 0.4% C leads to obtain steel with lower strengths of only 371 and 566M Pa of yield and ultimate tensile strengths, respectively.

On the other hand, **Figures 1 and 2** illustrate much higher effect of carbon on the strength and hardness of V-and Ti-microalloyed steels comparing with the non-microalloyed steels.

For non-microalloyed steels, the carbon content of steels (in the range 0.09– 0.40%) has its higher effect on the ultimate tensile strength than the yield strength. Whereas increasing the carbon content from 0.094 too. 395% results in increment of 126M Pa in the ultimate tensile strength, only 49M Pa increment of the yield strength is attained.

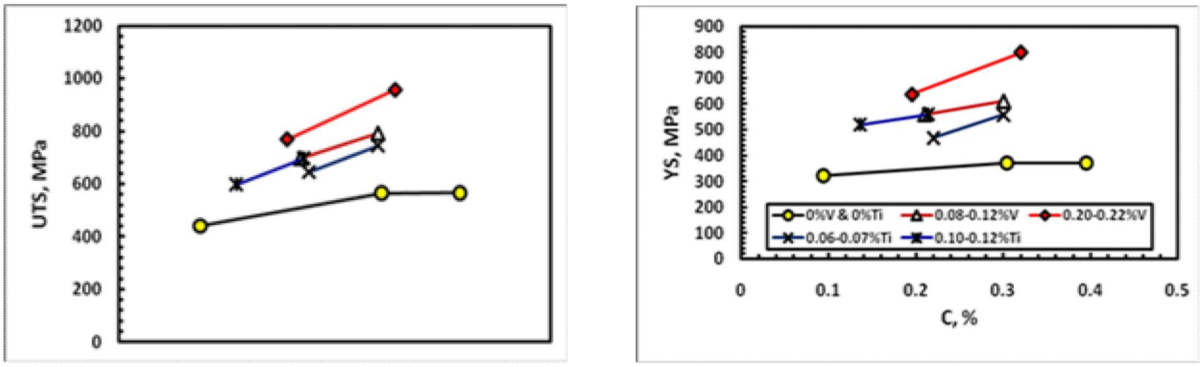


Fig. 1: Effect of carbon content on the yield and ultimate tensile strengths of non-microalloyed, V-microalloyed and Ti-microalloyed steels.

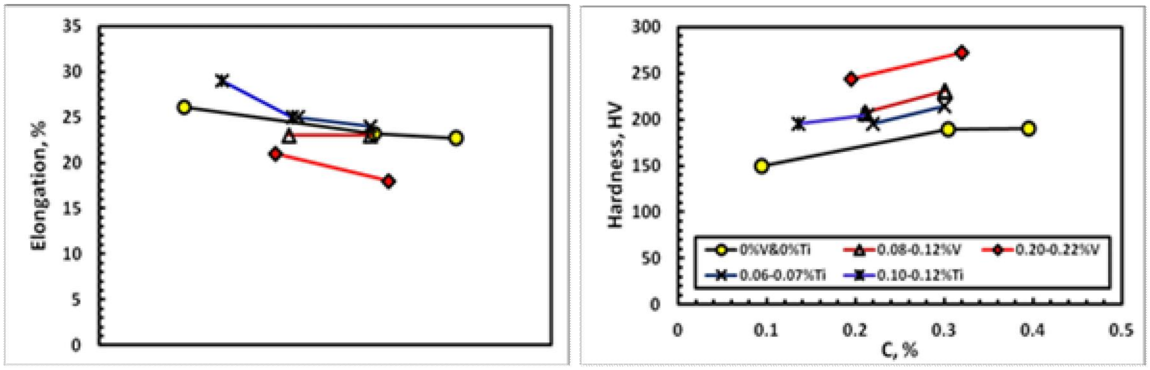


Fig. 2: Effect of carbon content on hardness and elongation of non-microalloyed, V-microalloyed and Ti-Microalloyed steels.

2.2 Effect of V-and Ti-microadditions on the mechanical properties

Figures3and4 illustrate the effect of V or Ti contents on the yield and ultimate tensile strengths, hardness and elongation of two series of steels with 0.20–0.25% and 0.30–0.32%C. For steels with 0.20 - 0.25%C, the yield and ultimate tensile strengths increase as either V or Ti content increases. Microaddition of either V or Ti up to 0.20% leads to increments of 244 and 171M Pain the yield and ultimate tensile strengths, respectively.

V-or Ti-microadditions have much higher effect on both yield and ultimate tensile strengths of steels with higher carb on content. For steels with 0.30–0.32%C, increments of 428 and 392 M Pa are Obtained by adding 0.2%V.

The same trend is seen when comparing the hardness of V-or Ti-microalloyed steels with that of non-microalloyed steels, **Figure 4**.

On the other hand, increasing the yield strength, ultimate tensile strength and hardness due to V-or Ti-microadditions is accompanied with decreasing the elongation. However, even with such high strength obtained at microaddition of 0.2%V or Ti, good elongation of 18-22% is also obtained.

From the results represented in **Figures 1 to 4,** it is clear that non-microalloyed plain carbon steel with 0.094% C has lower yield and ultimate tensile strengths of 322 and 440M Pa, respectively. Increasing the carbon content up to 0.395% results in a slight increase of strength and attaining steel with yield and ultimate tensile strength of 371 and 566M Pa, respectively. This slightly increment in Strength is accompanied with decreasing the elongation from 26.1 to 22.7%.

Vanadium-or titanium-microalloyed steels have higher strength comparing with non-microalloyed steels. Microaddition of low carbon steel (0.23%C) with 0.2% Ti is effective to attain steel with yield and ultimate tensile strengths of 637 and 733M Pa, respectively. Microaddition of 0.2% Vintosteel with higher carbon content (0.32%C) results in higher yield and ultimate tensile strengths levels of 799 and 957M Pa, respectively. These much high strength increments are accompanied with slightly decrease in elongation from 22% (for steel with 0.23% C and 0.2% Ti) into 18% (for steel with 0.32% C and 0.2%V).

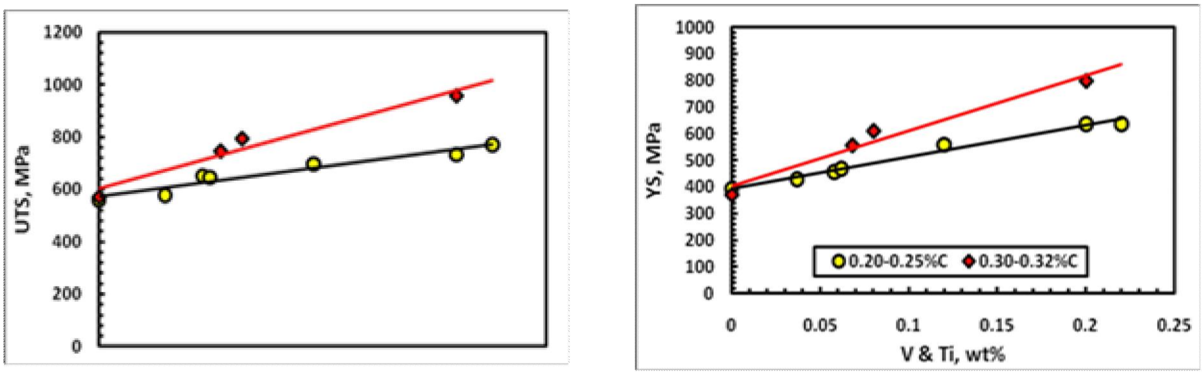


Fig. 3: Vanadium or titanium contents versus the yield and ultimate tensile strengths of steels with different carbon contents.

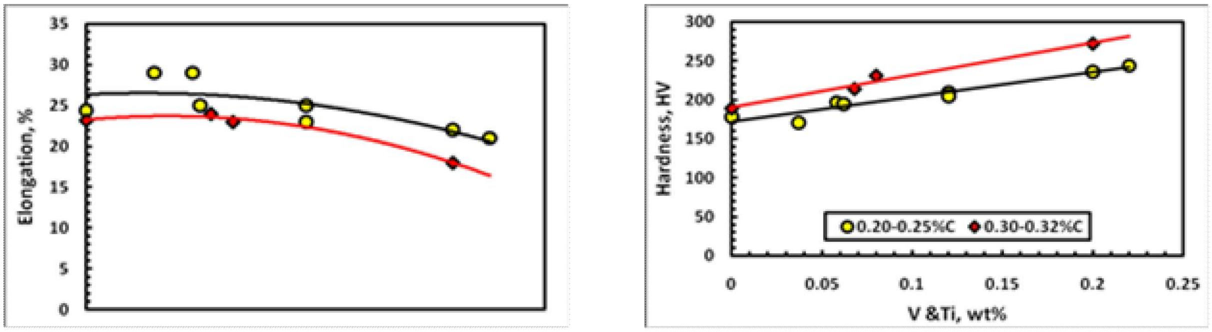


Fig. 4: Vanadium or titanium contents versus the hardness and elongation of steels with different carb on contents

2.3 Mechanical properties relation ships

From the obtained results, it is clear that there are correlations between yield, ultimate ensile strengths and hardness of non-microalloyed, V- microalloyed and Ti-microalloyed steels. As the hardness increases, both the yield and ultimate tensile strength increase. **Figure 5** illustrates linear correlations in yield strength-hardness and ultimate tensile strengths-hardness relationships in the investigated non-microalloyed, V-microalloyed and Ti-microalloyed steels at the investigated chemical composition range.

The results obtained also reveal a decrease of elongation as the hardness and strength increase. The data given in **Table 1** are plotted in **Figures 6 and 7** illustrating the different correlations between hardness, yield strength, ultimate tensile strength and elongation. From these relationships, it is obvious that V-and Ti-microalloying is positive in obtaining steels with higher elongation comparing with the non-microalloyed steels of the same levels of hardness, yield strength and ultimate tensile strength.

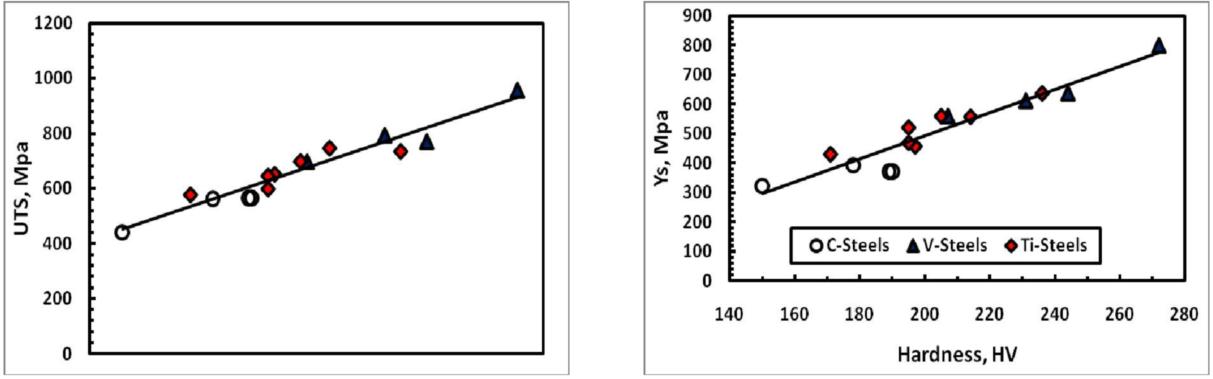


Fig. 5: Yield strength–hardness and ultimate tensile strength–hardness relationships in the investigated non-microalloyed, V-microalloyed and Ti-microalloyed steels.

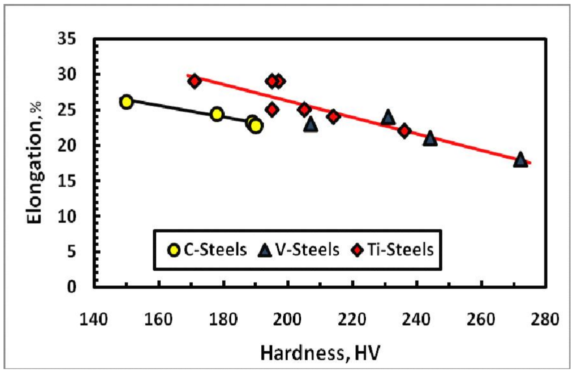


Fig. 6: Elongation–hardness relationship in the investigated non-microalloyed, V-microalloyed and Ti-Microalloyed steels.

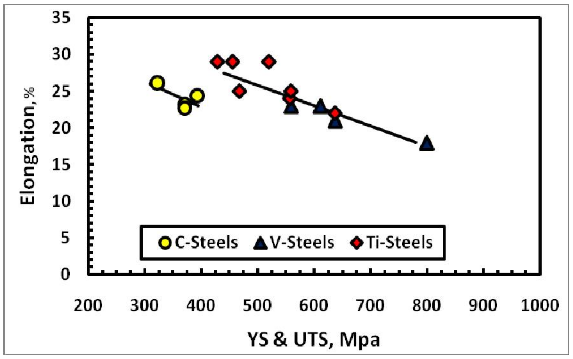


Fig. 7: Elongation–yield strength and elongation-ultimate tensile strength relationships in the investigated non-microalloyed, V-microalloyed and Ti-microalloyed steels.

2.4 Microstructure and grain refinement of the investigated steels

Light microscopic observations carried out on specimens of hot rolled steel bars showed ferrite–pearlier structure in all investigated non- microalloyed, V- and Ti-microalloyed steels. Selected micrographs of microstructure of investigated steels are shown in **Figure 8.**

For non-microalloyed steels, increasing the carbon content was found to slightly increase of hardness and strength. This strengthening effect of carbon could be attributed to increase of the pearlier fraction. The most important factor controlling the pearlier content is the carbon content of steel **(21, 22).** The volume fraction of pearlier may be expressed by **(22)**:

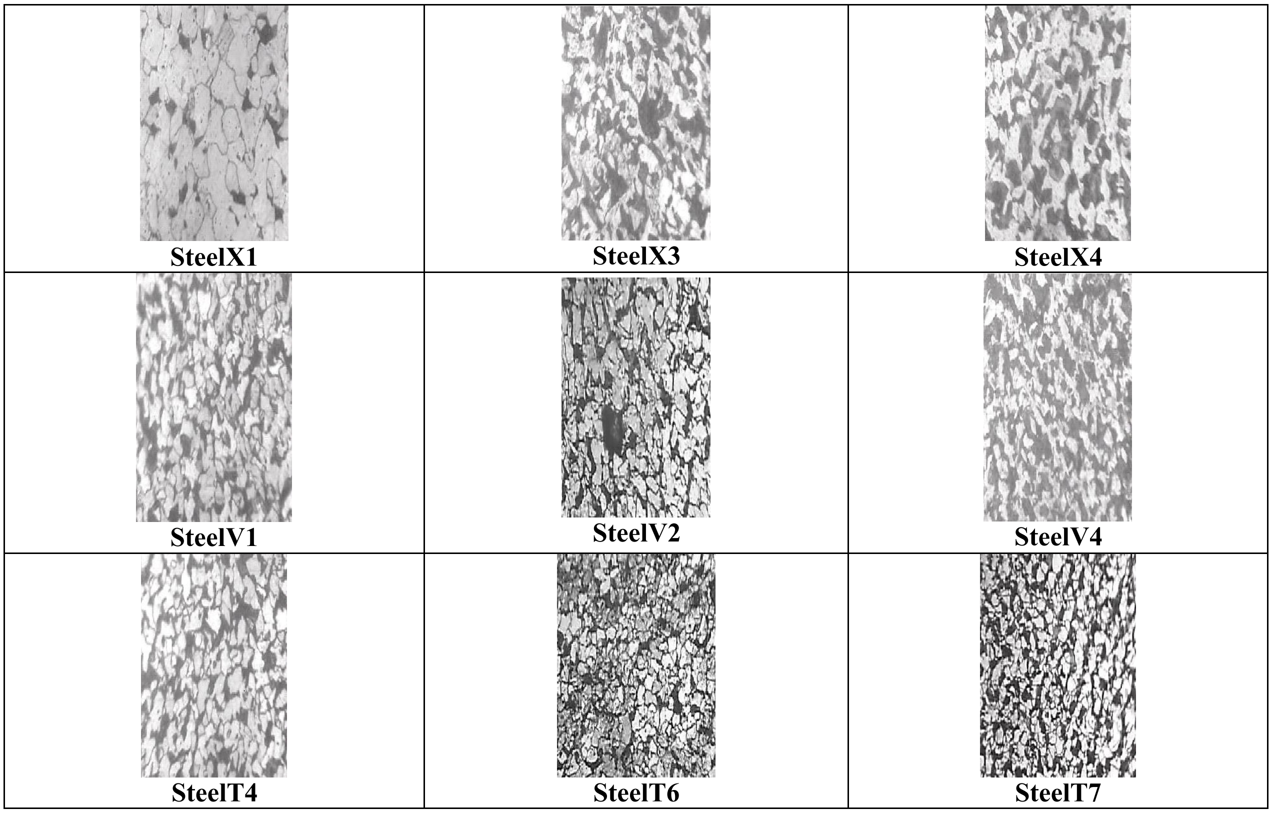
$$fP=1.307CP \quad (1)$$

Where f**P:** pearlier volume fraction

CP: proportion of C in pearlier, wt%

The amount of pearlier mainly affects the tensile strength, due to the greater rate of work-hardening of pearlier than of ferrite, but not in general the yield strength, which is controlled by the ferrite **(21)**. Glad man et al **(23)** concluded that for steels containing pearlier fraction less than 0.3%, this range did not have a significant effect on the yield stress. However, it must be pointed out that, if the amount of pearlier is increased, this frequently causes a refinement of the ferrite grain size because the pearlier interruption occurs early in the growth of the ferrite grains during trans formation and this can lead to an increased yield strength which is not a direct consequence of the amount of pearlier **(23).**

The present study, microstructure observations showed finer grain size at higher carbon content.



SteelX1 **SteelX3** **SteelX4**

SteelV1 **SteelV2** **SteelV4**

SteelT4 **SteelT6** **SteelT7**

Fig. 8: Selected micrographs of microstructure of the investigated steels, X500.

From grain size measurements, **Table 2**, the reciprocal square root of the grain size (d-1/2) was calculated. **Figure 9** shows the reciprocal square root of the grain size (d-1/2) plotted against the carbon content for non-microalloyed, V- and Ti- microalloyed steels. It is clear from this figure that increasing the carbon content in the non- microalloyed steels results in finer grain size. Further grain refinement is observed when adding either V or Tiata given carbon content and this effect increases as carbon content increases.

One of the effects of microalloying additions is to restrict the austenite grain growth at the reheating temperature by particles of carbides and/ornitrides which pin the grain boundaries resulting in a small starting austenitegra in size would be beneficial for fine ferrite grain size **(24, 25)**. This is because the original austenite grain size, in general controls the number offer rite nuclei, due to ferrite nucleation on the austenite grain boundaries. In addition, the effect of strain-induced precipitation on preventing grain growth of the recrystallized austenite or retarding of recrestallization during deformation causes further refining of ferrite.

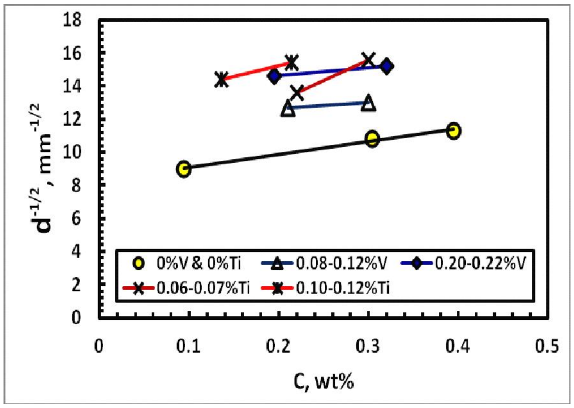


Fig. 9: Effect of carbon content on the grain size of non-microalloyed, V-microalloyed and Ti-microalloyed steels.

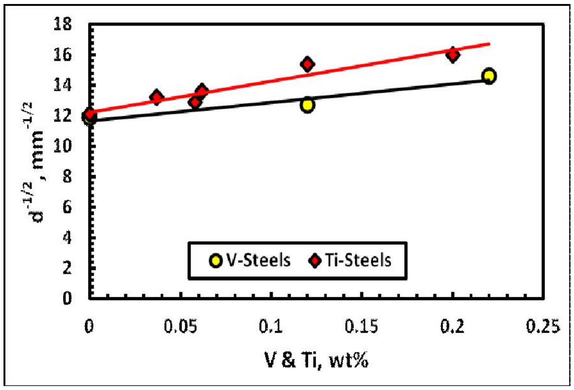


Fig. 10: Effect of both V-and Ti-microadditions on the grain size of steels with 0.20–0.25%C.

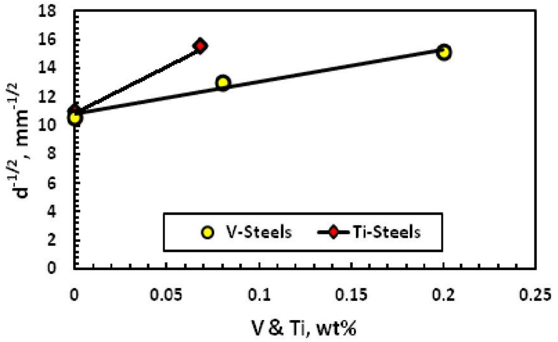


Fig. 11: Effect of both V-and Ti-microadditions on the grain size of steels with 0.30–0.32%C.

The grain refinement effect of either V-or Ti-microaddition into steels with 0.20-0.25% C and steels with 0.30-0.32% Care illustrated in **Figures.**

10 and 11. These figures reveal much grain refinement effect of Ti-microaddition comparing with V-microaddition. These figures also illustrate finer grain size of microalloyed steels at higher carbon content.

Grain boundaries are very effective barriers to dislocations movement and it is to be expected therefore that the flow stress will be increased as the grain boundary area/unit volume is increased, i.e. as the grain size decreased.

2.5 Precipitation strengthening

The contributions to the yield strength of hot-rolled on-microalloyed steels can be expressed by the following equation. (26-27)

$$\sigma y=\sigma o+\sigma s+\sigma g \qquad (2)$$

where **σy** is the measured yield strength, **σo** is the ferrite fraction stress, **σs** is the contribution from solid solution strengthening and **σg** is the strengthening attributable to ferrite grain size. The value of **σo** can be taken as 104M Pa (28) and σs in M Pa has been calculated from the formula (29) **(29)**:

$$\sigma s=32[\%Mn]+85[\%Si]+670[\%P]+39[\%Cu]+11[\%Mo] \qquad (3)$$

where [%Mn], [%Si], [%P], [%Cu] and [%Mo] are the wt% of these elements in steel produced. The value of **σg** has been calculated from the Hall-Petch equation (30-31):

$$\sigma g=Kd-1/2 \qquad (4)$$

where d is the grain intercept in mm and K represents the difficulty of transmitting slip across grain boundaries. Value of 18M Pa has been used for the hot-rolled steels. (32)

Thus, equation (2) can be written as the following:

$$\Sigma y\ [MPa] = 104 + 32[\%Mn] + 85[\%Si] + 670[\%P] + 39[\%Cu]+11[\%Mo]+18(d-1/2) \qquad (5)$$

For non-microalloyed steels, the calculated yield strengths are nearly the same as the measured yield strength, confirming the validity of the strengthening model adopted.

However, all V-and Ti-microalloyed steels showed higher strength compared with that calculated according to the strengthening model. This strength increment can be attributed to the precipitation strengthening as are results of V-or Ti-microadditions which strengthen the ferrite matrix by forming fine precipitates. Precipitation occurs either in austenite or ferrite grains. Precipitation which forms in austenite, whether or not they influence grain growth and recrystallization, usually grow up to be too large to strengthen the structure (33)**.** The precipitates formed in austenite do not contribute to the precipitation strengthening in the ferrite. However, only a portion of the available precipitates is formed in the austenite. The alloys remaining in solution become available for precipitation during the austenite to ferrite transformation or subsequently from the ferrite, and the particle size is then sufficiently small (about 10nm or less) to cause appreciable dispersion (precipitation) hardening $^{(34)}$.

The experimental values of precipitation strengthening component, **σp**, of the nominal yield strength in M Pa were determined by the difference between the observed yield strength and the value predicted by equation (5).

The effects of both V-and Ti-micraddition on the value of the precipitation strengthening component of steels with 0.20–0.25% C is illustrated in **Figure 12**.

This figure reveals increase of precipitation

Strengthening as either Vor Ti content increases. It is also noticed that V-microaddition is more effective in increasing the precipitation strengthening comparing with Ti-microaddition. Whereas microalloying of steel containing 0.21% C with 0.12% Ti was found to induce precipitation strengthening of 100 M Pa, the same level of V- microaddition (0.12% V) resulted in higher precipitation strengthening component of 121M Pa. Higher Ti content of 0.20% induced precipitation strengthening of 151M Pa, whereas then early same level of V-microaddition (0.22% V) induced higher precipitation strengthening component of 192M Pa.

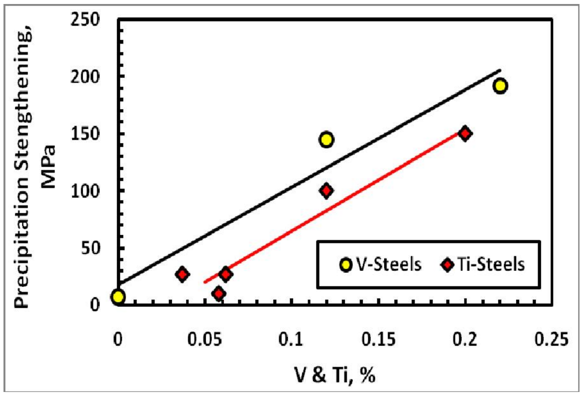


Fig. 12: Effect of both V-and Ti-microadditions on the precipitation strengthening of steels with 0.20–0.25% C.

This precipitation strengthening effect of V-or Ti-microaddition increases with increasing the carbon content, as shown in **Figure 13.**

The effects of carbon content on the value of the precipitation strengthening component due to adding 0.1% V or Ti are illustrated in **Figure 14.** This figure clarifies the significant precipitation strengthening.

Of either V-and Ti-micro additions which increases.

By increasing the carbon content. Moreover, this figures also clarifies the higher precipitation strengthening of V-micraddition comparing with Ti-microaddition.

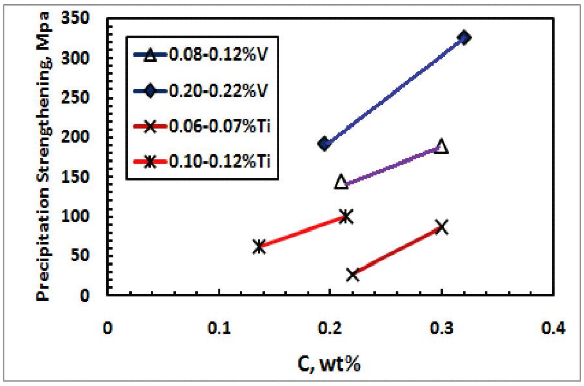


Fig. 13: Effect of carbon content on the precipitation strengthening of V-and Ti-microaalloyed steels.

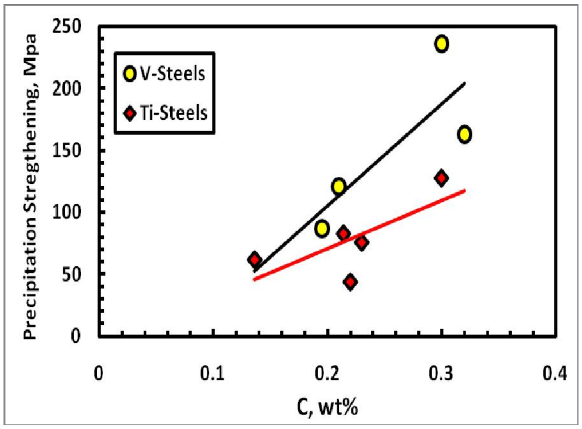


Fig. 14: Effect of carbon content on precipitation strengthening of 0.1% vanadium or titanium additions.

Economic considerations

Microalloyed high strength low alloy steels have yield strength higher than hot rolled weldable carbon steels. However, the use of microalloying elements increases the production cost. On the other hand, increasing the yield strength of steel reduces the weight of steel used as concrete rein forcing bars. The key factor is the benefits both to steel producers and steel users from substitution the microalloyed steels instead of carbon steels.

In the present work, all investigated steels were produced using the same conventional electric arc furnace (EAF) production route and the conventional hot rolling practice with the same reheating and finishing conditions. The only different parameter is the addition of ferrovanadium in V-microalloyed steels or ferrotitanium in Ti- microalloyed steels. So, for the same base composition, the additional production cost for V-or Ti-microalloyed steels is no more than the price of vanadium or titanium additive.

Aiming at producing high strength steel rebars having yield strength level of 550M Pa, steel with base carbon content of 0.21% and either 0.12%V (Steel V1) or 0.12% Ti (Steel T7) can realize this strength requirement.

For economic calculations, these two microalloyed steels can be compared with non-microalloyed C- steel with the same base carbon content of 0.21% (Steel X2). These three steels have approximately the same base composition.

The following simplified calculation illustrates the benefits both to steel producers and steel users resulting from producing and using either conventional C-steel or microalloyed steels. The input costs are based on world average costs for producing ametrictonne of deformed rein forcing bars using the EAF route and conventional hot rolling practice with the ferrous scrap at $350/ton, billet at $520/ton.

Cost of non-microalloyed C-steel, V-microalloyed steel and Ti-microalloyed steel, $ /ton.

	C-steel	**V-steel**	**Ti- steel**
Base	580	580	580
Microalloying element	-----	40	15
Production cost	580	620	595
Selling price	640	700	700
Steelmaker’s profit	60 (10.3%)	80 (12.9%)	105 (17.6%)

By substituting a stronger microalloyed steel (YSMA) for commodity carbon steel (YSC), the resulting weight reduction (WRED) can be calculated according to the following approximate formula. [36]

WRED=1–(YSC/YSMA)1/2 (6)

Using this formula, the resulting weight reduction due to substitution V-microalloyed steel (Steel V1) or Ti-microalloyed steel (Steel T7) instead of non-microalloyed C-steel (Steel X2) can be calculated:

WRED for V-microalloyed steel=1–(393/559)1/2=0.16 or 6%.

WRED for Ti-microalloyed steel=1–(393/559)1/2=0.16 or 16%.

Consequently, the consumer can use 0.84 ton of either V-or Ti-microalloyed steel instead of 1 ton of non-microalloyed C-steel.

2.7 Material cost to consumer, $

1tonnon-microalloyed C-steel=640

0.84 ton V-microalloyed steel=588
0.84 ton Ti-microalloyed steel=588

Cost of 0.84 ton of either V- or Ti-microalloyed steel for the user is less by $52 or 8%.

By using less steel of high strength V-or Ti-microalloyed steel, the consumer saves money in material cost (8%). Additional savings are: lower transportation and fabrication cost.

By producing high strength V-or Ti-microalloyed steel instead of non-microalloyed C-steel, the steelmaker increases his profit from 10.3% when producing on-microalloyed C-steel to 12.9% when producing V-microalloyed steel and 17.6% when producing Ti-microalloyed steel. Consequently, the steelmaker increases his profit by 33% and 90% when switch to produce V-microalloyed and Ti-microalloyed steel bars, respectively.

From the preceding calculation results, it is evident that producing Ti-microalloyed steel bars is more profit than V-microalloyed steel bars for the steel maker. This because ferrovanadium is more expensive than ferrotitanium with the result of increasing the production cost of V-microalloyed steel bars comparing with Ti-microalloyed steel bars having the same microalloying content. To reduce the production cost and enhance the cost- effectiveness of V-microalloyed steel bars, it is recommended to use ferrovanadium bearing nitrogen. Using such Vn microalloying technique can reduce the vanadium additive and consequently reducing the production cost.

Conclusions

From the results of this study, the following conclusions can be deduced.

Microaddition of low carbon steel (0.23% C) with 0.2% Ti is effective to attain steel with yield and ultimate tensile strengths of 637 and 733M Pa, respectively. Where as microaddition of 0.2% Vintosteel with higher carbon content (0.32% C) results in higher yield and ultimate tensile strengths levels of 799 and 957M Pa, respectively.

The much high strength increments obtained in V-and Ti-microalloyed steels are accompanied with slightly decrease in elongation from 22% (for steel with 0.23% C and 0.2% Ti) into 18% (for steel with 0.32% C and 0.2% V).

There are linear correlations in yield strength-hardness and ultimate tensile strengths-hardness relationships in the investigated on-microalloyed, V-microalloyed and Ti-microalloyed steel sat the investigated chemical composition range.

V- and Ti-microalloying is positive in obtaining steels with higher elongation comparing with the non-microalloyed steels of the same levels of hardness, yield strength and ultimate tensile strength.

Ti-microalloying is more effective than V-microalloying ingrain refinement, while V-microalloying is more effective than Ti- microalloying in precipitation strengthening.

Replacing non-microalloyed C-steel with higher strength level (550M Pa YS) V-or Ti-microalloyed steel bars using the EAF route and conventional hot rolling practice improves the profitability of both the steelmaker and the steel user. However, producing Ti-microalloyed steel bars is more profit than V-microalloyed steel bars for the steelmaker.

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