

## Development of micro alloyed structural steels in secondary steel sector using induction melting furnace and controlled rolling route

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Micro alloyed steels with mild steel base were produced through induction furnace and controlled rolling route to produce ribbed bars used in constructions. The aim was to introduce micro alloyed steels in the secondary steel sector to produce all sections of structural steels, thus countering the limitation of TMT process which is considered to be suitable only for round sections. Mainly, % vanadium and % niobium were varied in trial heats. Combinations of vanadium-nitrogen were also tried. Total 12 heats were made using induction melting furnace. Castings in the form of ingots of 88×112×1400 mm were made which were further rolled to 12 mm bars with different cooling parameters. Commonly, 12 mm CTD bars result on 450 N-mm<sup>-2</sup> UTS and 15% EL, while standard 12 mm TMT bar produces 650 N-mm<sup>-2</sup> UTS and 25%EL. Micro alloyed steels with vanadium and niobium employing conventional air cooling on bed produced better results for strength and ductility values as compared to TMT bars. Neither twisting nor water cooling/quenching was required. The best cost effective combination of 790 N-mm<sup>-2</sup> UTS, 590 N-mm<sup>-2</sup> YS, 23% EL and 59% RA was obtained with low % vanadium.

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Major trend in development of metallurgy of iron and steel is directed towards increase of useful engineering properties and cost savings. These are two major concerns in structural application also. Special features looked into are: High strength to weight ratio, good weldability and cost effectiveness. Commonly structural steels at present have yield limit of around 410 N-mm<sup>-2</sup>. In order to attain reasonable material saving, it is necessary to use structural steels with increased strength properties and a yield limit of at least 490 N-mm<sup>-2</sup>. Such, yield limit can be achieved either by an increase of carbon percentage or through a special process, e.g., TMT or by micro alloying<sup>1</sup>. Unfortunately, even more stringent requirements for weldability do not allow an increase of carbon content and TMT process requires capital due to costly plant and accessories.

A reasonable way of attaining yield limit of 490 N-mm<sup>-2</sup>, is by micro alloying of steels, i.e., utilisation of precipitation hardening and strengthening due to ferrite grain refinement<sup>2</sup>. Cost control requires low alloying additions without sacrificing high strength requirements. The combination of these two coined the term: high strength low alloy (HSLA) steel. These steels are generally produced with emphasis on

mechanical property requirements<sup>3,4</sup>. Traditionally, low carbon mild steel has been used for structural steel (in riveted, bolted or welded joints) in the form of shapes, plates and bars. Such steel, for example ASTM A36, containing up to 0.29% carbon and up to 1.20% manganese, has a minimum yield strength (YS) of 260 N-mm<sup>-2</sup>. Similarly, low carbon sheet steel traditionally been used in automobiles; e.g., hot rolled SAE 1010 steel, having 0.08-0.13% carbon and 0.30-0.60% manganese, has a minimum YS value of about 200 N-mm<sup>-2</sup>. HSLA steels evolved from this carbon steel base. HSLA steels may be defined as steels having YS of over 280 N-mm<sup>-2</sup> with alloying additions designed to provide specific desirable combination of properties such as strength, toughness, formability, weldability and atmospheric corrosion resistance.

In the historical developments listed chronologically<sup>5</sup>, there was mention of high strength with cost control achievable through direct rolling, use of water, reduction of alloying and processing costs<sup>6</sup>. HSLA steels find applications as automotive structural components, pipelines for oil and gas systems and for construction industry<sup>7</sup>.

Addition of small quantity of niobium (Nb) to carbon manganese mild steel has enabled the production of material<sup>8</sup>. Addition of vanadium can

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produce similar effects but a greater amount is required. Titanium is also used for this purpose. Effect on grain refinement increases in the order of Ti, V and Nb additions, whereas, precipitation strengthening effects increase<sup>9,10</sup> from Nb, V to Ti. In a study<sup>11</sup>, it was found that extensive niobium carbides precipitate in austenite upon cooling in the range of 830-600°C before transformation to ferrite begins. Such precipitate is later inherited by transformed ferrite resulting in a considerable increase in hardness of ferrite<sup>12</sup>. Physical metallurgy of micro alloy additions of vanadium and niobium, and of structure-property relationship in plain carbon steels has already been established.

A small addition of vanadium (0.1%) in presence of nitrogen, increases the strength by about 20% due to the formation of dispersion of fine particles of vanadium carbide nitrides V(CN) in ferrite during cooling<sup>1,13,14</sup>. Strengthening from vanadium averaged between 10 and 15 N-mm<sup>-2</sup> per 0.01% V addition<sup>15</sup>.

Objective of controlled rolling is to achieve a very fine ferrite grain size. It helps to increase the yield strength, ductility and toughness. Ferrite grain size of ASTM 5-6 was reported on rolling in the range of 960-894°C, 10 passes for 46% reduction, while rolling in the range of 960-840°C, 20 passes for 73% reduction presented<sup>16</sup> GS of 7-8.

Encouraged by various laboratory results in India, industrial scale trials were first made of Nb containing steel in 1972 at SAIL's Rourkela Steel Plant. A large volume of micro alloyed steels are produced in the form of rolled flat products or bars due to their cost effectiveness *vis-à-vis* property levels. In real terms, techno-economical benefit can be judged by the term "Strength Specific Cost".

### Strength Specific Cost (SSC)

Strength specific cost is considered to be an important factor for selection or development of a material. It is expressed in terms of total cost incurred per tone of finished product to raise per unit strength (UTS) of a material from a base value. Total cost incurred may include all direct and indirect cost components. The base UTS value for 12 mm diameter mild steel structural ribbed bar is around 410 N-mm<sup>-2</sup>. TMT bars of 12 mm diameter having acceptable metallurgical quality presents a value of 650 N-mm<sup>-2</sup>. If an amount of Rs 'X' is to be incurred per tone to produce the TMT bars, then SSC would be X/(65-41) or X/24. A lower value of SSC is desirable when two materials are to be compared.

Until recently, plain carbon mild steels with varying carbon contents were used for common constructional job. With the advent of thermo mechanical treatment (TMT) process and its application to mild steel rods, attainment of higher strength values become achievable. Yield strength values of common mild steels are 370-470 N-mm<sup>-2</sup>, whereas, that for TMT steels are 550-650 N-mm<sup>-2</sup>. This improvement in YS values shall be responsible in tonnage saving of constructional materials. But in turn may be offset by high cost of TMT plant and accessories. Moreover, it is also understood that TMT process is applicable to round sections only. It is also difficult to obtain desired microstructure of ribbed bars to designate those as proper TMT bars. There are structural steels designated as TMT but have normal ferrite-pearlite microstructure with stray bainite at limited areas of surface. A reasonable percentage of tonnage TMT steel bars are available in the market which fall into this category.

The cheaper alternative does not always provide proper metallurgical characteristics. Hence micro alloying was adopted to produce structural steels at lower cost and of consistent quality in secondary steel sector comprising induction furnaces and re-rolling units. The present paper is aimed at the following objectives: to lower down the cost of production of high strength ribbed bars; apply high strength concept to all sections and size of constructional steels e.g. angle, channel, girder, etc., which may lead to considerable material saving and hence cost reduction; provide the steel users of our country (India) the value for their money by replacing TMT bars with cheaper HSLA bars and other sections having compatible and consistent property levels; adopt induction melting furnace route and small rolling mill in SSI sector for production, so that, such steels can also be produced in the secondary steel sector of the country. It is believed, that production of HSLA steels requires a route that provides process flexibilities in steelmaking. Induction furnaces have never been thought for as a melting route; and reduce SSC, i.e., to attain a higher strength values at a lower cost.

### Experimental Procedure

Micro alloyed steels have been developed through induction melting furnace and controlled rolling route to replace TMT bars used for construction purposes. In order to achieve this, an induction furnace was selected for making steel ingots and a re-rolling mill

was chosen for rolling the ingots to 12 mm diameter ribbed bars. For investigation, a base chemistry given in Table 1 was selected.

The percentages of both vanadium and niobium were varied. With the aim of having nitrogen content as 150 ppm in some heats, a total of 12 heats were cast. Melting was done in a 500 kg (converted to 250 kg) induction melting furnace, 3½"×4½" sized pencil ingots were cast and rolled to 12 mm diameter ribbed bars. Three different sets of cooling parameters of rolled products were adopted. One set was made with full water quenching, as applied in TMT production (WQ). One large set was made without water cooling. It was air cooled on cooling bed. One bar from each heat of this set was twisted after cooling [CTD (AC)] and rest was kept as it is (AC). The third set was again water cooled, but with much less water as compared to the first set (WC), as shown in Table 2.

## Results and Discussion

Samples were taken from each stage of production. One test piece was cast from each heat, it was normalized and tested for chemical analysis through direct reading spectrometer, metallographic studies like micro structure, grain size and inclusion rating, hardness in BHN, mechanical tests like UTS, YS, %EL and bend-rebend tests were carried out. Tests pieces were cut from each heat of 4 sets of rolled products and each set was tested for microstructure, hardness, UTS, YS and %EL. Figures 1a-1f depict the microstructure of trials of phosphorus, vanadium and a combination of vanadium and nitrogen. Figures 2a-2c give the microstructure of WQ, AC and WC rolled product, respectively. The results have been presented in Table 3 for inclusion rating and Table 4 through Table 9 for mechanical tests.

### Scanning electron microscopy (SEM)

Scanning electron microscopic analyses of fractured surface of tensile test specimens were

Table 1 — Base chemistry of steel ingots

	%C	%Si	%Mn	%S	%P	%Cr	%Ni	%Mo	%Cu
Min.	0.20	0.25	0.80	--			-----traces-----		
Max.	0.25	0.35	1.00	0.04	0.04				

Table 2 — Four different sets of trial

Set	Heat No	Designate	Post rolling treatment
A	1-12	WQ	Water quenching as in TMT
B	1-12	AC	Normal air cooling in cooling bed
C	1-12	CTD (AC)	Normal air cooling and CTD (cold twisted deformed)
D	1-12	WC	Water cooling with 50% lesser water as compared to set A

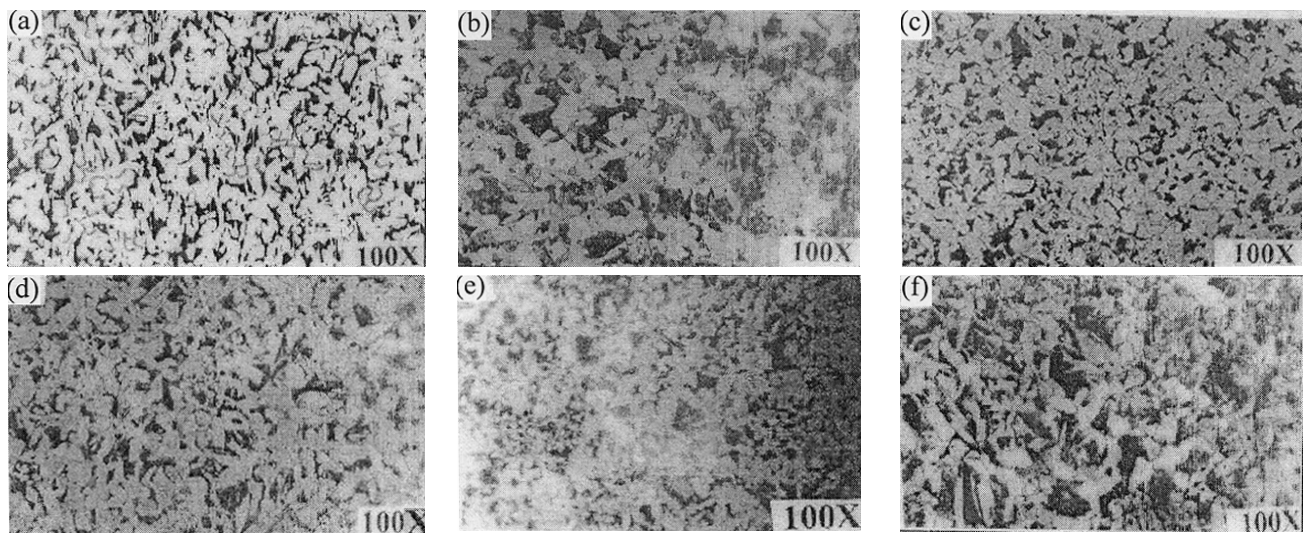


Fig. 1 — Microstructure of trial of (a) P, (b) V<sub>2</sub>, (c) V<sub>4</sub>, (d) V<sub>6</sub>, (e) V<sub>2</sub>N and (f) V<sub>4</sub>N

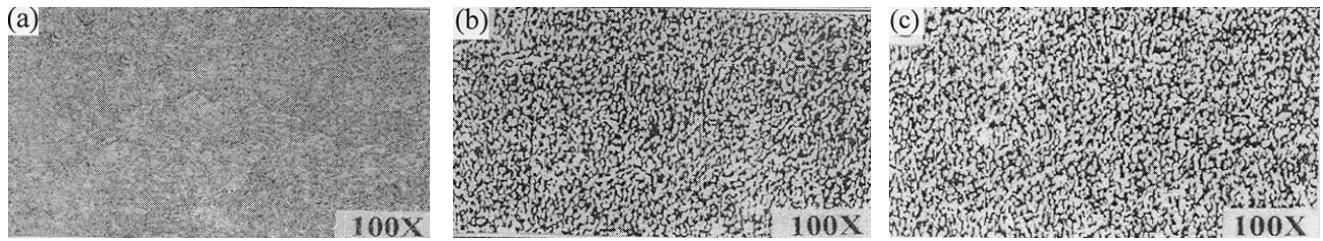


Fig. 2 — Microstructure of (a) WQ rolled product, (b) AC rolled product and (c) WC rolled product

Table 3 — Inclusion rating of trial heats

Sl.No.	Code	Inclusion rating (thin/thick)			
		Sulphide (a)	Alumina (b)	Silicate (c)	Mixed oxides (d)
1	P	1/-	0.5/-	-/-	2/-
2	V <sub>2</sub>	0.5/0.5	-/-	-/-	2/-
3	V <sub>4</sub>	1/-	1/-	0.5/-	2/1
4	V <sub>6</sub>	0.5/-	-/-	0.5/-	2/1.5
5	V <sub>2</sub> N	1/-	1/-	-/-	2.5/1.5
6	V <sub>4</sub> N	1/-	-/-	0.5/-	2.5/-
7	V <sub>6</sub> N	1.5/-	-/-	0.5/-	1/0.5
8	Nb <sub>2</sub>	0.5/-	1/-	-/-	1.5/-
9	Nb <sub>4</sub>	0.5/-	0.5/-	-/-	2/0.5
10	Nb <sub>6</sub>	1/0.5	-/-	-/-	2/-
11	30V <sub>4</sub> N	1/0.5	-/-	0.5/-	1.5/-
12	30VNb <sub>4</sub> N	0.5/0.5	-/-	-/-	1/-

Table 4 — Hardness, (BHN) values of trial heats

S. No.	Code	Test piece (NOR)	12 mm Dia rolled products			
			Water quenched (WQ)	Air cooled (AC)	CTD (AC)	Water cooled (WC)
1	P	180	200	210	286	237
2	V <sub>2</sub>	200	234	226	271	286
3	V <sub>4</sub>	153	253	237	286	271
4	V <sub>6</sub>	200	234	210	279	237
5	V <sub>2</sub> N	195	226	222	253	231
6	V <sub>4</sub> N	190	234	237	247	301
7	V <sub>6</sub> N	195	226	216	237	231
8	Nb <sub>2</sub>	172	253	258	253	247
9	Nb <sub>4</sub>	200	264	222	286	258
10	Nb <sub>6</sub>	210	226	253	247	258
11	30V <sub>4</sub> N	216	258	258	294	264
12	30VNb <sub>4</sub> N	190	264	253	286	258

performed on samples under WQ and AC conditions only.

#### SEM analysis of WQ rolled products

SEM photographs of WQ rolled products of 12 trial heats have been taken and are presented in Figs 3a-3l. In all the heats level of inclusion types A, B and C were very good. Duly the mixed oxides were high in almost all the heats. It is possible that some of these particles were present in SEM photograph and might

have affected strength and ductility values. During steel melting though measures were taken to reduce inclusion levels, some more precautions are needed to reduce the level of mixed oxides in steels. It is important to control both indigenous and exogenous inclusions to improve mechanical properties. These are possible with little care in steel melting and casting.

Samples of heat nos.1 and 2 were taken at 1500 $\times$ , that of heat no.6 at 1000 $\times$  and the rest were at 500 $\times$ . It was done to present few micrographs at higher magnification.

SEM photograph of unalloyed specimen consisted of a few coarse dimples and closely spaced large voids as can be seen in Fig. 3a. This is in accordance with the low UTS value (700 N-mm<sup>-2</sup>) and high ductility (23%). Sample of V<sub>2</sub> resulted in the fractured surface to have distribution of coarse and fine dimples and a few large voids (Fig. 3b at 1500 $\times$ ) giving a high UTS (810 N-mm<sup>-2</sup>) and a high ductility (24%). The surface of V<sub>4</sub> (Fig. 3c) showed fine network of micro dimples coupled with coarse and fine voids. This is because of high UTS (830 N-mm<sup>-2</sup>) and a low ductility (16%). Figure 3d presents the SEM picture of the specimen of V<sub>6</sub> and shows a few coarse dimples and large voids and presence of some fine particles. This might have resulted in low UTS (740 N-mm<sup>-2</sup>) and moderate ductility (20%).

In its SEM photograph, specimen of V<sub>2</sub>N contained a few fine and coarse dimples and closely spaced voids with a fine network (Fig. 3e). There was a huge void having some particles embedded in it. The result was a good UTS (780 N-mm<sup>-2</sup>) and a high ductility (24%). In Fig. 3f (at 1000 $\times$ ), tensile specimen of V<sub>4</sub>N has been shown depicting a fine network of micro dimples and coarse voids. There were fine voids also. This produced high UTS (830 N-mm<sup>-2</sup>) and a moderate ductility (20%). The specimen of V<sub>6</sub>N has produced the SEM, which has been shown in Fig. 3g and shows a few large voids, fine dimples and a distribution of some particles. Resultant UTS was low (770 N-mm<sup>-2</sup>) and ductility was also very low (15%).

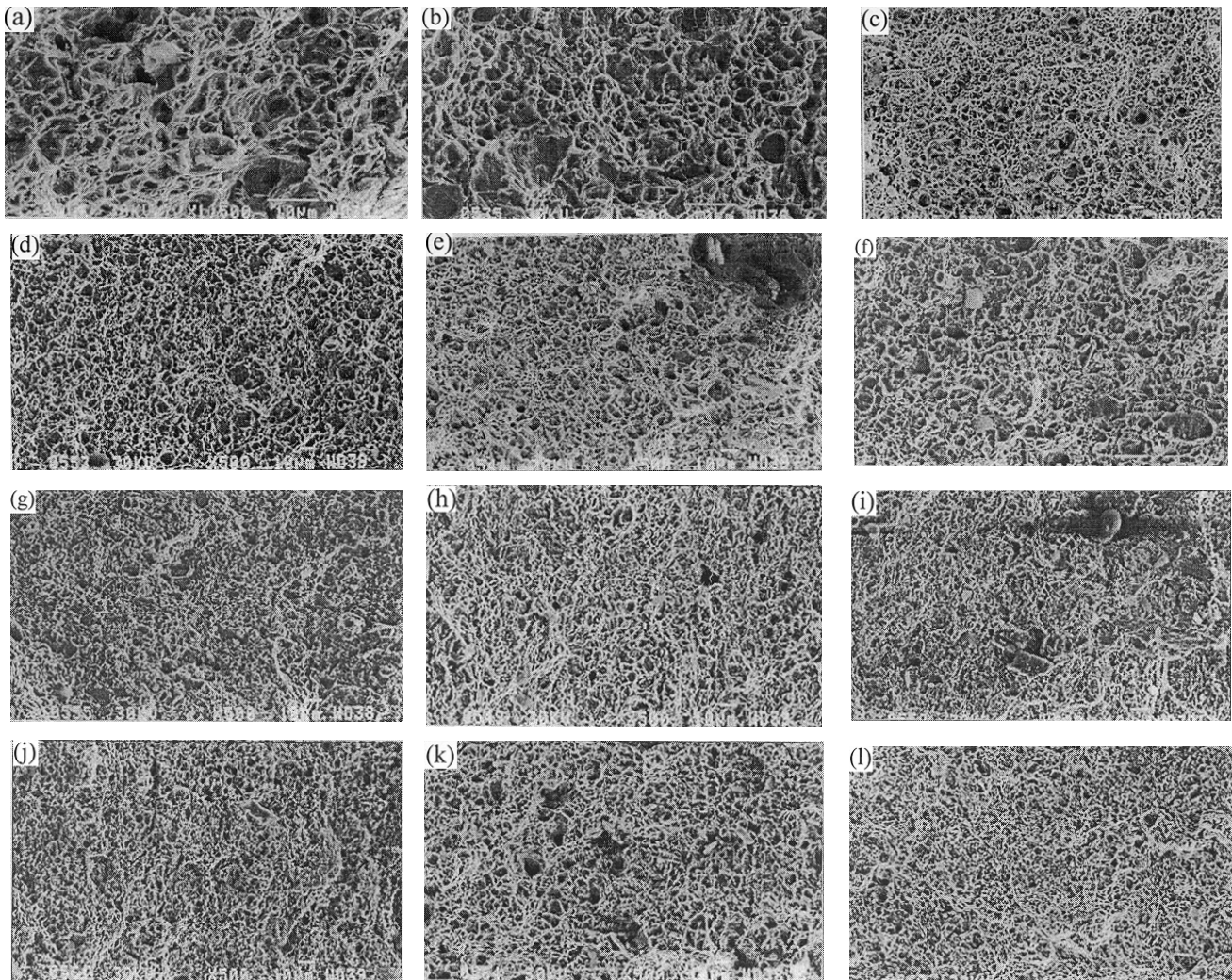


Fig. 3 — SEM photograph of WQ rolled product of (a) P, (b) V<sub>2</sub>, (c) V<sub>4</sub>, (d) V<sub>6</sub>, (e) V<sub>2</sub>N, (f) V<sub>4</sub>N, (g) V<sub>6</sub>N, (h) Nb<sub>2</sub>, (i) Nb<sub>4</sub>, (j) Nb<sub>6</sub>, (k) 30 V<sub>4</sub>N and (l) 30 VNb<sub>4</sub>N

Figure 3h presents the fractured tensile specimen of Nb<sub>2</sub> showing a few coarse dimples and distributed fine dimples. There were a few voids also. This is because of low UTS ( $720 \text{ N-mm}^{-2}$ ) and moderate ductility (21%). The sample of Nb<sub>4</sub> resulted in the SEM photograph (Fig. 3i) showing a fine distribution of micro dimples, fine radial cracks coupled with some large particles. The UTS of the sample was very high ( $860 \text{ N-mm}^{-2}$ ) but the ductility was very low (15%). The fractured SEM of the tensile specimen of Nb<sub>6</sub> had a few dimples, network of micro dimples and small voids as depicted in Fig. 3j. This produced very low UTS ( $650 \text{ N-mm}^{-2}$ ) and a good ductility (22%).

In Fig. 3k, fractured specimen of 30V<sub>4</sub>N has been shown to have coarse and fine voids. Micro dimples were also present resulting in high UTS ( $830 \text{ N-mm}^{-2}$ ) and a moderate ductility (20%). The SEM

photograph of the specimen of 30VNb<sub>4</sub>N has been shown in Fig. 3l. It shows a distribution of micro dimples and small voids. Coarse voids are extremely low. Resulting UTS was low ( $760 \text{ N-mm}^{-2}$ ) but the ductility was high (24%).

#### SEM analysis of AC rolled products

SEM photographs for AC rolled products of 12 trial heats have been taken at 500 $\times$  and are presented in Figs 4a-4l. Photomicrograph of unalloyed steel presented in Fig. 4a shows the presence of coarse dimples and small clusters of large voids, resulting in low UTS ( $690 \text{ N-mm}^{-2}$ ) and high ductility (25%). Steel containing V<sub>2</sub> resulted in the fractured surface to contain a distribution of coarse and fine dimples and large voids (Fig. 4b). The UTS of the sample was high ( $790 \text{ N-mm}^{-2}$ ) and ductility was good (23%).

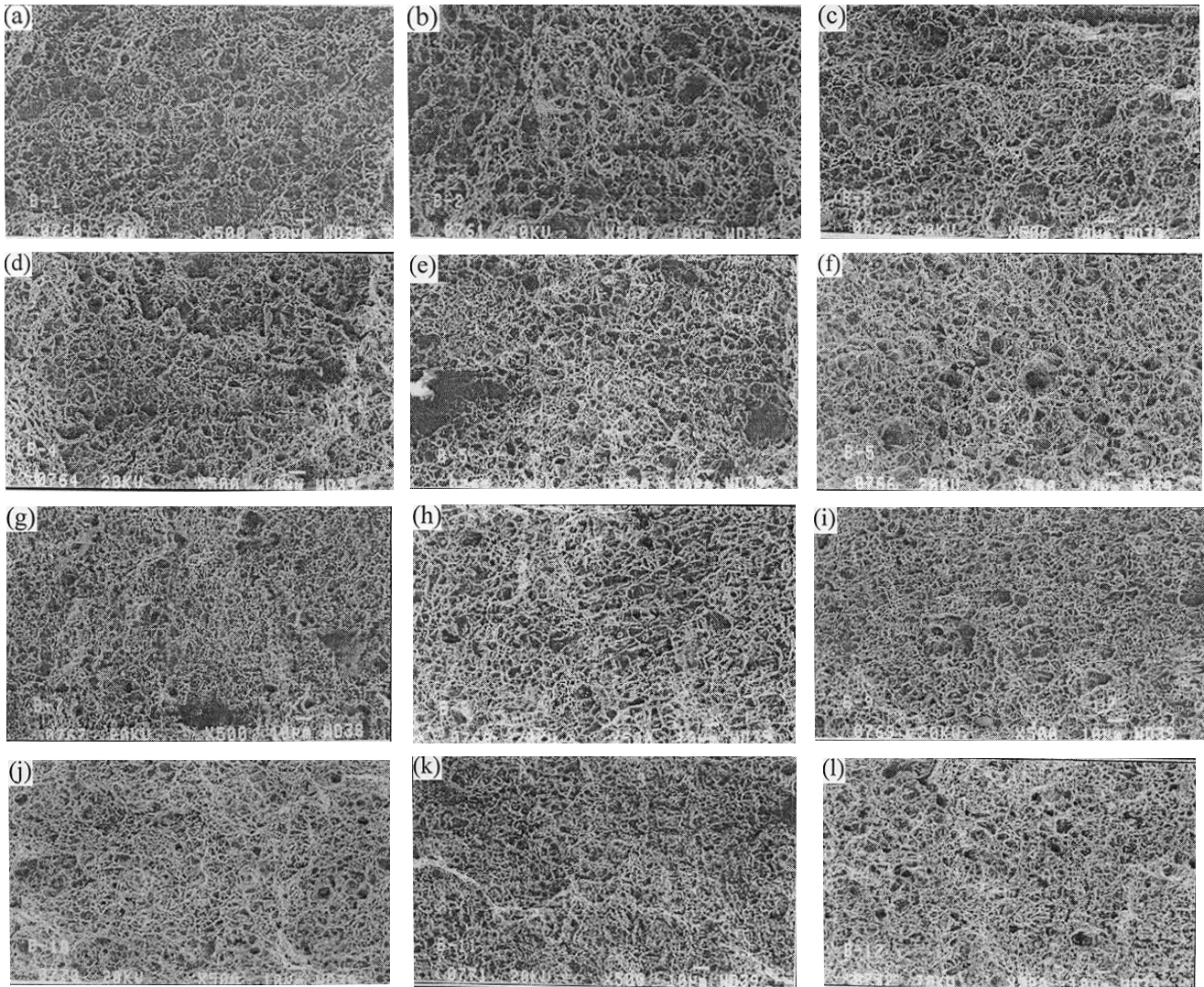


Fig. 4 — SEM photograph of AC rolled product of (a) P, (b)  $V_2$ , (c)  $V_4$ , (d)  $V_6$ , (e)  $V_2N$ , (f)  $V_4N$ , (g)  $V_6N$ , (h)  $Nb_2$ , (i)  $Nb_4$ , (j)  $Nb_6$ , (k) 30  $V_4N$  and (l) 30  $VNb_4N$

The fractured surface of  $V_4$  containing steel shows (Fig. 4c) distribution of small and large dimples, large voids and a linear cluster of voids. The resulting UTS was low ( $700 \text{ N-mm}^{-2}$ ) and the ductility was very high (28%). Figure 4d shows SEM photograph of  $V_6$  to contain small dimples and very large voids. A dipped region also seemed to have formed. UTS of the sample was the lowest ( $610 \text{ N-mm}^{-2}$ ) but the ductility was good (24%).

The SEM photograph of  $V_2N$  containing steel (Fig. 4e) presented network of small dimples, cluster of big voids and large voids. UTS of the sample was moderate ( $730 \text{ N-mm}^{-2}$ ) and ductility was good (24%). Figure 4f presented the photograph of  $V_4N$  containing sample and shows a few coarse voids coupled with network of fine dimples. There were

coarse dimples also. The UTS of the sample was good ( $750 \text{ N-mm}^{-2}$ ) while the ductility was good (25%). The sample of  $V_6N$  as presented in Fig. 4g, contained a few large voids and fine dimples. There was presence of some particles also. UTS value was very low ( $650 \text{ N-mm}^{-2}$ ) and the ductility was also low (20%).

SEM photograph of  $Nb_2$  at Fig. 4h shows network of fine and coarse dimples and large voids. This produced good UTS and ductility values,  $750 \text{ N-mm}^{-2}$  and 23%, respectively. The sample containing  $Nb_4$  presented SEM photograph as shown in Fig. 4i. It contains network of fine and coarse dimples. Large voids are also more. The UTS of the sample was very good ( $780 \text{ N-mm}^{-2}$ ) with low ductility (20%). Fig 4j presents the SEM photograph of the sample having

Nb<sub>6</sub>. It shows fine distribution of micro dimples along with some coarse dimples and small voids. Resultant UTS was very low (650 N-mm<sup>-2</sup>) with moderate ductility (22%).

The sample designated as 30V<sub>4</sub>N resulted in a SEM photograph as shown in Fig. 4k. There is a distribution of micro dimples and coarse dimples. Evidence of large void with cluster of small voids and typical bands of low lines are also present. UTS of the sample was the highest (810 N-mm<sup>-2</sup>) but the ductility was the lowest (17%). Figure 4l shows the photograph of 30 VNb<sub>4</sub>N and presents a distribution of fine and coarse dimples. Large and small voids are also there. UTS and ductility values of the sample were good at 750 N-mm<sup>-2</sup> and 23%, respectively.

#### Inclusion rating

In all the heats level of inclusion types A, B & C were very good. Duly the mixed oxides were high in almost all the heats. It is possible that some of these particles were present in SEM photograph and might have affected strength and ductility values. During steel melting though measures were taken to reduce inclusion levels, some more precautions are needed to reduce the level of mixed oxides in steels. It is important to control both indigenous and exogenous inclusions to improve mechanical properties. These are possible with a little care in steel melting and casting.

#### Mechanical properties

The results of mechanical tests have been presented in Tables 4-9. In unalloyed steel, air cooling (AC) resulted in almost equal or better strength and ductility as compared to water quenching (WQ) but

were lower than water cooling (WC) as shown in Table 1. In the cases of V combinations though strength values under AC were lower (2-13) than those under WQ, ductility values were better in AC as shown in Tables 7 and 8. Here again, UTS values were higher under WC than those obtained under WQ and AC as shown in Table 5. Though % elongation values were lower under WC than under WQ and AC, % RA values were more as shown in Tables 7 and 8.

Strength went down with increasing vanadium percentages, under almost all cooling conditions as shown in Tables 5 and 6. But %EL values were the lowest with WC and were higher under AC conditions, with the highest value obtained with V<sub>4</sub> as shown in Table 7. Vanadium produces strengthening effect through precipitation hardening and only AC enhances strength without sacrificing the ductility.

Table 6 — YS, N/mm<sup>2</sup> values of trial heats

S.No.	Code	Test piece (NOR)	12 mm Dia rolled products			
			Water quenched (WQ)	Air cooled (AC)	CTD (AC)	Water cooled (WC)
1	P	400	510	490	640	630
2	V <sub>2</sub>	430	630	590	830	800
3	V <sub>4</sub>	440	730	550	620	670
4	V <sub>6</sub>	350	640	480	640	600
5	V <sub>2</sub> N	430	650	570	-LC	690 LC
6	V <sub>4</sub> N	460	680	590	-LC	720 LC
7	V <sub>6</sub> N	600	680	510	-LC	740 LC
8	Nb <sub>2</sub>	400	490	610	600 LC	630
9	Nb <sub>4</sub>	390	760	610	-LC	740 LC
10	Nb <sub>6</sub>	360	640	500	-LC	630
11	30V <sub>4</sub> N	470	700	670	660	650 LC
12	30VNb <sub>4</sub> N	470	740	610	680	710 LC

Note: Suffix LC denotes longitudinal cracks on tensile test specimen

Table 5 — UTS, N/mm<sup>2</sup> values of trial heats

Sl.No	Code	Test piece (NOR)	Water quenched (WQ)	Air cooled (AC)	CTD (AC)	Water cooled (WC)
1	P	630	700	690	800	790
2	V <sub>2</sub>	670	810	790	860	890
3	V <sub>4</sub>	540	830	700	820	830
4	V <sub>6</sub>	510	740	610	820	720
5	V <sub>2</sub> N	650	780	730	840	850
6	V <sub>4</sub> N	590	830	750	840	830
7	V <sub>6</sub> N	610	770	650	940	850
8	Nb <sub>2</sub>	620	720	750	780	750
9	Nb <sub>4</sub>	580	860	780	870	840
10	Nb <sub>6</sub>	540	750	650	680	730
11	30V <sub>4</sub> N	500	830	810	880	820
12	30VNb <sub>4</sub> N	680	870	760	900	880

Table 7 — Percentage elongation values of trial heats

S. No.	Code	Test piece (NOR)	12 mm Dia rolled products			
			Water quenched (WQ)	Air cooled (AC)	CTD (AC)	Water cooled (WC)
1	P	30	23	25	20	25
2	V <sub>2</sub>	20	24	23	20	18
3	V <sub>4</sub>	27	16	28	17	18
4	V <sub>6</sub>	27	20	24	19	20
5	V <sub>2</sub> N	19	24	24	19	19
6	V <sub>4</sub> N	11	20	25	18	20
7	V <sub>6</sub> N	9	15	20	17	18
8	Nb <sub>2</sub>	25	21	23	10	19
9	Nb <sub>4</sub>	24	15	20	17	20
10	Nb <sub>6</sub>	21	25	22	20	19
11	30V <sub>4</sub> N	7	20	17	18	20
12	30VNb <sub>4</sub> N	18	18	24	20	16

Table 8 — Percentage reduction in area values of trial heats

S. No.	Code	Test piece (NOR)	12 mm dia rolled products			
			Water quenched (WQ)	Air cooled (AC)	CTD (AC)	Water cooled (WC)
1	P	52	57	61	26	66
2	V <sub>2</sub>	53	46	59	38	55
3	V <sub>4</sub>	63	51	57	44	64
4	V <sub>6</sub>	30	54	59	58	70
5	V <sub>2</sub> N	50	56	54	58	49
6	V <sub>4</sub> N	17	64	61	51	51
7	V <sub>6</sub> N	23	55	65	18	58
8	Nb <sub>2</sub>	48	33	66	37	67
9	Nb <sub>4</sub>	34	51	63	32	58
10	Nb <sub>6</sub>	29	54	60	60	62
11	30V <sub>4</sub> N	5	54	56	47	65
12	30VNb <sub>4</sub> N	13	39	54	45	53

Table 9 — Bend re-bend test results of trial heats

S. No.	Code	Test piece (NOR)	12 mm dia rolled products			
			Water quenched (WQ)	Air cooled (AC)	CTD (AC)	Water cooled (WC)
1	P	NC	NC	NC	LC	NC
2	V <sub>2</sub>	NC	NC	NC	LC	NC
3	V <sub>4</sub>	NC	NC	NC	LC	LC
4	V <sub>6</sub>	NC	NC	NC	NC	NC
5	V <sub>2</sub> N	NC	NC	NC	NC	NC
6	V <sub>4</sub> N	NC	NC	NC	LC	NC
7	V <sub>6</sub> N	NC	NC	NC	LC	LC
8	Nb <sub>2</sub>	NC	NC	NC	LC	NC
9	Nb <sub>4</sub>	NC	NC	NC	NC	LC
10	Nb <sub>6</sub>	NC	NC	NC	NC	LC
11	30V <sub>4</sub> N	NC	NC	NC	LC	NC
12	30VNb <sub>4</sub> N	NC	NC	NC	LC	LC

NC represent no cracks or OK and LC represents longitudinal cracks

Table 10 — Summary of results

Code	Test piece (normalised)		Microstructure			Rolled product, mechanical properties			
	VF (P)	GS	WQ	AC	WC	WQ	AC	CTD	WC
P	25	5-6	B	FP	FP	Nor	Nor		High
V <sub>2</sub>	40	5	B	FP	FP	High	High	High	Nor
V <sub>4</sub>	20	6	B	FP	FP	High	Nor	&	V High
V <sub>6</sub>	25	5-6	B	FP	FP	Low	Poor	Brittle	Nor
V <sub>2</sub> N	25	5-6	B	FP	FP	Low	Nor	L C	High
V <sub>4</sub> N	55	4-5	B	FP	FP	High	Nor		High
V <sub>6</sub> N	40	4-5	B	FP	FP	Poor	Low		Low
Nb <sub>2</sub>	40	7	B	FP	FP	Low	Nor		Nor
Nb <sub>4</sub>	40	5-6	B	FP	FP	V High	High		Low
Nb <sub>6</sub>	30	6-7	B	FP	FP	Poor	Poor		Low
30V <sub>4</sub> N	58	6-7	B	FP	FP	High	V High		Poor
30VNb <sub>4</sub> N	50	6	B	FP	FP	Low	Nor		Nor

When V+N combinations were used, similar trend as with V<sub>4</sub> was followed. All the WC samples developed LC. No appreciable improvement observed with N additions. %EL values decreased with more %V under AC and WQ. Under WQ and WC, values of %EL and %RA were lower than obtained under AC. Faster cooling enhanced strength values but reduced the ductility. Nb combinations also presented high strength and ductility values almost comparable to vanadium combinations. Different cooling conditions did not appreciably change the UTS values but faster cooling rates resulted in marked reduction in ductility as shown in Table 5.

There was no appreciable change with V+Nb+N combination having 0.28%C. All the samples (other than with V<sub>4</sub>) under CTD (AC) developed LC and resulted mostly low %EL and %RA values, though the UTS values were above 800 N-mm<sup>-2</sup>. CTD

resulted in raising dislocation density level of already stressed rolled products.

Best combination of strength and ductility values were obtained with V<sub>2</sub> (UTS: 790, YS: 590, %EL: 23 and %RA: 59) and Nb<sub>2</sub> (UTS: 750, YS: 610, %EL: 23 and %RA: 66). Typical values obtained with 12 mm + TMT of SAIL/RINL, were UTS: 650, YS: 560, %EL: 25 and %RA: 45. Summary of all the results are presented in Table 10.

#### Strength specific cost (SSC)

Commonly, a typical 12 mm diameter TMT bar of SAIL/RINL has a UTS value of 600 N-mm<sup>-2</sup> and that of an ordinary mild steel ribbed bar is around 400 N-mm<sup>-2</sup>. Assuming, similar quality of TMT bar is produced in the secondary steel sector with an annual production of 12,000 MT, total cost of the TMT plant and accessories as Rs 1.5 crores, IRR of 18% and an

expected pay back period of 5 years, the SSC may be calculated as Rs 17.50.

In case of micro alloyed steels with low %V/Nb, expected UTS level shall be around  $750 \text{ N-mm}^{-2}$ . As far as the cost factor is concerned, requirement of vanadium shall be less than niobium, because in steel scrap, usually little vanadium comes as residual, but not niobium. Additional cost of micro alloyed steels with low vanadium ( $V_2$ ) shall be around Rs 200.00. In this case, the SSC may be calculated as Rs 5.72 only, which is about 2.5 times less. Moreover, if due considerations are given and applied in the design calculations for constructional activities, then there will be more savings of constructional materials for the users of micro alloyed steels than of TMT bars. Savings can be even more in case of other sections of constructional materials, because in those cases, the difference in UTS shall be more (from  $450 \text{ N-mm}^{-2}$  to  $790 \text{ N-mm}^{-2}$ ) as the TMT process cannot be applied to the sections other than rounds and squares.

### Conclusions

In this paper, the possibility of using micro alloyed steels in the secondary steel sector to produce all sections of structural steels has been explored by studying micro structure, grain size, inclusion rating and mechanical properties like hardness, UTS, YS, %EL. The results were found to be very encouraging and countered the limitation of TMT process which is considered to be suitable only for round sections. The following important conclusions are drawn from this work:

- (i) Induction melting furnace can be adopted for production of micro alloyed ribbed bars. In steel melting, measures should be taken to reduce inclusions in steels.
- (ii) No water quenching is needed for high strength values. The properties are better than TMT bars even under normal air cooling conditions.
- (iii) Micro alloyed steel ribbed bars should not be cold twisted and deformed.
- (iv)  $V_2$  and  $Nb_2$  steels produced the best results. But lower %V steel has lower SSC value than with same %Nb.
- (v) Because of very low SSC values, lower %V micro alloyed structural steel is the best alternative for TMT bars.

### Nomenclature

TMT	= thermo mechanical treatment
GS	= grain size
ppm	= parts per million
CTD	= cold twisted deformed
UTS	= ultimate tensile strength
YS	= yield strength
%RA	= percent reduction in area
%EL	= percent elongation
BHN	= brinell hardness no.
SEM	= scanning electron microscope
LC	= longitudinal crack
AC	= air cooled
WC	= water cooled
WQ	= water quenched
SAIL	= Steel Authority of India Limited
RINL	= Rashtriya Ispat Nigam Limited
VF(P)	= volume fraction of pearlite
FP	= ferrite-pearlite
B	= bainite
NOR	= normal
IRR	= internal rate of return (financial)
UHP	= ultra high purity

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