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MICROALLOYED BAR FOR MACHINE STRUCTURAL USE

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The effects of Nb and V and hot rolling on mechanical properties were studied in laboratory melted carbon steels(0.25-0.45%C). Adequately controlled rolled Nb bearing steel showed a good combination of strength and toughness, whereas in the condition of conventional rolling or hot forging V bearing steel was more favorable resulting in moderately good toughness. Further improvement of toughness was attempted in V bearing steel by addition of Ti as an austenitic grain refining element. Utilizing these results, successful mill trials were made for the production of high strength controlled rolled Nb bearing rod and of V bearing rod for hot forging. In these products, final or intermediate heat treatment(QT) could be completely eliminated.

RECENT technical trend in rod products for machine structural use is the introduction of energy or process saving type rod where heat treatment can be eliminated (1,2). Many automotive components such as steering shaft, knuckle arm and others typically require adequate carbon content and heat treatment such as quenching and tempering to obtain the necessary properties. On the other hand, by microalloying in medium carbon steel and/or controlled rolling in bar mill, this heat treatment can be eliminated since the desired properties are obtained as rolled or as hot forged. For the development of energy saving type rod, the following technical consideration is required : establishing controlled rolling technique in bar mill (optimization of rolling temperature, speed, cooling condition, etc.) and/or optimized utilization of microalloying elements (Nb,V and Ti). There are some reports on the controlled rolling of bar products (3-5) and on the influence of microalloying elements in medium carbon steels (6-9). However, the carbon range of most of them is limited to below 0.30% and information on the optimized use of microalloying elements is not necessarily sufficient.

This paper concerns the development of microalloyed bar products in which quenching and tempering can be eliminated. In the first part, the result of laboratory experiment on the influence of Nb and V on mechanical properties in medium carbon steels (0.25 - 0.45%C) is reported from standpoint of optimization of chemistry and processing. The effect of Ti as austenitic grain refiner in V-(N) steel is also presented for the case of conventional rolling or hot forging in which addition of V is beneficial. In the second part, the results of manufacturing trials are reported for two cases of application. The first case is the as rolled rod from which a machined shaft can be manufactured without quenching and tempering. The second case is V bearing bar which can be used as hot forged without further heat treatment.

EXPERIMENTAL PROCEDURES

The steel ingots were prepared by 50kg air induction melting or 150kg vacuum induction

Table 1. Chemical composition of steels (wt%.

Series	C	Si	Mn	P	S	Nb	V	Ti	Sol.Al	T.N
I (C,Nb)	0.25/0.44	0.25	1.0	0.020	0.003	tr.	tr.	tr.	0.020	0.0060
	0.24/0.45	0.25	1.0	0.020	0.003	0.035	tr.	tr.	0.020	0.0060
	0.35	0.30	1.0	0.020	0.003	0.015/0.025	tr.	tr.	0.020	0.0060
II (V)	0.45	0.30	0.70	0.015	0.015	tr.	tr./0.140	tr.	0.020	0.0060
III (Nb,V)	0.33	0.25	1.10/1.87	0.007	0.020	tr.	0.05	tr.	0.020	0.0060
	0.33	0.25	1.08/1.84	0.007	0.020	0.025	tr.	tr.	0.020	0.0060
IV (Ti,V,N)	0.45	0.30	0.80	0.015	0.020	tr.	0.10	tr.	0.020	0.0030/0.0097
	0.45	0.30	0.80	0.015	0.020	tr.	0.10	0.006/0.026	0.020	0.0031/0.0122

melting. Chemical composition of steels is shown in Table 1. The base composition of steels was 0.25/0.45%C - 0.60/0.80%Mn - 0.020%sol.Al. The maximum content of Nb,V and Ti was 0.040%, 0.160% and 0.036%, respectively. The content of total N in V or V-Ti steels was varied from 0.0020 to 0.0160%. The blocks which had been hot rolled to 80mm thickness and air cooled were reheated to the temperature range from 1050°C to 1200°C, and were hot rolled in 20mm thick plate with various finishing rolling temperature from 800°C to 1150°C. Mechanical properties of the steels were evaluated by the tensile test, full size V or U notch Charpy impact test and rotating bending type (10mm dia.) fatigue test. Solubility product of Nb(CN) was obtained on steels of Series I by analyzing electrolytically extracted precipitates from specimens heated to 900-1300°C for 1 hour and subsequently water quenched. Finally trial manufacture of energy saving type rod in bar mill was made based on the experimental results.

LABORATORY RESULTS AND DISCUSSIONS

NIOBIUM AND VANADIUM IN MEDIUM CARBON STEEL - The effects of Nb addition on tensile and Charpy V notch impact properties of controlled rolled 0.33%C - 0.30%Si - 1.10%Mn - 0.020%sol.Al - 0.0055%N steels are shown in Fig.1. The yield and tensile strength increase with Nb. However, The increase of strength diminishes above about 0.025%Nb. The impact property is remarkably improved with Nb for 1100°C reheating. Since at this temperature a part of Nb can remain as precipitates, both grain refinement and precipitation hardening can be effective.

Solubility products are shown in Fig.2. In this figure, the dashed line is the results by Irvin et al (10) for low carbon steels and the solid line is the results of the present investigation for medium carbon steels. The present solubility product is expressed by the following equation :

$$\log [Nb][C+12/14N] = -5576/T + 1.53 \quad \text{Eq.(1)}$$

It can be concluded that in medium carbon steels, Nb is somewhat more soluble in austenite in comparison to low carbon steels.

The influence of V content on tensile and Charpy U notch impact properties of controlled rolled 0.45% C- 0.30%Si - 0.70%Mn - 0.020%sol.Al - 0.0080%N is shown in Fig.3.

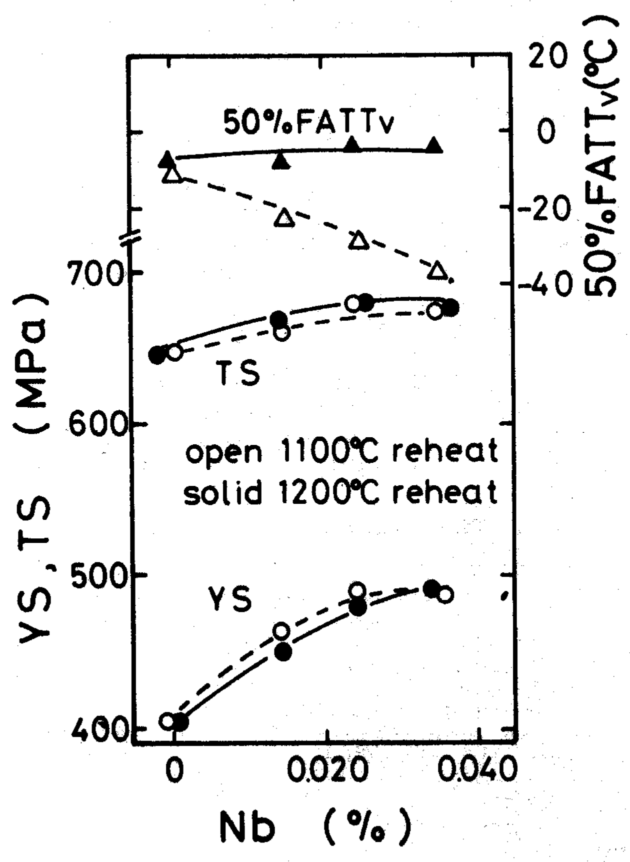

Fig 1. The effect of Nb on tensile and Charpy V notch impact properties (0.35%C - 0.30%Si - 1.0%Mn)

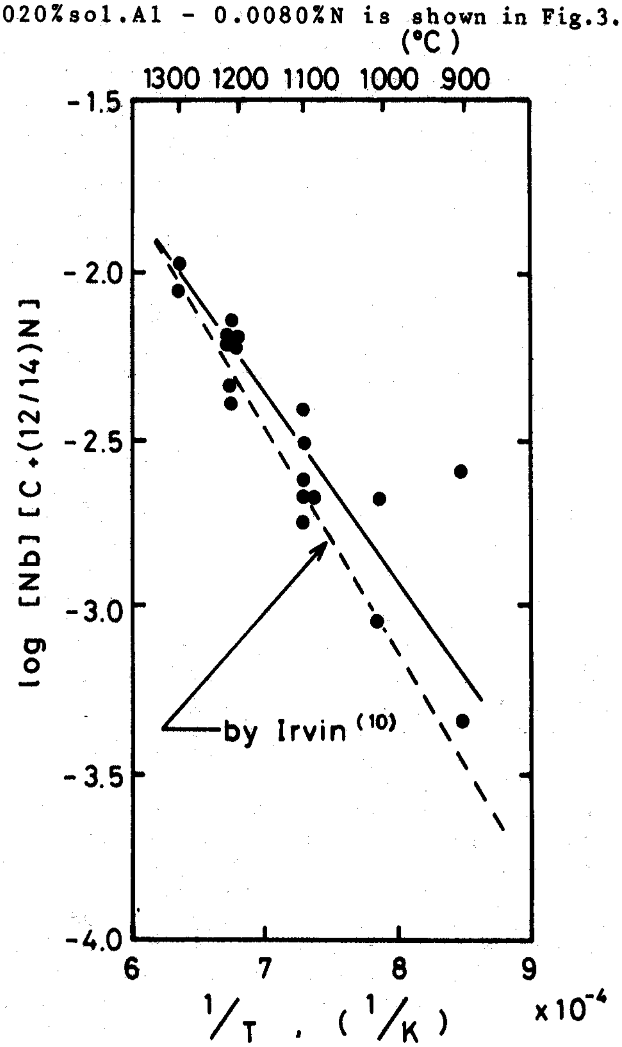

Fig 2. Solubility products for Nb(CN) in austenite. (0.25/0.45%C - 0.25%Si - 1.0%Mn - 0.015/0.035%Nb)

Yield and tensile strengths increase linearly with V content up to 0.140% unlike the Nb bearing steels. Difference of characteristic effect on impact property between Nb and V is shown in Fig.4. Strength level of steels is varied with Mn content. Generally, impact property is deteriorated corresponding to increase of strength. However, with adequate controlled rolling, deterioration of impact property does not take place and the 50%FATT in

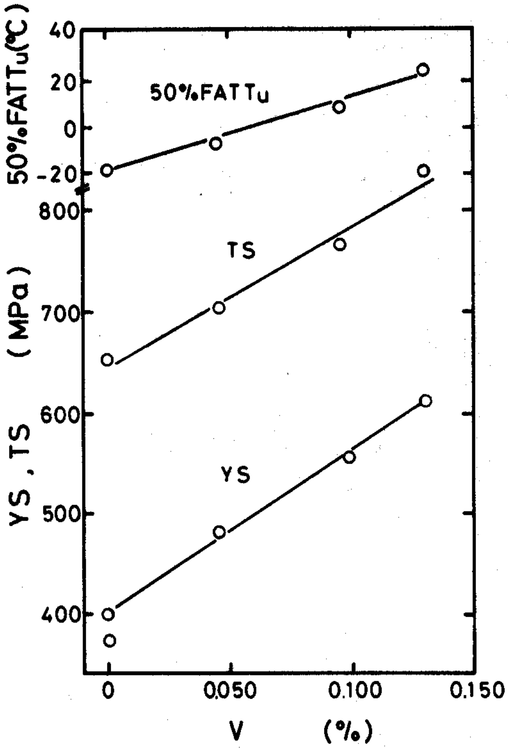

Fig 3. The effect of V on tensile and Charpy U notch impact properties. (0.45%C - 0.30%Si - 0.70%Mn)

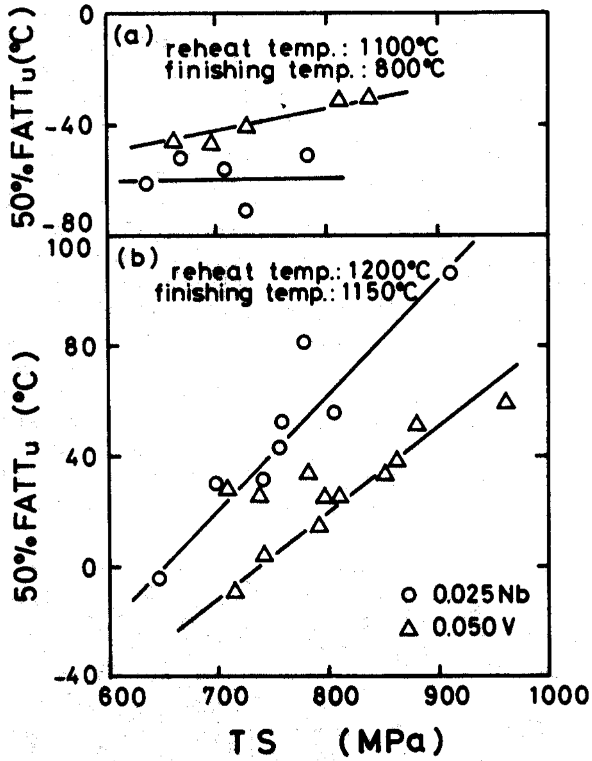

Fig 4. The effect of Nb and V on impact property in two rolling conditions. (0.33%C - 0.25%Si - 1.1/1.9%Mn)

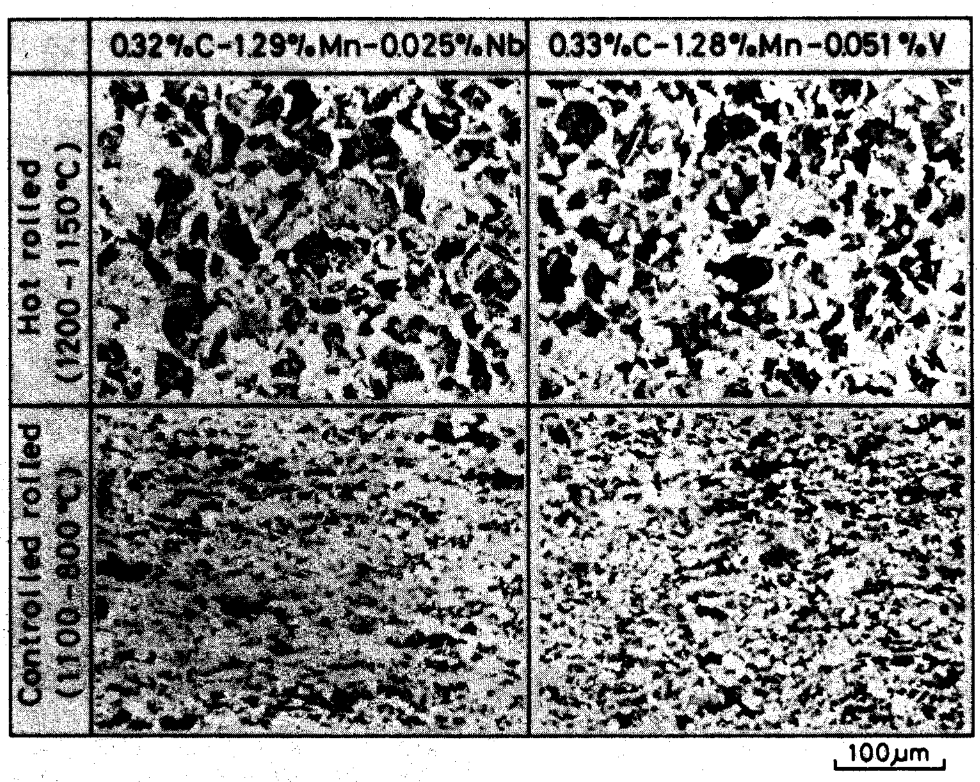

Photo 1. Microstructure of Nb and V bearing steels.

Nb bearing steels is far better than in V bearing steels. On the other hand, in conventional rolling, V bearing steels stably show moderately good impact property.

The difference of the effect between the two elements can be explained by their different effect on microstructure as shown in Photo.1. With controlled rolling the microstructure of Nb bearing steel is finer. On the other hand, with high temperature finishing, the microstructure of V bearing steel is homogeneous and finer whereas that of Nb bearing steel is inhomogeneous. These effects on microstructure are similar to those in low carbon steels and can be reduced to the well known effects of these elements on recrystallization kinetics of austenite and on transformation behavior. In practical consideration, V is more favored element for particular bar mills where controlled rolling can not be accommodated. When some measures are taken to give adequate degree of controlled rolling, Nb bearing steel demonstrates superior low temperature toughness.

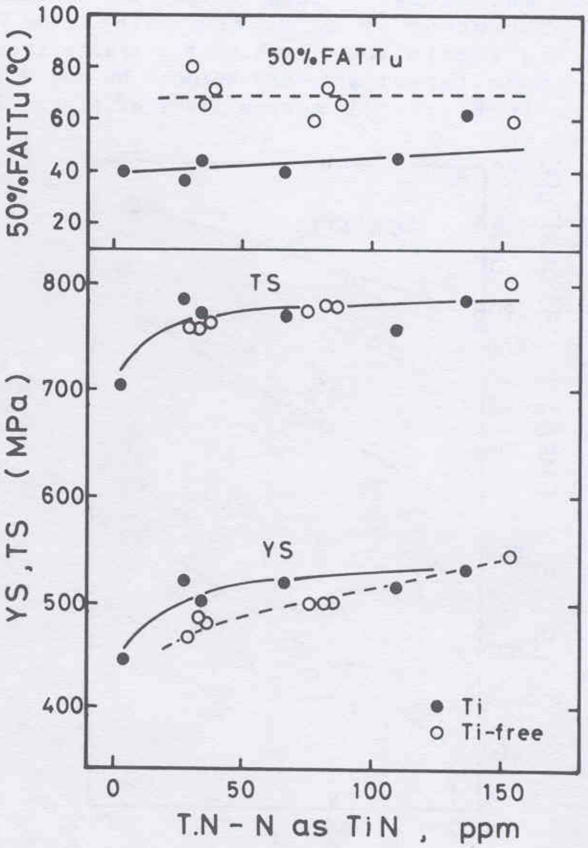

Fig 5. The effect of T.N (Ti free steels) or T.N-N as TiN (Ti added steels) on mechanical properties of 0.45%C - 0.80%Mn -0.10%V steels. (reheating temp. 1200°C, finishing temp. 1150°C)

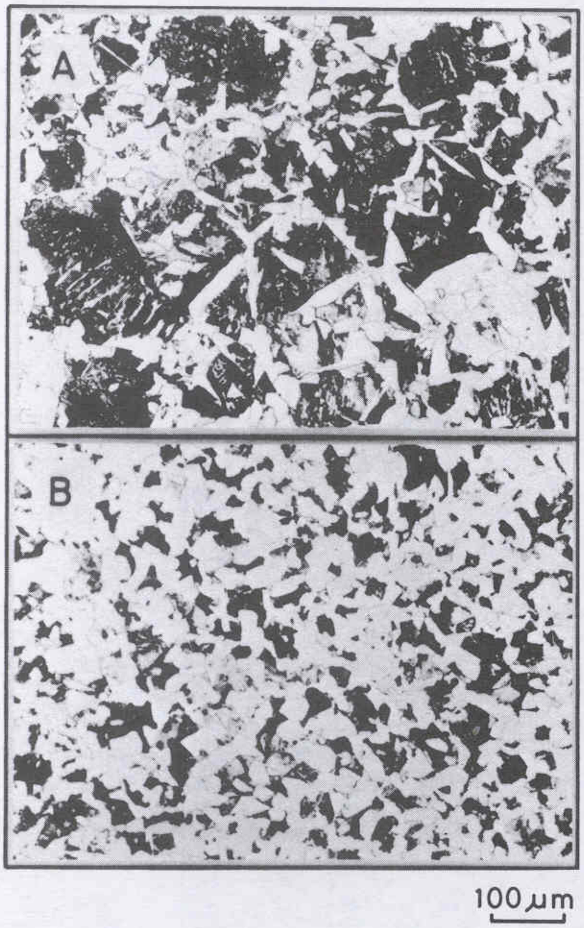

Photo 2. Microstructure of hot rolled (A)Ti free and (B)V-Ti steels. (0.33%C - 0.24%Si - 1.1%Mn - 0.10%V, reheating temp. 1200°C, finishing temp. 1150°C)

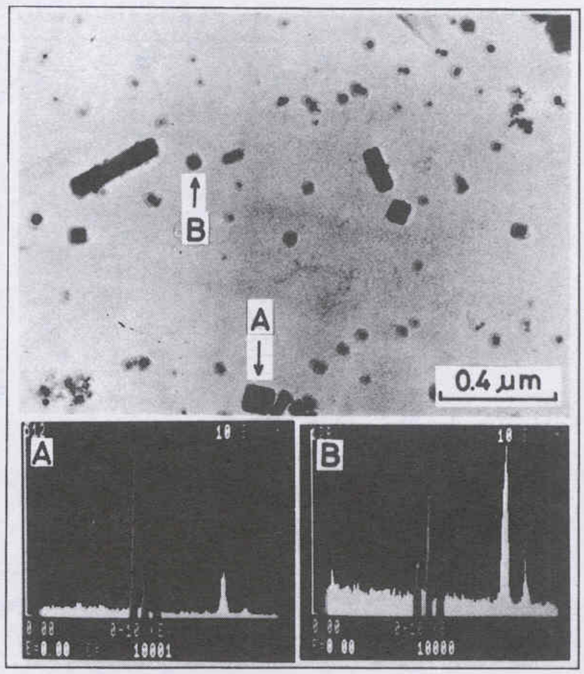

Photo 3. Identification of Ti-V-N precipitates by EDS. (0.32%C - 0.26%Si - 1.45%Mn-V-N)

TITANIUM AS GRAIN REFINING ELEMENT - The refinement of initial austenite grain size at reheating temperature is effective to improve impact property especially in conventional rolling or hot forging. It is well-known that a small amount of Ti is effective to refine austenite grain because of the stability of TiN precipitates at the reheating temperature. By addition of a small amount of Ti to V bearing steels, improvement of impact property of conventionally rolled or hot forged steels was intended. However, possibility of lowering of strength due to reduction of VN precipitates was anticipated because a part of N was combined with Ti. Therefore, a study was carried out on the influence of balance of Ti and N content on tensile and Charpy U notch impact properties of 0.45%C - 0.80%Mn - 0.10%V - Ti steel. The result is shown in Fig.5. The abscissa of Fig.5 is the total N in Ti-free

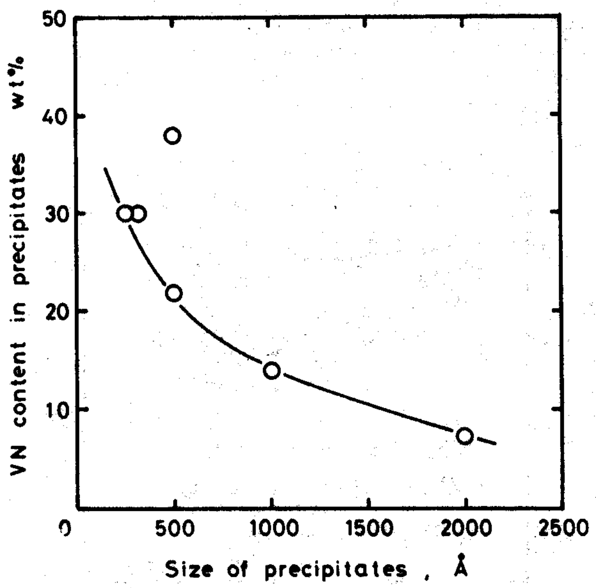

Fig 6. Relation between VN content and size of Ti-V-N precipitates.

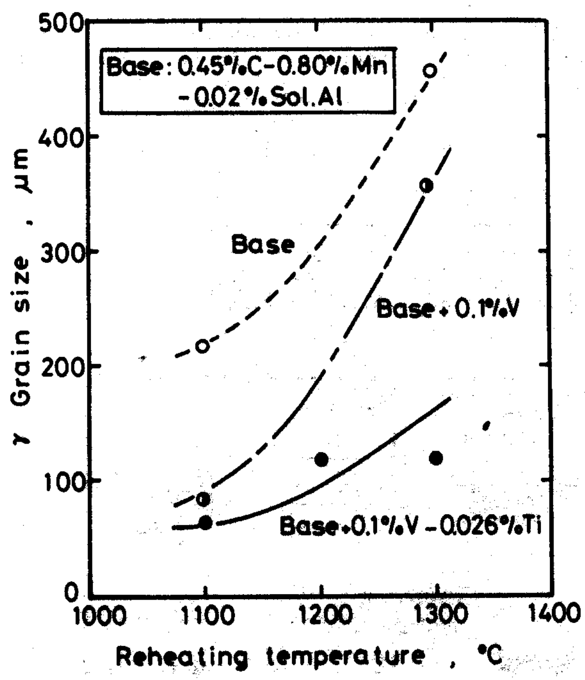

Fig 7. The influence of V and Ti on austenite grain size.

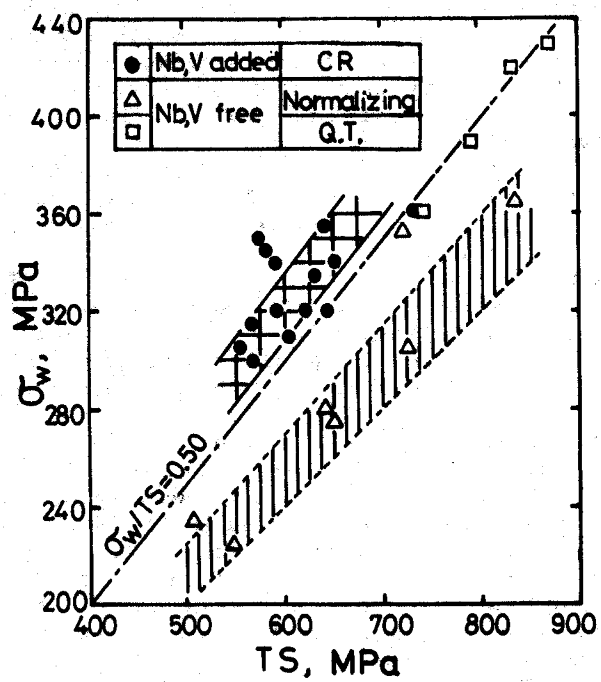

Fig 8. The relation of fatigue limit(σ_W) and tensile strength in controlled rolled microalloyed steels and plain carbon steels.

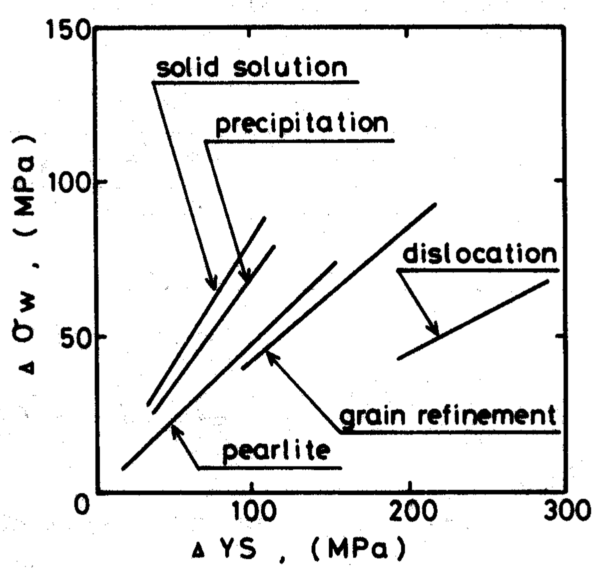

Fig 9. Quantitative analysis on the various strengthening factors and the increment of fatigue limit.

steels and the total N less the N as TiN in Ti bearing steels on the assumption that all the Ti combines with N in stoichiometric relationship. As the T.N or the (T.N-N as TiN) increases, yield and tensile strengths increase. It is found that to a first approximation, strength is controlled by the (T.N-N as TiN) in V bearing steels with a small amount of Ti. It is concluded that the (T.N-N as TiN) is to be secured above 0.0060% to obtain a sufficient increase of strength in V-Ti steels. The steels with a small amount of Ti have excellent yield strength and impact property combination as compared with Ti free steels because of the grain refinement, as shown in Photo.2.

The observation of precipitates in high magnification was performed by means of the carbon extraction replica using an analytical electron microscope that enables one to identify the very fine precipitates. The precipitates were identified as Ti-V-N by EDS as shown in Photo.3. X-ray diffraction analysis of insoluble Ti precipitates also supported this result. Quantitative analysis of V content in Ti-V-N precipitates was attempted. The results is shown in Fig.6. The fraction of V in Ti-V-N precipitates was 0.2-0.4 and larger V fraction was measured in the finer precipitates around 200 to 500Å. The reheated austenite grain size of plain carbon steel, V and V-Ti steels is shown in Fig.7 where in V-Ti steels, very fine TiN-VN precipitates in addition to TiN are seen to act to refine structure.

FATIGUE LIMIT OF MICROALLOYED STEEL - For steels for machine structural use, fatigue property is of utmost importance. The fatigue limit (σ_w) of microalloyed steels are shown in Fig.8 together with those of as rolled and quenched-and-tempered plain carbon steels. When compared at identical tensile strength level, the fatigue limit of microalloyed steel is just comparable to that of quenched and tempered steel, σ_w/TS of both steels being 0.50-0.55, and is higher than that of microalloy-free ferrite-pearlite steel. A detailed analysis on the various strengthening factors on fatigue limit by the present authors to be reported elsewhere gave the quantitative relationship, as shown in Fig.9. This relationship indicates a relative importance of precipitation strengthening to enhance fatigue limit. This is consistent with the fatigue mechanism where the hardening of ferrite matrix itself is the most effective to prevent the initiation of fatigue crack.

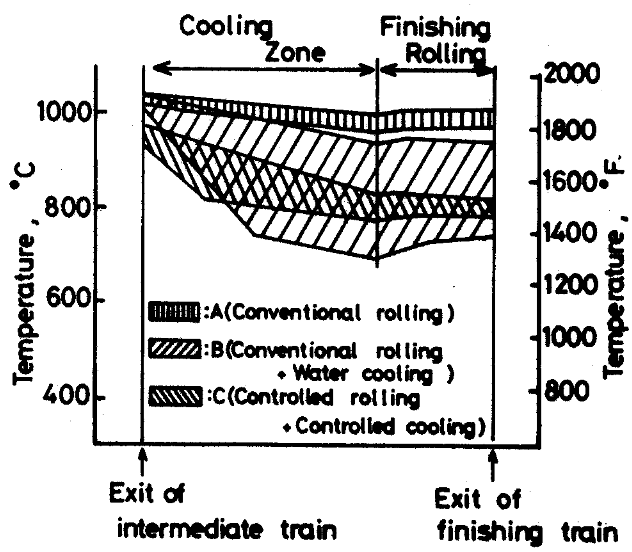

Fig 11. Schematic diagram showing calculated temperature distribution in rod cross section during rolling.

Table 2. Chemical composition of steels. (wt%)

Steel	C	Si	Mn	P	S	Nb	V	Ti	Sol.Al	T.N
Steel A	0.33	0.26	1.13	0.007	0.023	0.026	-	-	0.010	0.0049
Steel B	0.33	0.26	1.45	0.015	0.028	-	0.050	0.015	0.025	0.0085

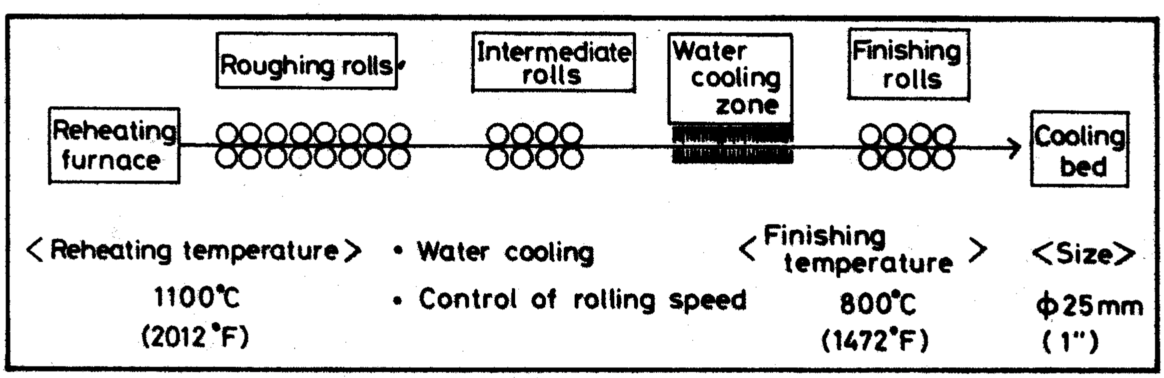

Fig 10. Schematic diagram of controlled rolling in bar mill.

MILL AND APPLICATION RESULTS

CONTROLLED ROLLED Nb STEEL - The trial manufacture of energy saving type rods was made based on the laboratory results. The chemical composition of steels are shown in Table 2. Steel A was designed for obtaining good toughness by adequate controlled rolling. This steel is to be used to make parts as rolled or as drawn. The billets of 114mm square were reheated to 1100°C, and were rolled in bar mill to 22mm round bar with finishing temperature of 800°C, where the control of rolling temperature was carried out by means of intermediate cooling between roll stands and controlling rolling speed as illustrated in Fig.10.

It was intended in this process that the temperature variation in the cross section of bar was as small as possible. The profiles of temperature in the cross section are shown in Fig.11 for the case of 25mm diameter. While water cooling in conventional rolling (B) produces temperature difference of 150-200°C in the cross section, water cooling with lowered reheating temperature and rolling speed gives rise to difference of only 50°C, simultaneously producing the optimum processing condition for the strength and toughness balance for Nb bearing steel.

The microstructure of as rolled steel A is shown in Photo.4. The homogeneous and fine structure is given over the whole cross section. As shown in Table 3, mechanical properties comparable with those of conventionally processed steel (SAE 1038) were

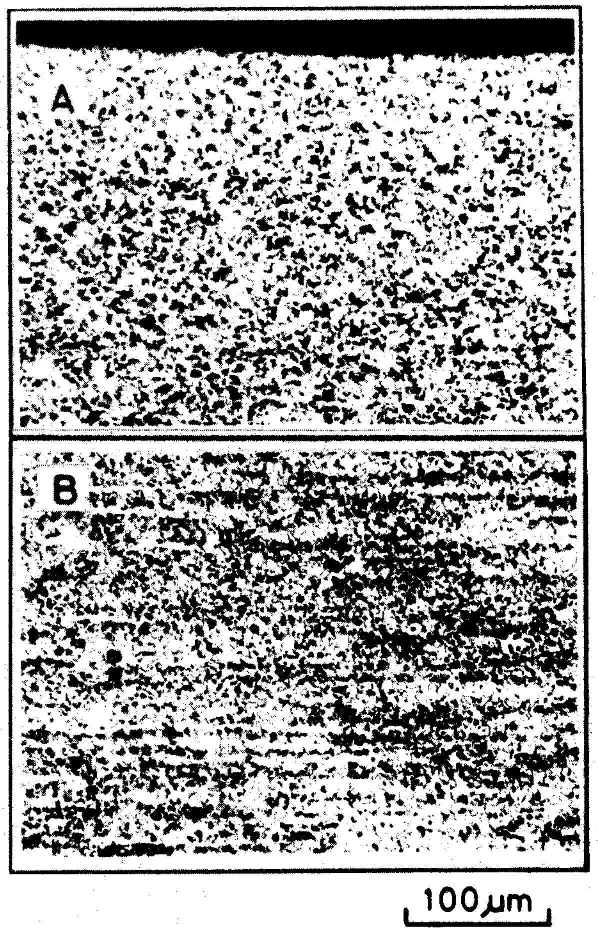

Photo 4. Microstructure of as controlled rolled steel A, (A)surface (B)center.

Table 3. Mechanical properties of steels.

Steel	Condition	YS MPa	TS MPa	El %	RA %	50%FATT °C	$uE_{20°C}$ J/cm^2	σ_w*** MPa	σ_w/TS
Steel A	as rolled*	463	632	31.5	56	-60	172	314	0.50
	as drawn (11%)	600	729	22.7	57	-40	157	338	0.46
	as drawn (19%)	790	834	14.1	51	-15	118	377	0.45
SAE 1038	Q-T**	437	619	32.5	72	15	166	-	-
	Q-T and drawn (19%)	671	733	19.5	62	16	155	328	0.45

* controlled rolled , ϕ22mm
** 850°C x 30min W.Q.- 680°C x 90min W.C.
*** fatigue limit

Table 4. Mechanical properties of steels.

Steel	Condition	YS MPa	TS MPa	El %	RA %	50%FATT °C	$uE_{20°C}$ J/cm^2	σ_w*** MPa	σ_w/TS
Steel B	as rolled*	509	713	31.3	66	-25	152	364	0.51
	as hot forged**	502	712	30.2	67	-22	160	357	0.50
SAE 1043	Q-T****	500	733	26.5	67	-40	204	353	0.48

* conventionally rolled, ϕ40mm
** hot forging temp.: 1200°C
*** fatigue limit
**** 850°C x 60min W.Q. - 600°C x 90min W.C.

obtained.

V-Ti STEEL FOR HOT FORGING - Steel B in Table 2 was designed for making parts as hot forged or as conventionally rolled. Steel B was rolled to 40mm round bar without control of rolling temperature, and subsequently it was hot forged to knuckle arm for automobile. The reheating temperature in hot forging was 1250°C, and two pass stamp forging without temperature control followed by air cooling was carried out.

Mechanical properties of conventionally rolled or hot forged steel are shown in Table 4. It is seen that the steel as rolled or as hot forged achieves satisfactory properties comparable with these of quenched and tempered plain carbon steel (SAE 1043).

CONCLUSIONS

The effect of microalloying elements (Nb,V and Ti) on microstructure and mechanical properties in medium carbon (0.25-0.45%C) steels were studied in various hot working conditions. Subsequently the beneficial effects of these microalloying elements were effectively applied to the production of energy saving type rods. The results obtained are as follows.

(1) The attainable impact property of Nb bearing steels is superior to that of V bearing steels with adequate controlled rolling. The reheating is preferrably to be carried out at the temperatures where a part of Nb(CN) can dissolve into matrix, because the most suitable balance of strength and toughness is obtainable through grain refinement and precipitation hardening.

(2) Solubility product for Nb in medium carbon steel is expressed by the following equation :

$$\log [Nb][C+12/14\ N] = -5576/T + 1.53$$

(3) V is more effective to strengthen medium carbon steel than Nb. Furthermore, V bearing steels stably give moderately good impact property in conventional rolling or hot forging where thermo-mechanical treatment is hard to be adopted.

(4) Addition of a small amount of Ti to V steels is effective in improving toughness of conventionally rolled or hot forged steels.

(5) Very fine complex precipitates of Ti-V-N are formed in V-Ti steels. It seems probable that in these steels Ti-V-N precipitates in addition to TiN act to refine microstructure.

(6) Tensile strength in V-Ti steels is controlled, to a first approximation, by the free N at the reheating temperature (total N-N as TiN) on the assumption that all the Ti combined with N in stoichiometric relationship.

(7) Trial manufacture of microalloyed energy saving type rod was made based on the laboratory results. They showed good mechanical properties comparable with those of quenched and tempered plain carbon steels.

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