

USE OF VANADIUM IN FLAT PRODUCTS (PLATE AND STRIP)

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Vanadium is used in the following flat products:

- 1) Heat-treated (quenched and tempered) plate
- 2) Normalized plate
- 3) Heavy thickness plate
- 4) Conventionally hot-rolled plate
- 5) Recrystallization controlled rolled plate (RCR)
- 6) High strength (350 to 600 Mpa YS) 4 to 15mm thick strip
- 7) Thin (less than 2mm) high strength strip
- 8) High strength strip made by thin slab technology

1 Interaction of Vanadium with Nitrogen

Because of high affinity of vanadium for nitrogen and cubic crystal structure of VN, the kinetics of VN precipitation in ferrite is rapid.

When added to steel, vanadium fulfills a dual role: (a) removes nitrogen from solid solution in ferrite by forming VN and makes the steel non-aging; and (b) by nucleating numerous fine VN particles increases the effectiveness of precipitation strengthening. Vanadium converts nitrogen from an "impurity" into a cost effective alloy. Nitrogen, by forming small VN particles, increases the strengthening contribution of vanadium.

In steel containing both vanadium and aluminum, on cooling from hot-rolling temperature, nitrogen combines preferentially with vanadium because of more rapid precipitation kinetics.

When reheating (normalizing) steels containing V and Al, part of V(C,N) precipitates will dissolve and N will form more stable aluminum nitrides, Al₃N.

2 Processing of V-Steels by RCR

Recrystallization controlled rolling represents deformation of steel in the high temperature regime, i.e. above the recrystallization - stop temperature.

The evolution of austenite micro-structure follows three steps.

- 1) flattening (pancaking) of grain
- 2) recovery and recrystallization; the size of the recrystallized grain depends on temperature, initial grain size and — most importantly — on the amount of deformation.
- 3) Grain growth of recrystallized grains during the time interval between passes.

During RCR processing, coarsening of recrystallized austenite (formed in step 2) is prevented by dispersion of fine titanium nitride particles: TiN.

To assure the formation of finely dispersed TiN particles, the titanium addition is small (less than 0.01%) and post-solidification cooling rate is fast (continuous casting)

3 Hot-Rolling of Thin Strip

For hot rolling HSLA steel as strip less than 2mm in thickness, vanadium (and not niobium) is the preferred microalloy.

The hot-rolling of thin strip results in a low finishing temperature (815°C), which is below the recrystallization stop temperature for Nb steel, but above for V steel.

Mill rolling loads are much lower when deforming fully recrystallized V-steel austenite, than when warm working pancaked (not - recrystallized) austenite grains of a Nb steel.

Low rolling loads assist in maintaining the desirable shape of strip.

4 Economic Advantages of V-Steels

Ease of concasting and less propensity for transverse cracking, compared to Nb steels.

Low-cost hot rolling practice: low reheat temperature (1150 °C) and high finishing temperature (900°C).

Ability to neutralize harmful effects of nitrogen and use it as a cost effective alloy.

In electric arc furnace (EAF) steels, the inherent high residual nitrogen content is an asset in vanadium steels.

Vanadium steels are fully compatible with TiN technology, enhanced nitrogen content and accelerated cooling practice.

Among various microalloy steels,

V-steels offer most economic strengthening by two mechanisms: grain refining and precipitation hardening.

Productivity of hot-rolling V-steels, especially by RCR practice, is high compared to controlled rolling of Nb steels.

5 Concerns Regarding V and V-N Steels

Fear of nitrogen: in V steels, N is removed from solid solution making steel non-aging.

Precipitation embrittlement: all precipitation strengthening reactions contribute to embrittlement, by rising the ductile-brittle transition temperature by about 0.3 °C for each 1 MPa of strengthening.

Precipitation embrittlement is effectively counteracted by grain refinement of ferrite; increase in yield strength by 1 MPa thanks to grain refinement contributes to lowering of the transition temperature by 0.6°C.

The desired level of toughness is achieved by balancing the strengthening by grain refinement and precipitation hardening components.

6 Concerns Regarding V and V-N Steels

Weldability: heat affected zone (HAZ) toughness depends on the nature of transformation products and not on the amount of nitrogen. Zone of coarse austenite is effectively refined by TiN particles. Good toughness is obtained for heat inputs up to 4 kJ/mm.

1) Vanadium in Quenched and Tempered Steels. (Ref. 2)

Aim: a low carbon equivalent (CE) heat treated plate (thickness 20-30 mm), of 700 MPa yield strength, 27J transition

temperature (TT) below - 40°C, and good weldability.

Base composition,%	C	Si	Mn	Cr	Mo
	0.15	0.35	1.35	1.0	0.2
<i>other elements</i>	<i>Al min</i>	<i>N</i>	<i>S</i>	<i>P</i>	
	0.015	0.01	0.015	0.015	0.05-015

Role of Vanadium: increase in hardenability (when in solution); austenite grain size control; strengthening on tempering by secondary hardening (precipitation).

Heat Treatment: water quench from 910°C, tempering at 650°C.

Repression Equations:

$$YS (MPa) = 547 + 1786 (\%V) + 343$$

$$(\%Mo) + 52 (\%Cr)$$

$$27JTT(^{\circ}C) = -112 + 470 (\%V) - 16 (\%Mo) - 1 (\%Cr)$$

2) Normalized Plate (Ref. 3)

Aim: Plate, 16 to 30 mm in thickness, with 380 to 490 MPa yield strength and 27J transition temperature below -40°C

Base Composition (%)

C	Si	Mn	V	N	Al
0.11-0.18	0.4-0.6	1.35-1.65	0.08-0.16	0.012-0.02	0.01-0.02

Role of Vanadium: contributes to grain refinement of ferrite upon normalizing; provides precipitation strengthening (VN) on cooling from the normalizing temperature.

Interaction of N with Al: during normalizing at 925°C, AlN will form in steels containing aluminum, depriving vanadium of nitrogen. For best results, soluble aluminum should be 0.01% max and silicon 0.45-0.60% to assure high V recovery.

Heat-Treatment: normalizing: 900-925°C.

Properties: YS=390-440 MPa; UTS =540-590 MPa;

EI = 20%; impact properties at -400°C; 27 to 40 J

3) Heavy Thickness Plate (Ref. 4)

Aim: low carbon equivalent, heavy thickness (40 to 75 mm) plate, of 350 MPa

yield strength, and good toughness both in as-rolled and normalized condition.

Base Composition (%)

C	Mn	Si	V	N	Al
0.09	1.40	0.40	0.09	0.017	0.014

Role of Vanadium: contributes to grain refinement by intragranular nucleation of ferrite on VN particles, and provides strengthening by precipitation in ferrite.

Properties (75 mm plate)

	YS MPa	UTS MPa	EI %	TT °C
As rolled	353	530	35	-50
Normalized	399	517	40	-85

Weldability: excellent; high toughness in the HAZ for as-welded and stress relieved conditions, for heat-inputs 2 to 5 kJ/mm.

4) Conventionally Hot-rolled V-Steel Plate (Ref. 5)

Aim: To demonstrate that the yield strength of V-steels is insensitive to

variations of the finishing temperature. For air cooled plate, the YS depends mainly on V x N.

Base chemistry (%)

Type of Steel:	C	Mn	Si	Al	V	N
Low VxN	0.10-0.13	1.12-1.35	0.21-0.30	0.025-0.05	0.05-0.08	0.009-0.014
High VxN	0.10-0.13	1.19-1.28	0.21-0.29	0.026-0.044	0.11-0.23	0.009-0.013

Thermal Practice: soaking temperature: 1175°C; finishing temperature: 870 to 1095°C, air cooling

Mechanical Properties: For high V x N steels, the mean YS is 410 MPa, and for low V x N steels: 350 MPa. The YS is insensitive to finishing temperature within a band of +10 MPa. The 20J transition temperature decreases by about 20°C, as the

finishing temperature drops from 1095 to 870°C.

5) Recrystallization Controlled Rolled (RCR) Plate (Ref. 6)

Aim: Determine benefits of RCR compared to CR hot rolling practice in terms of productivity, mill loads, and plate properties.

Steel composition (%)

Process	C	Mn	Si	Al	Ti	V	N
(RCR)	0.12	1.27	0.10	0.004	0.021	0.10	0.015
(CR)	0.11	1.10	0.11	0.007	0.019	0.10	0.017

Comparison of RCR and CR Rolling Practices (air cooling)

	RCR			CR		
Plate thickness (mm)	12	25	40	12	25	40
Finishing temp. °C	1000	1075	1050	850	900	410
Holding time (sec)	-	-	-	160	260	400
Grain size μ m	9.9	11.5	12.4	9.1	11.8	12.4
Yield Strength, MPa	415	400	370	410	405	360
UTS, MPa	540	515	500	520	500	480
Elongation, %	25.0	27.1	28.7	26.7	26.9	28.0
Trans. Temp (35J), °C	-28	-28	-27	-27	-26	-25

Conclusion: In hot rolling V-steels, application of RCR practice contributes to higher productivity and lower rolling loads, compared to CR practice. Properties obtained by both practices are similar.

6) High Strength Strip (Ref. 7,8)

Aim: HSLA steel strip, (4 to 15 mm thick), ranging in yield strength from 350 to 550 MPa, with good formability, weldability, and toughness.

Base composition (%)

Grade	C	Mn	Si	Al	V	Nb	N
350YS	0.08	0.75	0.05	0.03	0.03		0.006
		0.12	1.10	0.15	0.07		0.012
550YS	0.12	1.20	0.30	0.03	0.10		0.015
		1.55	0.55		0.14		0.022
600YS*	0.09	1.55	0.25	0.025	0.14	0.035	0.015

*thickness 3.0 to 8.0 mm

Grade	Thermal Practice		Properties	
	Finishing, C	Coiling, C	YS, MPa	UTS, MPa
350	870-920	580-620	372	482
550	870-920	580-620	590	720
600	850-910	570-630	670	765

To assure good formability and bendability to a tight bend radius, the sulphur is reduced below 0.005%. This

practice replaces inclusion shape control by rare earth elements.

8) High Strength Strip Made by Thin Slab Casting (Ref. 10)

Aim: to demonstrate the feasibility of producing HSLA steel strip (4.0 to 15.0 mm) in the yield strength range: 350 to 550 MPa, in spite of the low carbon content: 0.04 to 0.06%.

Base composition (%) and Tensile Properties

Grade	Gage,mm	C	Mn	V	N	YS,MPa	UTS,MPa	EI%
350	9.6	0.05	0.6	0.03	0.010	364	462	26
420	9.6	0.04	0.7	0.05	0.012	420	500	25
460	6.0	0.04	0.9	0.08	0.014	460	522	27
550	4.8	0.06	1.5	0.12	0.020	597	681	24

Microstructural Analysis

Grade	Grain size m	Precipitation	Strengthening, MPa		% of YS
			Grain Size	Total	
350	11.9	115	132	247	68
420	11.5	147	140	287	68
460	6.5	150	187	337	73
550	4.8	208	218	426	71

Simplified Regression Equation:

$$YS \text{ (MPa)} = 255 + 19 \text{ Mn}^* + 900 \text{ V} + 8100 \text{ N}$$

$$\text{Mn}^* = \text{Mn equivalent} = \text{Mn} + \text{Ni} + \text{Cu} + \text{Cr} + \text{Mo}$$

The equation highlights the role of N in V steels.

Summary the desired strength is mainly the result of grain refinement and precipitation hardening, accounting for about 70% of the yield strength. This explains the excellent economics of V plus N steels.

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