Vanadium Microalloying in Steel Sheet, Strip and Plate Products

Robert J. Glodowski

STRATCOR

Process Developments in the Production of Flat Rolled Products

Flat rolled steel products, including sheet, strip and plate, have seen nearly a century of development since the first continuous rolling processes were installed. Through these years of development, the product has been continually refined, initially with emphasis on improved properties through chemistry control and subsequent heat treatments. Later, with continued pressures to improve the cost effectiveness of steelmaking, more efficient process methods have evolved to produce the desired properties at a lower cost. One of the most effective ways to reduce the cost of production of steels is to shorten the process routing, eliminating operations that add unnecessary cost. As a result, a major objective in the industry today is to produce steel as directly as possible from liquid steel to final product. Medium and thin slab casting processes along with direct charging into reheat or equalizing furnaces characterize this quickly developing technology in the production of steel sheet and plate.

Alloy design has also evolved in concert with the process technology changes to achieve the desired objectives of improved properties with minimum processing. Metallurgical response to the hot rolling process has replaced the metallurgical response to heat treatment as the principal alloy design criteria. One of the more important innovations in steel technology in recent years is the combination of microalloying along with controlled hot rolling practices. This processing technology became known as controlled rolling (CR), or thermomechanical controlled processing (TMCP). Various versions of TMCP, sometimes identified with conflicting and confusing terminology, have developed over the years.

As the term thermomechanical controlled processing implies, controlling the rolling process for optimum metallurgical response involves control of both the mechanical and thermal aspects of the rolling. Mechanical control involves the reduction pass schedule, including total reduction and the number of passes and reduction per pass. The thermal control involves the deformation temperature throughout the rolling schedule from the reheat furnace through each rolling pass. In addition, the technology exists today for close control of the cooling cycle after the final rolling pass. This technology includes laminar water cooling after rolling, first adapted to hot strip mills, and later added to plate rolling mills as well.

In plate mills, the controlled water cooling after rolling has become known as accelerated cooling (AC), or accelerated controlled cooling (ACC). In this process, the cooling rate can be controlled to optimize the austenite to ferrite/pearlite transformation, or even to quench the steel to alternate microstructures. In all cases, the technology involves controlling the rate and the extent of cooling to achieve the desired microstructure.

Metallurgical aspects of HSLA Steels produced by Thermomechanical Controlled Processing (TMPC)

With the development of process technologies including thermomechanical controlled processing and accelerated cooling, the emphasis has been and continues to be on optimizing the alloy system to meet property requirements at low cost.[1)] High Strength Low Alloy (HSLA) steels have been developed using limited additions of microalloys to achieve higher strength levels in the as-rolled condition. Microalloying has generally replaced increased carbon levels as the primary strengthening process for structural steels in sheet and plate. The low toughness and poor weldability of the higher carbon grades restricted their acceptability, and therefore created the demand for alternatives. Microalloyed HSLA steels rely primarily on two strengthening mechanisms – ferrite grain refinement and precipitation strengthening – to increase strength levels beyond the base strength achieved from carbon additions for pearlite strengthening and from manganese and silicon additions for solid solution strengthening. Integrating the new processing conditions with an appropriate alloy system to optimize the grain refinement and precipitation strengthening mechanisms became the primary metallurgical objective.

- **Grain Refinement**

To achieve ferrite grain refinement in the final as-rolled product, several approaches are used separately or in combination.[2,3)] First, the austenite should be “conditioned” during the rolling process to provide the maximum amount of grain boundary surface area. One way this conditioning can be accomplished is by rolling at temperatures below the recrystallization stop temperature, thereby producing flattened or “pancaked” austenite grains. These flattened grains then promote the formation of small ferrite grains in the final product. Niobium alloyed steels using these “controlled rolling” (CR) processes were developed over 30 years ago. In the CR process, the temperature for the final rolling passes must be held below the temperature at which recrystallization will occur, the “recrystallization stop temperature”.

Recrystallization controlled rolling (RCR) was developed later. The RCR process relies on repeated interpass recrystallization to achieve a fine austenite grain size, with controlled temperatures and reduction schedules to achieve the desired results. The RCR rolling process involves finish-rolling temperatures more typical for plain carbon steels, while the CR process requires lower finish rolling temperatures. These higher rolling temperatures promote repeated recrystallization. Since niobium has been shown to raise the recrystallization temperature, vanadium microalloying was naturally more compatible with the RCR process. Vanadium does not inhibit the austenite recrystallization necessary for the RCR process.

Ferrite nucleation occurs primarily on the prior austenite grain boundaries. Both CR and RCR rolling generate an austenite with a large amount of grain boundary surface area (austenite interfacial area), promoting transformation to a small ferrite grain size. These small ferrite grains contribute to both strength (via the Hall-Petch relationship shown in Figure 1.) and to increased toughness. The effect of the ferrite grain size on the final properties of the steel is independent of the austenite conditioning process used to achieve that ferrite grain size. As long as small ferrite grains are produced, it does not matter which rolling process is used to achieve those results. At an equivalent ferrite grain size, the contribution of grain size to the final properties (strength and toughness) will be comparable. Therefore, the test of the process is the final ferrite grain size, and not the condition of the austenite that produced the ferrite.

Accelerated cooling can be applied after finish rolling, using either the CR or RCR rolling process, to lower the austenite-ferrite transformation temperature. Lowering the transformation temperature generates smaller ferrite grains by two mechanisms. First, an increased ferrite nucleation driving force is generated because of the undercooling effect. This undercooling is the difference between the equilibrium transformation temperature and the actual transformation temperature. The higher ferrite nucleation driving force will increase the number of ferrite grains initiating at the austenite grain boundaries and other favorable sites.

After ferrite nucleation, the lower transformation temperatures will inhibit the ferrite growth rate. Interphase precipitation of grain boundary pinning microalloy constituents may also suppress the ferrite growth rates. Lowering the transformation temperature, and thereby reducing the ferrite growth rate, may also be accomplished by alloying to increase the hardenability of the steel. Typically, manganese additions are used to provide increased hardenability. However, increasing the ferrite nucleation driving force through the undercooling effect can only be achieved by using accelerated cooling.

In plain carbon steels, ferrite nucleation is normally expected to occur at the austenite grain boundaries. Ferrite nucleation may also be initiated at precipitates within the austenite grains. Work has been published by Kimura et.al.4) suggesting the precipitation of vanadium nitrides can be effective for promoting fine ferrite grains, even in larger sections where the cooling rates cannot be accelerated greatly. In this model, the fine microalloy precipitates not only reduce the recrystallized austenite grain growth rate, but also promote ferrite nucleation. The relative effectiveness of VN to enhance ferrite nucleation compared to other precipitates was explained in terms of the change in interfacial energy as shown in Figure 2. The end result is a finer ferrite grain size as a direct result of microalloy precipitation in the austenite phase prior to transformation as well as interphase precipitation during transformation from austenite to ferrite. Figure 3 is the schematic illustration used by Kimura et.al. to show a first stage of rolling to promote repeated recrystallization of the austenite. A second stage of rolling at a somewhat lower temperature is shown to promote deformation induced VN precipitation. The VN will precipitate at both the austenite grain boundaries reducing austenite grain growth, and within the interior of the grain boundaries providing ferrite nucleation sites.

- **Precipitation Strengthening**

To provide effective precipitation strengthening, the microalloy used should have the ability to stay in solution during the heating and rolling stages, then precipitate in fine, well-dispersed particles during or after the austenite to ferrite transformation. Vanadium has the demonstrated properties to be well suited for this purpose. The higher solubility of vanadium carbonitrides compared to the other microalloying choices available makes vanadium a strong and predictable precipitation strengthener.

Because the solubility product of VN is significantly lower than VC, nitrogen plays a significant roll in the strengthening process with vanadium.5) Also, because nitrogen has a much higher solubility in ferrite than carbon, the availability of nitrogen for VN precipitation in ferrite is quite high. For those microalloys that require carbon for effective precipitation, the amount of carbon available in ferrite can be much less than the available nitrogen. As a result, vanadium precipitation strengthening can be predictable over a relatively large range of vanadium addition levels. Most chemistry-strength models show a linear effect of vanadium additions as long as an appropriate amount of nitrogen is available in the steel. This allows vanadium to be used as a "trim" element that can be adjusted to meet property requirements. As grade or thickness changes are made, the desired properties can be predictably achieved by adjusting the vanadium levels. The vanadium adjustments can be made on a grade to grade basis, or even adjusting vanadium levels from heat to heat within a grade to compensate for thickness changes or variations in other alloys, including residual elements.

Figure 4 is a schematic showing the relative contribution of each of the strengthening mechanisms to HSLA steels. The relative effects of each strengthening mechanism can be visualized in this figure, illustrating the importance of both ferrite grain size control and precipitation strengthening to achieve the 550 MPa yield strength level. This example was derived from analysis of a production grade of HSLA strip, direct rolled from a 50mm cast slab.

Advantages of Vanadium for Flat Rolled HSLA Steels

Traditional microalloying systems are being challenged by the new production developments that have been commercialized in flat rolled products. These new production processes include thin slab cast and direct rolled strip steel production, and the plate mills with medium thickness slabs directly charged into reheat furnaces for final rolling. While the use of vanadium has always been a viable option, these new processes have added new reasons to consider vanadium as the alloy of choice.

Desirable characteristics of an alloy system for HSLA steels using the newer low cost steelmaking processes include the following:6,7,8)

- Compatibility with the electric furnace melting process widely used in many new facilities.
- Minimal precipitation during solidification to reduce cracking problems during casting.
- Low solution temperature (high solubility) to insure the microalloy is in solution prior to rolling.
- Precipitation strengthening should occur after finish rolling to minimize roll force requirements.
- Compatibility with high finish rolling temperatures to minimize roll wear and facilitate gauge control.
- Compatibility with RCR rolling for maximum ferrite grain refinement.
- Predictable precipitation strengthening, providing yield strengths from 350 to 550 MPa.

Vanadium microalloying clearly demonstrates the capability of meeting all of these characteristics. Many of the new mills are predominately electric furnace melting processes. The raw material is predominantly scrap steel, causing the metallic residuals to be higher than normally seen in steels produced from blast furnace iron in basic oxygen furnaces (BOF). Even more significant, the nitrogen levels are substantially higher than in the BOF steels. Because vanadium utilizes nitrogen as an integral part of the alloy system, the normally undesirable presence of the higher nitrogen can be turned into an advantage. Compatibility with higher nitrogen levels is a desirable characteristic of vanadium, but vanadium strengthening can be used effectively in BOF steels with managed nitrogen levels.

The castability of vanadium steels has been demonstrated in the literature,8,9) and the wide use of vanadium in use in structural grades of plate and sheet provides verification of minimal cracking problems. The low solution temperatures of the vanadium precipitates insure that the alloy is in solution even if energy saving practices dictate lower reheat temperatures and shorter soaking cycles. Additionally, the low solution temperatures allow for excellent gauge control and minimal roll wear in strip steels because the roll forces are minimized at finish rolling temperatures, typically from 900 °C to 950 °C.

With accelerated cooling, much of the vanadium precipitation will occur randomly in the ferrite after transformation. This preferred precipitation will occur at temperatures that are typical for coiling strip and light plate, near 600°C. For heavier plates where accelerated cooling is less effective, the precipitation will still occur predominately during or after transformation. Using the rolling practices previously described, final ferrite grain sizes below 5μm are readily produced in hot rolled strip. In plate steels, final grain sizes of 10 μm or less have been demonstrated.10)

Hot Rolled Sheet Applications

- **Strengthening**

Recent publications6,11) have reported on an evaluation of production lots of low carbon sheet steels containing various levels of manganese, vanadium and nitrogen. The steel samples were from three different steel mills, each producing steel using electric furnace melting processes, casting thin (50 mm) slabs and direct charging into equalization furnaces prior to rolling. The sheet samples were evaluated for mechanical properties, microstructure, and strain aging characteristics. Table 1 is a summary of the chemistry, mechanical properties, grain size and strain aging index for each of these steels.

Regression analysis of the mechanical property data provided a reasonable estimate of the strengthening effects of vanadium and nitrogen. Within the range of vanadium additions of this data (0.04% to 0.13%), the strengthening contribution of vanadium was 15 MPa for each 0.01% V added. For nitrogen, the estimated strengthening was 7.5 MPa for each 0.001% N added. These strengthening coefficients are valid for the data range from this data set, and can be expected to be reliable as long as the nitrogen level is sub-stoichiometric with respect to the vanadium addition. They are also consistent with the nitrogen strengthening rates reported in previous studies.5,7)

These results support the well established observations that vanadium provides more strengthening when nitrogen is available up to the stoichiometric levels of V:N. The implication for thin slab casting operations is that the nitrogen levels of electric furnace steels can be used to an advantage to optimize the cost effectiveness of the vanadium alloy addition. With appropriate management of nitrogen levels, vanadium can be effectively used in steels melted in basic oxygen processes as well.

Ferrite grain size measurements were determined by microstructural analysis of samples using the intercept method. Figure 5 shows the ferrite grains size as a function of the sheet thickness. The dependence of grain size on sheet thickness reveals the effects of processing conditions on grain size, since both total reduction and cooling rate are directly dependent on the sheet thickness. In particular, the faster cooling rate of the thinner sheets would be expected to promote a finer ferrite grain size. The higher alloy levels, and possibly optimized processing conditions, of the higher strength sheets greater than 500 MPa resulted in finer grain sizes compared to the lower strength grades. This again demonstrates the additive effects of grain size and precipitation strengthening that allows the production of these higher strength grades. The 3 to 7 micron grain size for the vanadium microalloyed high strength grades is comparable to 3 to 8 micron results reported for ultra-high strength (750 MPa) grades using Nb and Ti along with special processing for maximum effect.12)

- **Strain aging**

Strain-aging test data were also reported, demonstrating the ability of vanadium to eliminate the aging effects of “free” nitrogen in these steels, even when the total nitrogen levels exceeded 200 ppm. In this study, the strain-aging index is defined as the amount of increase in flow stress after aging a prestrained sample at 100 C for 1 hour.13) The amount of prestrain used for these tests was 7.5%. The results of the strain aging index study are summarized in Figure 6. The average strain aging index (A.I.) from the results shown in Table 1 (average of 1 MPa for 16 different steel samples) are compared to average results from 5 different samples of C-Mn steels (average 39 MPa). The nitrogen level for the vanadium steels ranged from 80 to 200 ppm, while the carbon steels samples had nitrogen levels from 70 to 110 ppm.

Another recent publication14) described the development and production of 550 MPa HSLA V-N-Mo microalloyed sheet steels, rolled from 55 mm and 65 mm thin slabs above the recrystallization stop temperature (RCR rolling) and followed by accelerated controlled cooling (ACC). The typical chemistry used for these grades is shown in Table 2.

In this publication, the author describes the process development work needed to optimize the rolling practice to obtain consistently high properties of this grade. The key TMCP parameters that were monitored and controlled were described as follows:

1. Tunnel furnace discharging temperature
2. F1-F6 reduction ratios and deformation strains
3. Roll forces and flow stresses
4. Total processing time
5. Mill speeds (F1 entry and F6 exit speeds)
6. Finishing temperature
7. Coiling temperature
8. Cooling rate

A recrystallization control rolling - accelerated controlled cooling (RCR-ACC) process technique was adopted as best suited for both the mill capabilities and the chemistry used. The author concluded that the RCR-ACC technique was an effective in producing a fine, uniform, transformed ferrite structure with a fine grain size in the ASTM range of 10.5 too 11.5. Heavy reduction passes at a higher temperature regime were determined to be critical at the start of hot rolling, providing complete recrystallization of the austenite. Short processing times (i.e. fast rolling speeds) and ACC with intensive cooling rates were also stated to be important to promote a rapid precipitation of V(C,N) and Mo_2C. The performance of the steels from this process has been exceptional, safely exceeding the minimum 550 MPa yield strengths required for the grade.

Plate Applications

Vanadium has been widely used in plate steels for many years in North America, particularly for 350 MPa grade steels like ASTM A572, Gr. 50. The benefits of vanadium addition in plates are similar to those identified in sheet steels, principally the enhancement of properties, through grain refinement and precipitation strengthening in the as-rolled condition. Mitchell, et.al.10) published the results of an extensive laboratory study documenting the potential properties of 20-25 mm plates using vanadium microalloying and various thermomechanical treatments, including hot rolling, recrystallization controlled rolling (RCR) and accelerated cooling (ACC) after rolling.

A summary of the chemistry and mechanical properties of a series of RCR plates is shown in Table 3. In this case, the nitrogen levels were not enhanced beyond a normal residual level. Two different levels of Ni and Cu were investigated, representing what one might expect for BOF vs. EAF melting processes.

Because of the differences in carbon, nickel and copper levels, it was necessary to normalize the strength data to compare the strengthening effects of vanadium. This was accomplished by utilizing available equations to predict the strengthening effects of the elements included in a carbon equivalent model, specifically C, Mn, Cr, Mo, Ni and Cu. The model used was as follows:

$$YS = 41.4 + 575.2 \times CEV + (27401 \times N_{eff} - 2) \times V^{1/2} + 419.5 \times t^{-1/2} \qquad \text{(Eq. 1)}$$

$$UTS = 74.1 + 985.1 \times CEV + (31125 \times N_{eff} - 39) \times V^{1/2} + 181.5 \times t^{-1/2} \qquad \text{(Eq. 2)}$$

Where $CEV = C + Mn/6 + (Cr + Mo)/5 + (Ni + Cu)/15$

$N_{eff} = \%N - Ti\%/3.42$

t = thickness

The effect of vanadium on the tensile properties was determined by correcting for differences in CEV. The results are shown on the Figure 7, plotted for a constant CEV value of 0.38. The strengthening rate of the vanadium additions appears to be substantially less than that determined for sheet steels and reported previously. A linear regression analysis of the yield strength data in Table 3 produced a coefficient for vanadium of about 6.5 MPa for each 0.01% V added. This value approximates the slope of the data in Figure 7 quite well. It is likely that the strengthening effects of vanadium were reduced in part because the nitrogen levels were not enhanced as they were in the sheet steel data. Also, the author determined the contribution to yield strength from precipitation strengthening accounted for over 10 MPa for each 0.01%V added when adjusted for the effects of carbon, solid solution strengthening and grain size.

The impact properties of these steels were all quite good, as shown in Table 3. 53J impact transition temperatures (ITT) were in the range of –70 to –95 °C. There appears to be some effect of the carbon levels, with a tendency for the 0.12 – 0.14% carbon to exhibit a marginally higher level of ITT than observed in the 0.01% carbon steels. The microstructures of these steels were all equiaxed ferrite/pearlite with a relatively uniform grain size of the order of 8 – 11 µm. Weldability tests were also performed on these steels, with excellent levels of HAZ toughness being observed at heat inputs up to 5 kJ/mm. Because of the low levels of CEV normally used in these steels, there should be no problems with cold cracking.

SUMMARY

Vanadium has proven to be a popular choice as a microalloy for flat rolled sheet and plate steels. Some of the observed advantages of vanadium as an alloy choice are as follows:

- Vanadium utilizes nitrogen as part of the alloy system. As such, vanadium can easily adapt to the increasing percentage of steels produced by Electric Arc Furnaces.

- Castability problems are minimized with vanadium compared to some other microalloy approaches.

- Higher solubility of the V(C,N) precipitates permits higher alloy levels in the steel even when restricted to the lower reheat temperatures common in modern steelmaking facilities.

- Recrystallization control rolling techniques produce refined austenitic grains at normal carbon steel rolling temperatures.

- Precipitation occurs primarily during or after transformation to ferrite, thereby not contributing to roll forces during finish rolling.

- Reasonable coiling temperatures for sheet products (580-620 °C) are compatible with normal mill equipment.

- The V and N strengthening effect in sheet and plate steels can be quantified with confidence, and the strengthening is predictable and reasonably linear over a large vanadium addition range.

- Nitrogen enhances the strengthening effect of vanadium, improving the cost effectiveness of the vanadium alloy system even when used in steel producing mills that may have inherently low residual nitrogen levels.

- Hot rolled ferrite grain size can be refined using the V-N alloy system, achieving levels competitive with other alloy systems.

- Impact toughness and weldability of vanadium bearing HSLA steels are competitive with other alloy systems when processing conditions are controlled to produce the optimum ferrite grain refinement.

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Table 1 Chemistry and mechanical properties of production grades of vanadium microalloyed hot rolled sheet steel.[6)]

		Product Chemistry							Mechanical Properties			
Steel Type	Gauge mm	C wt.%	Mn wt.%	Si wt.%	A lwt%	V wt%	N wt.%	G.S. μm	YS MPa	UTS MPa	El. %	A.I. MPa
V	15.3	0.050	0.83	0.01	0.046	0.085	0.0090	7.91	431	470	38	2
V	3.0	0.059	0.76	0.02	0.036	0.054	0.0098	5.72	404	474	29	2
V	6.3	0.056	0.79	0.04	0.039	0.057	0.0086	6.90	423	468	33	-6
V	4.7	0.054	1.10	0.02	0.043	0.066	0.0105	5.44	383	518	31	-6
V	2.1	0.051	0.83	0.03	0.034	0.057	0.0084	5.00	391	453	29	2
V-N	12.6	0.064	1.01	0.01	0.039	0.065	0.0140	9.19	467	502	36	2
V-N	7.8	0.053	0.99	0.01	0.036	0.067	0.0156	5.29	525	550	31	12
V-N	2.1	0.056	0.78	0.03	0.037	0.058	0.0136	4.30	430	512	34	3
V-N	3.8	0.058	0.86	0.02	0.037	0.086	0.0163	5.43	473	575	25	-2
V-N	6.3	0.050	0.80	0.01	0.050	0.057	0.0142	6.39	364	502	32	-3
V-N	2.0	0.054	0.99	0.19	0.024	0.050	0.0150	5.68	463	na	na	1
V-N	7.6	0.051	0.97	0.20	0.022	0.046	0.0140	6.38	430	na	na	3
V-N	5.7	0.053	1.62	0.35	0.026	0.130	0.0200	3.35	567	na	na	8
V-N	5.8	0.054	1.57	0.32	0.022	0.130	0.0200	4.35	572	na	na	5
V-N	5.7	0.052	1.58	0.36	0.026	0.120	0.0200	3.78	548	na	na	-1
V-N	5.7	0.057	1.62	0.35	0.025	0.130	0.0200	3.73	568	na	na	1

Table 2 Typical chemistry of 550 MPa HSLA sheet steels (zz) **wt.%**

C	Mn	Si	Mo	V	N	Al
0.056-0.075	1.25-1.45	0.02-0.15	0.010-0.055	0.120-0.130	0.0150-0.0205	0.013-0.035

Table 3 Product analysis and mechanical properties of RCR rolled 25 mm plate steel.[10)]

Steel	C wt.%	Mn wt.%	Si wt.%	Ni wt%	Cu wt%	Al wt.%	V wt.%	N wt.%	YS MPa	UTS MPa	El. %	J 40°C	54J ITT°C
1	0.12	1.39	0.26	0.18	0.18	0.049	0.000	0.0070	364	497	42	186	-75
2	0.14	1.43	0.26	0.02	0.02	0.029	0.050	0.0050	407	519	34	215	-75
3	0.13	1.38	0.24	0.16	0.18	0.042	0.050	0.0070	421	545	39	147	-75
4	0.13	1.39	0.25	0.17	0.17	0.049	0.100	0.0070	430	545	37	140	-70
5	0.09	1.46	0.25	0.15	0.18	0.046	0.000	0.0080	359	482	47	184	-70
6	0.10	1.41	0.25	0.02	0.02	0.032	0.029	0.0055	395	464	34	267	-70
7	0.11	1.40	0.26	0.02	0.02	0.030	0.028	0.0090	402	486	37	235	-95
8	0.10	1.45	0.26	0.02	0.02	0.025	0.054	0.0052	390	480	34	283	-90
9	0.10	1.47	0.27	0.18	0.18	0.047	0.060	0.0070	375	499	44	221	-90
10	0.09	1.46	0.25	0.18	0.18	0.040	0.100	0.0070	411	515	43	231	-90

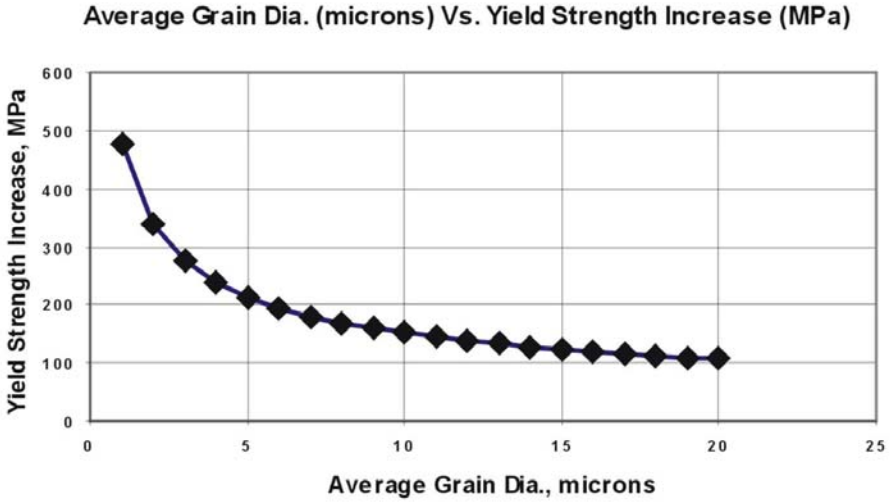

Fig. 1 Calculated effect of ferrite grain size on Yield Strength.

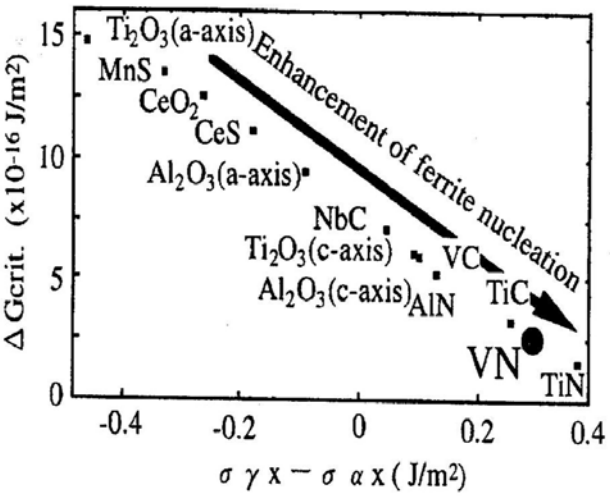

Fig. 2 Change in interfacial energy and driving force for ferrite nucleation form various precipitates.4)

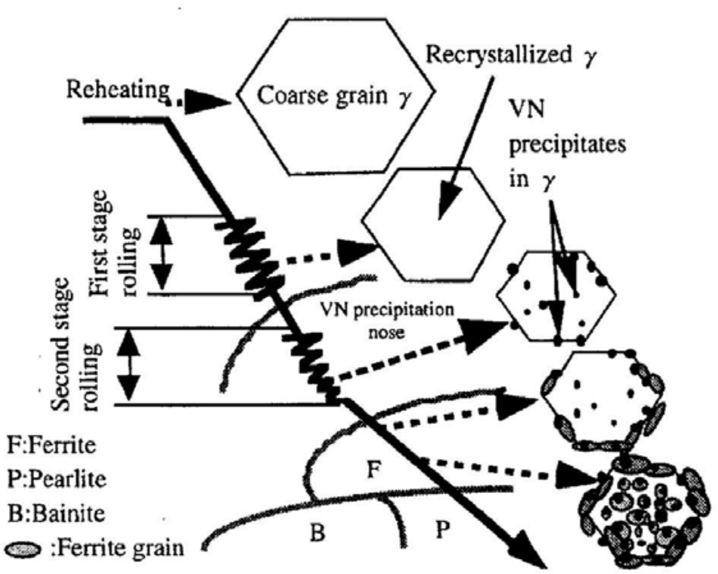

Fig. 3 Thermomechanical behavior during rolling of heavy section vanadium bearing steels.[4)]

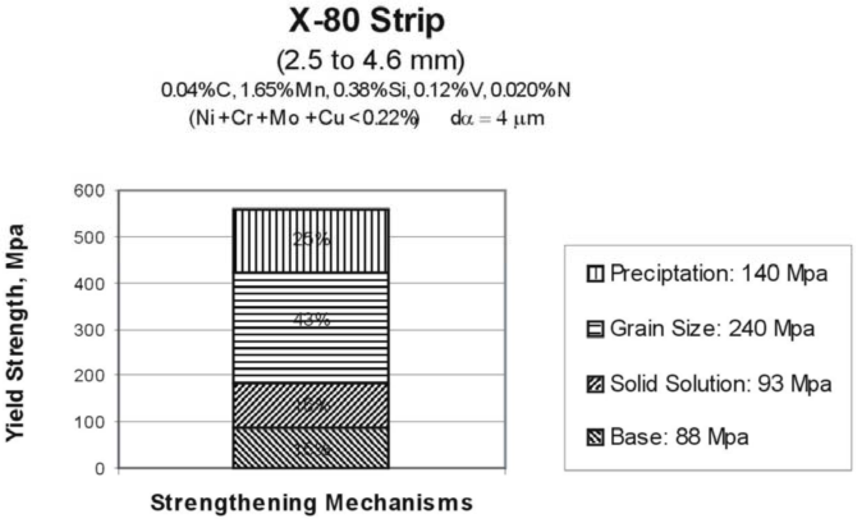

Fig. 4 Contributions of each strengthening mechanism in a 550 MPa hot rolled strip.[1)]

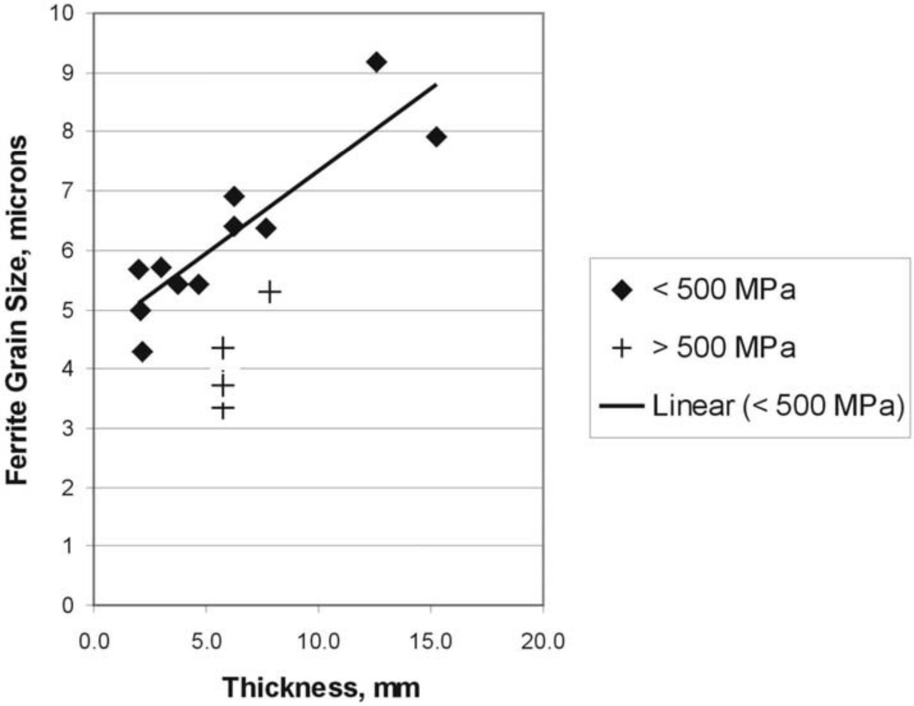

Fig. 5 Relationship of thickness and Yield Strength to ferrite grain size of hot rolled sheet steel.$^{6)}$

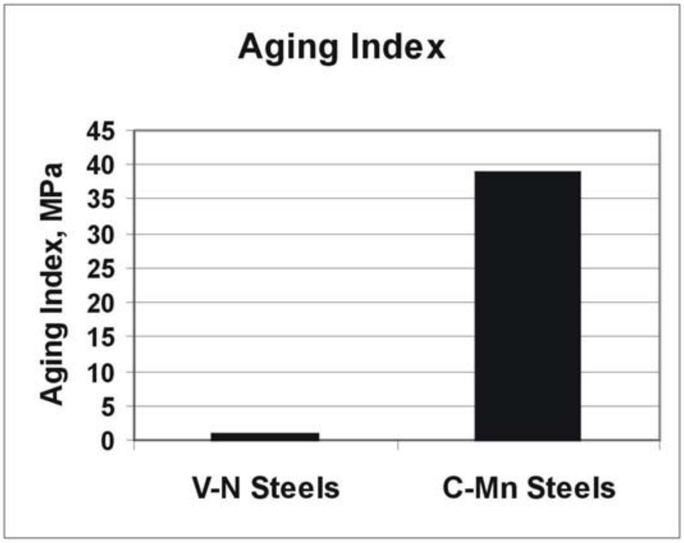

Fig. 6 Strain aging index results of vanadium steels compared to carbon steels.

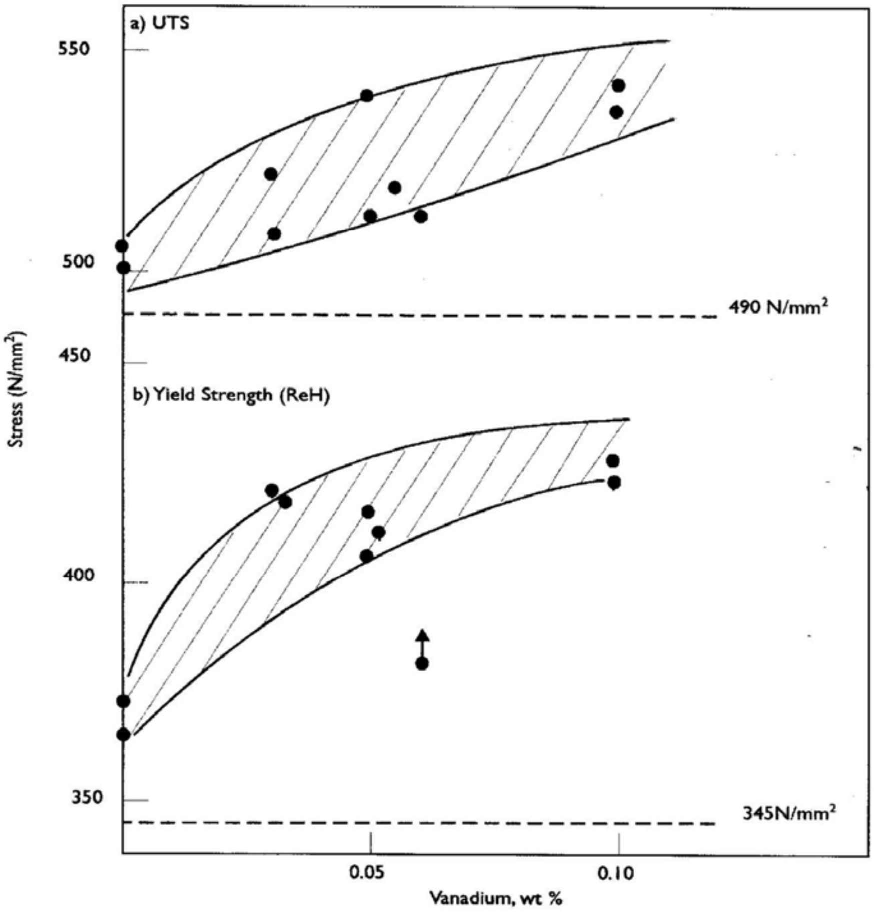

Fig. 7 Effect of vanadium on the tensile properties of 25 mm thick RCR plates.[10)]