**High Strengths At Lower Costs With Nitrovan® Vanadium**

**BOTH ADDITIONS INCREASE STRENGTH BY THE SAME AMOUNT**

<table>
<thead>
<tr>
<th></th>
<th>0.10%</th>
<th>0.06%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FERROVANADIUM</strong></td>
<td></td>
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<tr>
<td><strong>NITROVAN® VANADIUM</strong></td>
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**SUCCESSFUL APPLICATIONS**

Hot-Rolled or Hot-Forged Steels with Ferrite/Pearlite Microstructures, such as:
- Reinforcing Bars
- Forgings
- High-Strength Sheet, Plates, Bars and Structural
The high strengths provided by small vanadium additions allow steelmakers to produce the value-added high-strength, low-alloy (HSLA) steels that are widely used in engineering applications. By replacing ferrovanadium with Nitrovan® vanadium, steelmakers can achieve these high strengths more efficiently and at lower costs. Nitrovan® vanadium optimizes the strengthening mechanisms in high-strength, low-alloy steels, allowing steelmakers to use less vanadium to reach desired strength levels. This significantly reduces vanadium costs.

That is why Nitrovan® vanadium is the preferred addition worldwide for microalloyed high-strength steels.

A 0.053% vanadium addition of Nitrovan® vanadium yielded the same 425 MPa (60 ksi) yield strength as 0.070% vanadium added as ferrovanadium. This reduction is possible because Nitrovan® vanadium strengthens steel more efficiently than ferrovanadium. Depending on desired strength levels, steel producers using Nitrovan® vanadium can reduce vanadium additions by 20 to 40% compared to using ferrovanadium.
Reduce Vanadium Additions by Using Nitrovan® Vanadium

Nitrogen: Increases Effectiveness of Vanadium

In the presence of vanadium, nitrogen is converted from an impurity into a cost-effective alloying element. The vanadium nitrides formed by vanadium and nitrogen are more stable and more finely dispersed than vanadium carbides. For that reason, vanadium strengthening is more efficient in the presence of nitrogen.

Same Strength with Less Vanadium

By increasing strength, nitrogen allows steelmakers to use less vanadium, as shown in the graph above. Here, a 0.07% vanadium addition is needed to obtain a 110 MPa (16 ksi) increase in yield strength in a steel containing only 50 parts per million of nitrogen. If the nitrogen content is increased to 100 parts per million, only 0.04% vanadium is needed to obtain the same yield strength.

Substantial Savings

Reducing vanadium additions yields major cost savings. In the example below, equivalent yield strengths are obtained when either 0.10% vanadium is added as ferrovanadium or 0.06% vanadium is added as Nitrovan® vanadium. Using Nitrovan® vanadium reduces vanadium additions by 0.40 kg (0.90 lbs.) per metric ton of steel.

Obtaining Equivalent Yield Strengths with Less Vanadium

<table>
<thead>
<tr>
<th>Alloy Used</th>
<th>Vanadium Addition Per Metric Ton</th>
<th>Vanadium Content in Steel</th>
<th>Vanadium Savings Per Metric Ton of Steel Using Nitrovan® Vanadium Instead of Ferrovanadium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrovan® Vanadium</td>
<td>0.60 kg (1.35 lbs.)</td>
<td>0.06%</td>
<td>0.40 kg (0.90 lbs.)</td>
</tr>
<tr>
<td>80% Ferrovanadium</td>
<td>1.0 kg (2.25 lbs.)</td>
<td>0.10%</td>
<td></td>
</tr>
</tbody>
</table>

Hot-rolled steel containing 100 parts per million of nitrogen needs only 0.04% vanadium to obtain a strength increase of 110 MPa (16 ksi). In contrast, a steel containing about 50 parts per million of nitrogen requires 0.07% vanadium to obtain a similar increase in strength.
**TWO STRENGTHENING MECHANISMS**

The two key strengthening mechanisms accounting for high yield strengths in low-alloy steels are:

- Precipitation Strengthening
- Grain Refinement

Nitrovan® vanadium enhances precipitation strengthening and grain refinement – two mechanisms that provide up to 70% of the yield strength of a typical high-strength, low-alloy steel. Grain refinement is the only mechanism that improves both strength and toughness while reducing the embrittling effects of precipitation. By balancing grain refinement and precipitation hardening, good toughness is obtained in high-strength steels.
MORE EFFICIENT PRECIPITATES BUILD STRENGTH

When Nitrovan® vanadium is added to steel, vanadium preferentially combines with nitrogen to form nitrogen-rich vanadium-carbonitride precipitates. The nucleation rate of these precipitates increases at higher nitrogen contents and produces a large number of small particles, as shown below. For example, increasing the nitrogen content from 80 to 160 parts per million reduces the particle diameter by half but increases the number of particles eight times. Increasing the effectiveness of precipitation strengthening depends on reducing the distance between particles. The greater number of smaller vanadium-carbonitride precipitates formed by Nitrovan® vanadium strengthens steel more efficiently than the coarser vanadium-carbide precipitates formed by ferrovanadium.

MORE EFFICIENT STRENGTHENING FROM SMALLER PRECIPITATES

Increasing the nitrogen content of steel reduces the size of vanadium-carbonitride precipitates. These smaller precipitates provide more effective strengthening, reducing vanadium additions.

Reducing the particle diameter of precipitates from 4 to 2 nm gives eight times the number of precipitates in a given volume of steel. The larger number of small precipitates gives more efficient strengthening by reducing interparticle spacing.
How Nitrovan® Vanadium Provides More Efficient Strengthening Through Grain Refinement

**SMALLER GRAINS FORMED BY VANADIUM AND NITROGEN**

Austenitic grain refinement in high-strength steels is achieved by hot rolling in the recrystallization-temperature region. The coarse austenitic grains found at the beginning of the rolling process are refined by repeated deformation and recrystallization during hot rolling. Although grain growth between these rolling passes would normally be expected, grain growth is retarded by the presence of the vanadium and nitrogen in the steel.

The accelerated cooling that takes place after the final rolling pass helps produce a very-fine ferritic structure after the austenitic grains transform to ferrite. This rapid cooling enhances ferrite nucleation and slows grain growth, providing the desirable balance of strength and toughness that is characteristic of high-strength, vanadium-nitrogen steels.

**INTERGRANULAR FERRITE NUCLEATION IN HEAVY SECTIONS**

In heavy sections where accelerated cooling cannot be achieved, the vanadium-nitride precipitates produced during deformation promote the nucleation of ferrite grains within the grain boundaries. The combined nucleating effect within the grains and the grain boundaries produces a fine ferritic structure in the finished steel.

The smallest grains are found in the vanadium-nitrogen steel at the bottom. Therefore, this steel has the best combination of strength and toughness.

NO VANADIUM, 44 PARTS PER MILLION OF NITROGEN

0.48% VANADIUM, 212 PARTS PER MILLION OF NITROGEN
Concerned about Strain Aging? Not When Vanadium is Present!

For some steelmakers, adding nitrogen would seem to be the fastest way to send a heat to the scrap yard. So-called “free” nitrogen causes strain aging in carbon steels, increasing yield strength and brittleness after cold working. Strain aging is particularly detrimental in sheet products where it reduces formability.

However, when a nitride former such as vanadium is present, nitrogen becomes an extremely useful element. In high-strength, low-alloy steels, nitrogen combines with vanadium to become a very cost-effective strengthener. Of the three nitride-forming elements – vanadium, aluminum, and titanium – vanadium is the only element that effectively strengthens steel by combining with nitrogen.

For optimum strengthening

Slow cooling after austenite is transformed into ferrite will optimize strengthening from vanadium and nitrogen. This practice maximizes the precipitation of the vanadium nitrides that provide strengthening while eliminating strain aging. For strip steels, coiling temperatures of 600 to 630 deg. C (1,100 to 1,150 deg. F.) followed by slow cooling in the coil optimizes vanadium-nitride precipitation.

![Graph showing relationship between total nitrogen and aging index for C-MN and V Microalloyed steels](image)

Plain-carbon steels containing as little as 0.006% nitrogen showed significant strain aging after simulated coil cooling. On the other hand, strain aging was virtually eliminated in vanadium-strengthened HSLA steels containing as much as 0.020% nitrogen.

Excellent Weldability

Extensive research and technological studies have shown that the toughness of the heat-affected zone (HAZ) in vanadium-nitrogen steels depends on the transformation products and not on the nitrogen content. Excellent toughness can be obtained in these steels at heat inputs up to 4 kJ per mm (100kJ per in.) used in a majority of welding processes.
How Nitrovan® Vanadium Improves Steelmaking Operations

Nitrovan® vanadium is a high-purity product with low levels of residual elements. Its aluminum content is particularly low compared to ferrovanadium.

Each 0.01% added as Nitrovan® 12 vanadium raises the total nitrogen content in steel by about 10 parts per million (0.001%). A similar addition of Nitrovan® 16 vanadium raises the nitrogen content by about 13 parts per million (0.0013%).

Specifications: Nitrogen Strengthening Plus Low Aluminum

<table>
<thead>
<tr>
<th>ALLOY</th>
<th>VANADIUM</th>
<th>NITROGEN</th>
<th>CARBON</th>
<th>ALUMINUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrovan® 12 Vanadium</td>
<td>77-81%</td>
<td>10-14%</td>
<td>10% max.</td>
<td>0.15% typical</td>
</tr>
<tr>
<td>Nitrovan® 16 Vanadium</td>
<td>76-81%</td>
<td>14-18%</td>
<td>6% max.</td>
<td>0.15% typical</td>
</tr>
<tr>
<td>80% Ferrovanadium</td>
<td>78-82%</td>
<td>ALLOY</td>
<td>0.25% max.</td>
<td>1.5% max.</td>
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Nitrovan® vanadium briquets are packed in moisture-resistant bags containing 25 lbs. or 10 kg of vanadium.
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