# Vanadium in Medium and High Carbon Steels

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## Introduction

Medium and high carbon steels are widely used in many common applications. Increasing carbon as the primary alloy for higher strength and hardness of steels is usually the most economical approach to improved performance. However, some of the effects of elevated carbon levels include reduced weldability, ductility and impact toughness. When these reduced properties can be tolerated, the increased strength and hardness of the higher carbon materials can be used to a significant advantage. Common applications of higher carbon steels include forging grades, rail steels, spring steels (both flat rolled and round), prestressed concrete, wire rope, tire reinforcement, wear resistant steels (plates and forgings), and high strength bars.

To increase the performance of steels in these applications, it is common to maximize strength and hardness by raising the carbon to the highest practical level. The limiting factor to carbon additions will vary depending on the type of applications. For forging steels and bar products, it may be toughness or weldability. For high strength wire, the limiting factor for carbon addition is generally the eutectoid carbon level, above which the presence of grain boundary carbides will dramatically reduce drawability.

Regardless of the application, there will be a practical limit to increasing the carbon level. If there is a need to continue to improve the performance of the steels with additional strength or hardness, other strengthening mechanisms must then be considered. Of the available choices, precipitation strengthening using a microalloy addition is a common practice.

In addition to increasing the as-rolled or as-forged strengths, microalloy additions can also provide other advantages. Microalloys are used as for producing fine grain steels. Microalloy precipitates provide resistance to austenite grain growth during heat treating operations by pinning the grain boundaries, preventing the movement of these boundaries necessary for grain growth.

Microalloy precipitation, particularly with vanadium, can also provide temper resistance for quenched and tempered steels. Using these temper resistant properties, higher hardness and strength levels of tempered martensite can be maintained through a given tempering cycle. Using higher tempering temperatures, the toughness of tempered martensite can be enhanced while maintaining the hardness level.

## Advantages of Vanadium

The available choices for microalloying include niobium, titanium, and vanadium. Of these, vanadium is the preferred addition for several reasons. First, and probably most importantly, the high solubility of vanadium carbonitride [V(C,N)] compared to the other microalloying alloy alternatives allows the vanadium to be in solution during normal reheating temperatures, either for rolling or forging. Titanium nitride (TiN) has the lowest solubility, either as a nitride or carbide, and is generally ineffective as a precipitation strengthener in high carbon steels. Niobium carbonitride [Nb(C,N)] also has lower solubility than vanadium. Because carbon is the preferred element for precipitation with Nb, the high carbon levels in these steels reduce the solubility of Nb even further. The amount of Nb in solution during reheating of high carbon steels is limited and dependant on reheat temperature. For higher Nb additions, the strengthening effect will be unpredictable because small variations in reheat temperature will result in significant differences in the amount of Nb in solution.

V(C,N) is more easily dissolved in high carbon steels, and is less sensitive to the carbon level than niobium. Normal reheat temperatures (1150□C to 1250□C) are sufficient for dissolving all vanadium carbonitrides over the full range of expected alloy compositions. As a result, vanadium strengthening is proportional to the amount of vanadium added. This linear relationship between vanadium additions and strengthening is very useful for estimating the amount of alloy addition needed to meet minimum strength levels.

Vanadium has a natural affinity for nitrogen. When adequate nitrogen is available, V(C,N) precipitates have been determined to primarily nitrides, usually with a ratio of V(C0.2N0.8). Because of this preference of vanadium for nitrogen, nitrogen enhances the performance of vanadium steels. As a result, nitrogen is no longer is solid solution where it can contribute to embrittlement. Vanadium transforms nitrogen from an unwanted tramp element to an integral part of the alloy system.

Because medium and high carbon products are often continuously cast using metering nozzles without flow controls, the use of Al for grain refinement is not feasible because of reoxidation problems. Vanadium is easily cast under these conditions, making V an excellent alternative to Al as a grain refiner for heat-treated products.

## Applications

Some examples of applications for vanadium microalloyed medium and high carbon steels are described. Because of the author's experience, the applications are typical of the North American steel business. In other markets, there may be additional noteworthy examples of effective utilization of vanadium in these steel grades.

- Forging Steels:

Vanadium microalloyed forging steels represent a cost-effective replacement of quenched and tempered grades. The strength properties of these grades are derived from precipitation of V(C,N) during cooling from the forging temperature. Achieving the final strength properties in the as-forged condition eliminates the cost of additional heat treatments. The inherent cost advantages of these steels have been reinforced by recent studies showing that the reduction in machining costs compared to quench and tempered steels is substantial.

Medium carbon forging steels, microalloyed with vanadium enhanced by appropriate levels of manganese, silicon, chromium, nitrogen and sulfur, have replaced quenched and tempered forgings in many automotive applications. Crank shafts, connecting rods, and axle beams are parts that are successfully being produced with these microalloyed steels. Continuing advances in alloy and processing are extending the application of these steels to more difficult service conditions at higher hardness and strength levels.

- High Carbon Wire Rod

To reach higher as-drawn wire strengths for applications such as prestressed concrete tendons, higher starting rod strengths are required in the as-rolled condition. High strengths in pearlitic steels are obtained by maximizing the carbon level, and by producing as fine of a pearlite spacing as possible. The upper limit to the carbon level that can be used is dependent on the process capability of a given steel mill. The formation of a continuous grain boundary carbide film, usually in the segregated center of a billet or bloom cast steel, will determine the maximum carbon level that can be used. Typical maximum carbon levels for these applications are 0.82 to 0.85%. Since lead patenting is no longer a competitive alternative because of costs, additional strength is achieved by adding hardenability elements such as Mn and Cr to match hardenability to the controlled cooling capabilities of the rod rolling process. The objective is to produce a fine pearlite similar to a lead patented structure.

With the limitations of the rod cooling process compared to lead patented rods, strengths will still fall short of lead patented rods. Additional strengthening is achieved by precipitation hardening of the soft constituent of pearlite, the ferrite. Vanadium is widely used as a pearlite strengthener in eutectoid C-Mn steels for wire rod applications. Strength increases of 10 to 16 MPa per 0.01% V added are reported. The high solubility of the vanadium allows additions over 0.10% V to be added with predictable strengthening results. Because of this predictability, vanadium is the element of choice to be used as the strength control element when refining steel to specific strength levels. Direct drawn wire applications that require maximum strength, such as prestressed concrete tendons, tire bead wire, and wire rope are common applications of vanadium microalloyed pearlitic steels with eutectoid carbon levels.

In addition, the addition of Vanadium will remove nitrogen from solid solution as V(C,N). Nitrogen in solid solution contributes to strain aging during wire drawing, resulting in reduced ductility of the finished wire. Higher ductility, usually measured by the wire torsion test, is reported using vanadium microalloyed steels in direct drawn wire applications. Again, vanadium changes the nitrogen from an undesirable element to an integral part of the alloy system.

- Hot rolled bars, shapes and flats

Vanadium is used effectively in many long product applications where higher strengths are required using conventional rolling processes and with restricted carbon levels. One of the most common applications is for high strength rebar where carbon equivalent restrictions for weldability prevent the use of higher carbon. These applications are discussed at length in another presentation at this conference.

Modern high speed rolling equipment for long products make it difficult to finish roll at low temperatures necessary for conventional controlled rolling. Recrystallization controlled rolling practices using vanadium can be applied on these rolling mills, allowing the production of fine ferritic microstructures along with high precipitation hardening.

An example of using these practices is for high strength flat bars from 10 to 20 mm in thickness used as flanges in flat bed truck trailers. Minimum yield strengths from 410 to 550 MPa are produced using V-N or V-Ti-N microalloying. Rolling in a high temperature regime with recrystallization controlled rolling practices results in sufficient grain refining to meet impact requirements of 20J at –29°C. High strength structural beams for cross members of flat bed truck trailers are also made using similar practices. In all cases, care is taken to manage the nitrogen levels to insure maximum effectiveness of the vanadium additions.

Another example of a high strength bar steel application is for shafts in hydraulic cylinders. A C10V45 grade with a minimum 550 MPa yield strength is preferred. To achieve these strengths, vanadium is used in levels up to 0.10%, along with 0.45% C, 0.8% Mn and 0.25% Si to produce these bars up to 100 mm in diameter.

- Rail Steels

Another example using vanadium to strengthen pearlitic steels is rail steel applications. Railroad rails produced from vanadium microalloyed steels have been shown to have higher strengths and higher fatigue resistance. Because of these properties, rail steels microalloyed with vanadium show enhanced service durability. Although in the USA rail steels are not microalloyed, in many countries, including China, rail steel with vanadium is a commonly produced grade. These steels may be used in the as rolled or heat treated condition.

**Summary**

This brief review of applications of vanadium to medium and high carbon steels is only an indication of the many applications where vanadium is the microalloy of choice. Vanadium has many advantages in ease of processing and in effectiveness of achieving desired properties. These advantages, particularly ease of casting and high solubility, are particularly useful when manufacturing medium and high carbon steels. The proportional strengthening properties of vanadium, with no negative side effects on properties, makes vanadium the microalloy of choice for these applications. The following references are only a few examples of the literature supporting the conclusions of this paper.

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