A New Role for Microalloyed Steels – Adding Economic Value

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Abstract

Microalloyed (MA) steels have matured during the past 40 years into an important class of high-strength structural materials. Their cost-effectiveness has been enhanced by the growth of electric-arc-furnace (EAF) steelmaking and the thin-slab-casting process. A recent project involving an ultra-light-steel auto body (ULSAB) concluded that high-strength-steels are the materials of choice for the automotive industry. This project showed that replacing cheaper carbon steels with high-strength steels allowed automakers to reduce the weight of an auto body at the same or at potentially lower costs. The same economic principles can be applied to other applications.

The strengthening effects of vanadium make microalloyed steels particularly suited for high-strength-steel applications. By effectively combining grain refinement and precipitation hardening, vanadium maximises the strengthening process and is compatible with current steel-processing technology.

To dramatise the cost effectiveness of these high-strength-steels in potentially new applications, a series of demonstration projects is needed involving the cooperation of steel producers, fabricators, and users. In many applications, the decision to replace plain-carbon steel with higher strength vanadium-bearing microalloyed steel can be shown to improve the profitability of both the steelmaker and the steel user.

1. Introduction: Use of Microalloyed Steels Reduces Costs

The development of microalloyed steels, including their alloy design, processing, and applications, covers the last four decades.[1-4)] During this period, microalloyed, high-strength, low-alloy (HSLA) steels became an indispensable class of structural steels. Their ability to achieve final engineering properties in as hot-rolled conditions eliminated the need for heat treatments, such as normalising. Yield strengths ranging up to 550 to 600 MPa can be attained through small additions (less than 0.1%) of selected carbonitride formers without requiring costly alloying elements. The resulting cost-effectiveness of microalloyed steels led to the successful displacement of heat-treated steels in applications such as truck side rails and telescoping crane booms. Recent technological developments in steel melting and hot rolling further reduced the cost and enhanced the competitiveness of microalloyed steels.

Despite these improvements, the total consumption of microalloyed steel is currently estimated to be only 10 to 15% of the world's steel production (i.e., 80 to 120 million tons per year). This tonnage is about evenly distributed between flat and long products. As a result, there is plenty of room for growth. A major jump in the usage of microalloyed steels should have strong economic benefits for both steel producers and steel users.

2. Microalloying: Complimentary Strengthening Mechanisms

Hot-rolled plain-carbon steel is the most popular material used in construction. Its strength can be increased by raising the carbon content. In fact, its strength is proportional to the carbon equivalent (CE) which is essentially the combined effect of the carbon and manganese content of steel, based on the formula: [CE = %C + %Mn/6]. While raising the carbon equivalent increases strength, it also drastically reduces other engineering properties such as ductility, toughness, and weldability. Since welding is irreplaceable as a method of fabrication, the carbon-equivalent mechanism of steel strengthening cannot be used in many applications requiring weldability.

As shown in Figure 1, the success of microalloyed steels is due to complimentary strengthening mechanisms, specifically grain refinement and precipitation hardening.[5] Precipitation hardening increases strength but may contribute to brittleness. Grain refinement increases strength but also improves toughness. As a result, grain refinement counteracts any embrittling caused by precipitation hardening.

In practice, grain refinement can be achieved during hot rolling by the interaction between microalloying elements (niobium, vanadium, or titanium) and hot deformation. During the allotropic transformation, ferrite nucleates on austenitic grain boundaries. Maximum grain refinement can be achieved by increasing the austenitic grain-boundary area. This can be accomplished by either producing fine grains of austenite through repeated recrystallization between passes[6] or by flattening non-recrystallized austenite grains into "pancakes". The first process is generally used for vanadium steels and the second for columbium (niobium) steels.[7]

Grain refinement may be further enhanced by accelerating cooling after the completion of hot rolling. The undercooling of austenite enhances the rate of ferrite nucleation and slows down the rate of growth. A combination of these two factors contributes to the formation of smaller grains.

Significant strengthening is obtained by the precipitation of microalloying elements appearing as carbonitrides (or carbides) in ferrite.[8,9] Since their solubility in ferrite is much less than in austenite, there is strong supersaturation which provides the driving force for precipitation. The most desirable are those microalloys, which contribute to both grain refinement and precipitation hardening. The combined effect of these two strengthening mechanisms may provide as much as 70% of the yield strength, accounting for the remarkable cost-effectiveness of microalloyed steels.

Because these two dominant strengthening mechanisms operate in microalloyed steels, their carbon content (or CE) may be very low. A yield strength of 550 MPa can be obtained in a steel containing only 0.04 to 0.06% carbon.[10] This low-carbon content contributes to excellent weldability.

3. A New Function for Hot Rolling: Optimising Material Properties

Traditionally, the main objective of the hot-rolling process was to change the geometry of a slab or billet to meet the dimensions of the final product. For this purpose, the temperature of rolling was not well controlled, with the unwritten rule being "the hotter, the better".

Accomplishing the "miracle" of converting ordinary carbon steel into a sophisticated HSLA steel requires an understanding of the evolution of the austenite microstructure during hot rolling. At high temperatures, the size of a recrystallized grain after each deformation pass depends on the initial grain size, temperature, and the amount of deformation.[11] The tendency of grains to coarsen between passes can be prevented by precipitated particles within the grain boundaries. Finely dispersed titanium nitrides (TiN) formed by titanium additions as low as 0.005 to 0.007% effectively prevent grain coarsening. When the rolling temperature is low enough to prevent recrystallization, austenite is flattened into a "pancake". The temperature at which this occurs depends on the type of microalloy. Recrystallization is suppressed at a much higher temperature in niobium (columbium) steels than in vanadium steels.[7]

Grain refinement may be further enhanced by the intra-granular nucleation of ferrite in austenite.[12)] The precipitation of vanadium nitride in austenite provides the most effective intra-granular nucleation of ferrite. The highest rate of carbonitride precipitation in ferrite occurs at 600°C, which is the customary sheet coiling temperature.

4. Making Nitrogen A Friend, Not A Foe

Two new developments in steelmaking and steel processing – the growth of the electric arc furnace (EAF) and processing by thin slab casting have contributed to further cost reduction in the production of microalloyed steels.[13)]

EAF steelmaking is growing rapidly worldwide because it is less capital intensive than the conventional processes used by integrated steel producers. Virtually all new steelmaking capacity added either by mini-mills or integrated producers, uses electric arc furnaces. Soon, 50% of the world's steelmaking or about 400 million tons annually will be made in these facilities.

In a scrap based EAF practice, the nitrogen content is 70-100 ppm or 2 to 3 times higher than that typical of the basic oxygen or BOF practice. The nitrogen level of steels made in an EAF can be reduced by modifying the slag practice or changing the feed stock. Both these methods can increase costs.

Free nitrogen in solution in ferrite, has serious detrimental effects such as aging and brittleness. During concasting, excessive nitrogen may increase possible transverse or longitudinal cracking. Fears are also frequently expressed about the detrimental effects of nitrogen on weldability.

However, the harmful effects of nitrogen may be neutralised by nitrogen binding elements which acting as scavengers, remove nitrogen from solid solution in ferrite. Aluminium and titanium are effective scavengers; however, niobium (columbium) is not an effective nitrogen-binding element in high strength, low alloy steels. In niobium steels, niobium carbonitrides are only present when the carbon to nitrogen ratio ranges between 1:1 and 4:I. Thus, the effect of niobium depends on the nitrogen content of the steel.

Among the various microalloying elements, vanadium has a unique dual effect on nitrogen.[14)] Vanadium not only neutralises nitrogen by forming VN compounds but also uses nitrogen to optimise the precipitation reaction. Enhanced nitrogen increases the supersaturation in ferrite and promotes a more active nucleation of V(C,N) particles, as shown in Figure 2. Consequently, the interparticle distance is reduced (Figure 3) and the strengthening effect of precipitation is increased. In the presence of nitrogen, less vanadium is needed to achieve the desired yield strength. As a result, vanadium effectively converts nitrogen, previously considered an impurity, into a valuable alloy that helps strengthen steel, as shown in Figure 4.

The pioneering efforts of the Nucor Steel Corporation[15)] in commercialising thin slab casting have dramatically changed the economics of hot band production. The revolutionary effect of this new process can be compared to two previous developments which have changed the economics of steel production: the switch of steelmaking from open hearths to a basic oxygen (BOF) converter and the replacement of ingot casting by continuous casting.

The thin slab casting process converts in-line liquid steel into a marketable product.[16)] The process incorporates a series of steps that contribute to either cost reductions or to property improvements. The rapid solidification in the mould accounts for the small size of globular inclusions, which do not elongate during hot rolling. This promotes isotropic properties, such as bendability, in longitudinal or transverse directions. Near net-shape dimensions of the slab

(50 - 70 mm) facilitate rolling to an aim thickness of 1 mm (or less), allowing hot rolled steel to economically replace cold rolled sheet. In-line processing permits the slab to be directly charged into the rolling mill, contributing to energy savings. The amount of deformation per pass is 2 to 3 times higher than that on a hot strip mill rolling thick slabs. Excellent microstructure and properties are obtained in a 15-mm thick strip for a total deformation of less than 4:1.

Because of lower hot rolling costs, the market share for hot bands produced by thin slab casting is being increased at the expense of high cost integrated producers. In developing the concept of replacing carbon steels with microalloyed steels, we will limit our choice initially to strip made by thin slab casting technology.

5. Ultra-Light Steel Auto Body: Quantifying the Economic Benefits of Microalloyed Steel

The pressure to reduce the weight of automobiles and the ever-present threat from light-weight materials such as aluminium or magnesium led to the creation of an international consortium of steel producers whose goal was to produce a lighter-weight auto body. Over 30 steel producers jointly sponsored an ambitious project: Ultra Light Steel Auto Body (ULSAB).[17)] The objectives of the project were three-fold: (1) design a stronger and safer auto body, compared to best models available, (2) lower the weight, and (3) keep costs the same or less than auto bodies being built today. All three goals have been successfully attained. Three factors contributed to the success of the project: novel design concepts, material selection, and new fabrication methods.

In the area of materials, the most important change was the replacement of inexpensive carbon steel with higher value HSLA steels. More than 90% of the ULSAB structure used high strength steel ranging in yield strength from 210 to 420 MPa. One half of the steel used had 350 MPa yield strength. Both cold and hot rolled sheet, 0.65 to 2.0 mm in thickness, have been used. The use of steel stronger than 420 MPa was minimal.

HSLA steel emerged as the material of choice for modem automobile design. For a cost conscious automobile industry, the use of more expensive HSLA steel was found to be economically attractive as a replacement for cheaper carbon steel.

Years ago, a GM executive made a controversial statement: “What is good for General Motors is good for America." Today, we may paraphrase this slogan: "What is good for ULSAB may be good for many steel processing industries." The ULSAB project demonstrated that the competitiveness of steel hinges on the following parameters: engineering properties and fabricability, weight reducing potential, and cost.

Thanks to technology advances and the successful adaptation of a series of cost reduction steps, microalloyed steels have all the necessary attributes to successfu11y replace inefficient and often higher cost carbon steels in such areas as construction, transportation, and machine building.

6. Weight Reduction: The Key to Adding Economic Value

Microalloyed, high strength, low alloy steels may have yield strengths that are 2 to 3 times higher than hot rolled, weldable carbon steels. The weight reduction achievable through substitution depends not only on the difference in strength but also on the mode of loading. For straight loading in tension, the weight reduction is proportional to the difference in strength. An increase in yield strength by a factor of two may reduce the weight of steel by two - a situation found in concrete reinforcing bars. The range of weight savings is shown in Figure 5.

For other types of loading (e.g., bending), a two fold increase in strength may contribute to a weight reduction of 34% or more. Considering a safety factor, one may as same as the HSLA steel, being twice as strong as carbon steel, may reduce the weight by at least 25%. The following simplified calculation illustrates the economic value obtained through substitution:

HIGHER PROFITS FOR STEELMAKERS
(Dollars per Ton of Steel)

	Carbon Steel	Microalloyed Steel
Selling Price	350	415
Microalloying Cost	-0	-15
Other Production Costs	-300	-300
Steelmaker's Profit	50	100

Because of 25% Weight Reduction,
0.75 Ton of Microalloyed Steel
Replaces
1 Ton of Carbon Steel

LOWER COSTS FOR USERS
(Dollars per Ton of Steel)

Carbon Steel (1 Ton x $350)	350
Microalloyed Steel (0.75 Ton x $415)	311
Cost Savings	**39**

It is evident that the substitution is economically attractive for both the producer and user. The producer may enjoy twice as much profit for the value added microalloyed steel. The user pays $39 less for the material. His additional benefits include ease of fabrication, improved overall properties (e.g., toughness, ductility), and lower transportation cost. The range of cost savings is shown in Figure 6.

7. Vanadium: Offering the Lowest Cost Per Unit of Strength

In selecting the most economical microalloyed steel, the following factors should be considered: (1) alloy design that maximises the strengthening effect of the two cost effective mechanisms grain refinement and precipitation hardening), (2) low processing cost affected by reheat and finishing temperatures, and (3) compatibility with the typical nitrogen content of electric furnace steels.

Of the three microalloying elements - niobium, vanadium, and titanium - only vanadium contributes to cost reductions in all three areas listed above. By incorporating vanadium in an alloy design, both grain refinement and precipitation hardening will be fully utilised, providing up to 70% of the total yield strength. In addition, vanadium permits the use of the lowest cost hot rolling practice. Because of the high solubility of vanadium nitride (VN) in austenite, a low reheating temperature (1150°C) may be used. This contributes to energy savings. At the same time, the finishing temperature may be high (900 to 1000°C), since grain refinement is obtained by repeated recrystallization. Finally, vanadium not only neutralises the ill effects of "free" nitrogen; it uses this "impurity" as a valuable alloying element - a unique characteristic among microalloying elements.

There are virtually unlimited sources of vanadium on earth.[18)] Vanadium is extracted from vanadium bearing ores (Australia), as a by-product of steel production from iron ore containing both vanadium and titanium (South Africa, Russia, and China), from spent catalysts (U.S.A.), and from oil products (U.S.A.). At present, the existing industrial capacity for vanadium production exceeds the demand. With new sources of supply on the horizon, shortages are not likely to occur in the foreseeable future.

8. Unlocking the Commercial Benefits

Based on the example in the ULSAB project, it can be seen that substituting a higher value steel in an existing application brings economic and performance benefits. One way of achieving this objective is through the use of demonstration projects. These demonstrations must be conducted on carefully selected products with a full understanding of the potential benefits for the steel producer, fabricator, and the user.

As an example, microalloyed steel might be substituted for commonly used carbon steel in the production of spirally welded water pipe. For steel producers, this substitution would increase their share of value-added products, which command a higher profit margin. For the fabricator, the ease of welding a low carbon (0.04-0.06% C) microalloyed steel provides a strong incentive in the form of reduced labour costs. In addition, the user will benefit not only from lower material cost but improved strength and fracture resistance for safe operation.

To deliver these benefits, each demonstration project must fully document and evaluate the service performance and provide a detailed cost analysis. The project should also assure that mandatory standards and specifications are met. Finally, the results of the demonstration project should be incorporated into pertinent engineering specifications and brought to the attention of designers and engineers through educational and promotional efforts.

9. New Opportunities for Producers and Users

The selection of high strength steels as the material of choice by the automotive industry suggests new opportunities for microalloyed steels in a variety of applications. Their high strength compared to hot rolled carbon steels offers an opportunity for significant weight reduction. This lower weight more than offsets the slightly higher unit cost of microalloyed steels, adding economic value to both steel producers and steel users. For steelmakers, selling more value-added high strength steels improves their competitive position against light-weight materials and allows increased profit margins. For users, value-added high strength steels offer lower material costs, better product performance, and reduced fabrication and transportation costs.

The feasibility of satisfying all engineering needs with less steel is also advantageous for the national economy. It reduces the pressure of capital intensive demands for replacing obsolete traditional steelmaking facilities. In addition, any shortfall in the capacity of integrated producers will be balanced by cheaper and more flexible electrical furnaces.

The path from a theoretically attractive concept of substitution to commercial reality requires a dedicated effort, mainly by the steel industry. Nevertheless advances achieved during the past 40 years in the science, technology, and applications of microalloyed, high strength steels make them ready for this economic challenge.

In fact, the importance of weight reduction and greater emphasis on value-added products are squarely in line with the trends of the steel industry as reflected in the following quotations:

"The steel industry's weight paring campaign is an investment in the future." (Al Wrigley, American Metal Market, June 26, 2000)

"Innovative technology will help us to produce the high-value-added steels, critical to our success and the success of our customers." (Paul J. Wilhelm, President, U .S. Steel, New Steel, June 2000, page 56)

10 Conclusion

The new role of microalloyed steels in adding economic value through replacement of hot rolled carbon steels is feasible today. Potential economic benefits to the steel industry and its customers could reach billions of dollars annually.

The competitive advantages of microalloyed steel compared to hot rolled carbon steel include superior fabricability, weight reduction by at least 25%, and lower overall cost. To fully exploit these benefits requires vision and dedication on the part of the steel industry and its customers. The economic advantages to both producers and users - typical for a "win-win" situation, provide a strong incentive for initiating a drive in this direction.

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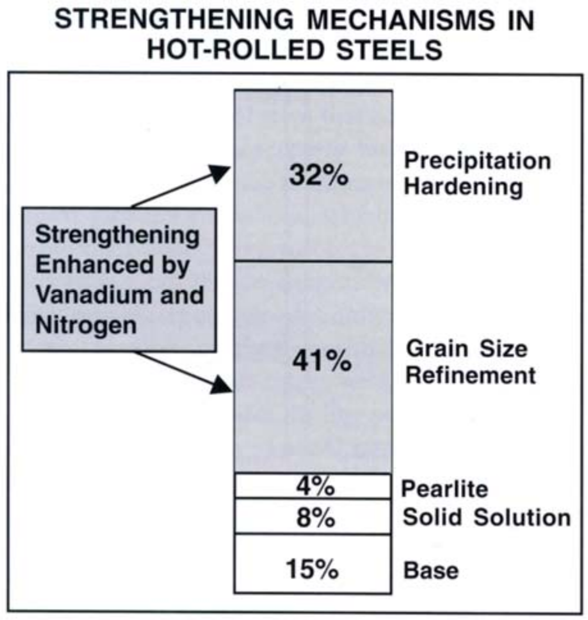

Fig. 1 The strength of hot-rolled steel depends on the five mechanisms shown above. In high strength low alloy steels, microalloying elements such as vanadium and nitrogen provide up to 70% of the strength by contributing to grain refinement and precipitation hardening.[5)]

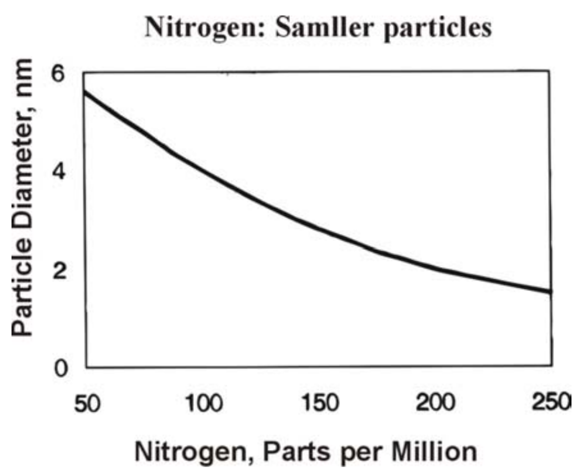

Fig. 2 Increasing the nitrogen content promotes nucleation, forming smaller vanadium-nitride particles.[8)]

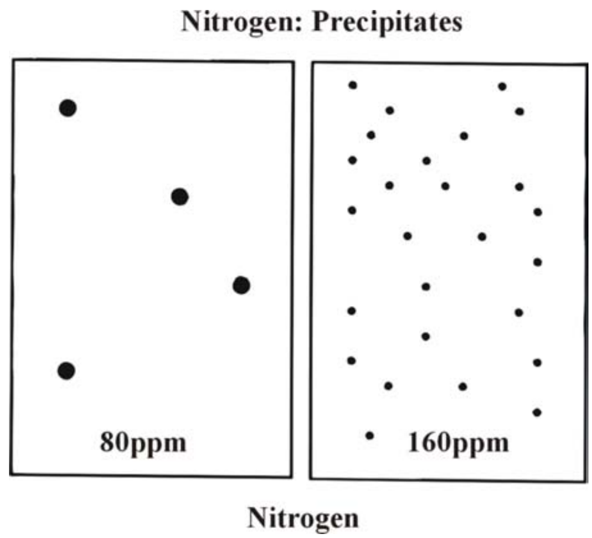

Fig. 3 Reducing the particle diameter of precipitates from 4 to 2 nm gives eight times the number of precipitates in a given volume of steel. The larger number of small precipitates gives more efficient strengthening by reducing interparticle spacing,

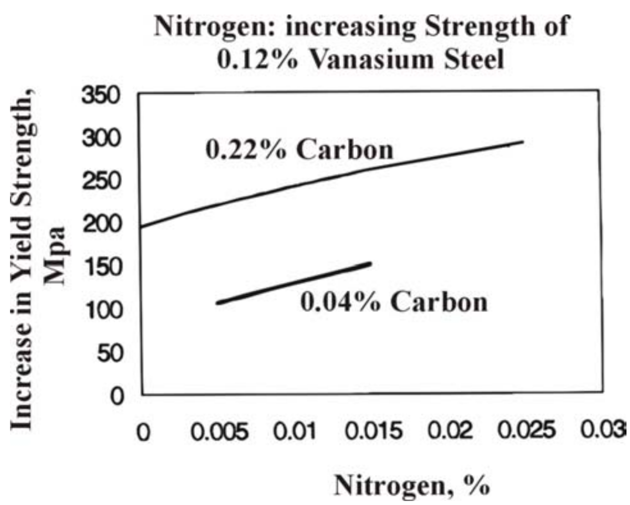

Fig. 4 In vanadium steels, nitrogen acts as a valuable alloy that helps increase yield strength.[14)]

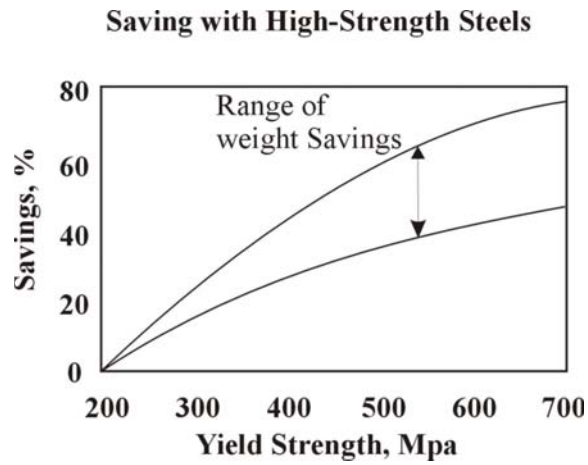

Fig. 5 The weight of components can be reduced substantially by substituting high-strength steel for low-strength carbon-manganese steel (SSAB Sheet Steel Handbook).

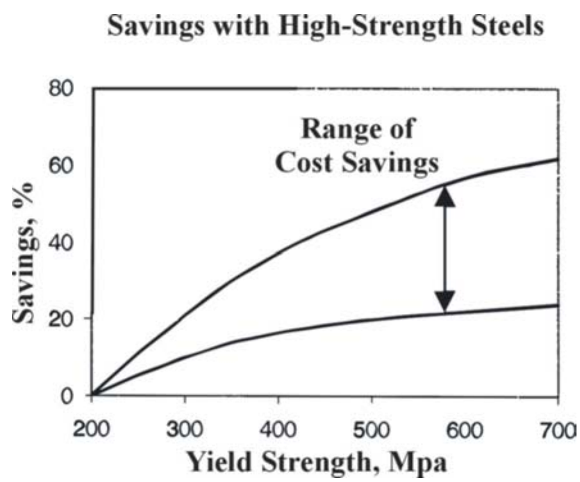

Fig. 6 Because of the cost effectiveness of microalloyed steels, the weight reduction more than offsets the difference in prices between microalloyed and carbon-manganese steels (SSAB Sheet Steel Handbook).