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The Role of Microalloyed Steels in the Age of Explosive Growth of Steel Usage

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Abstract: The beginning of the 21st century coincided with a surge in steelmaking capacity, driven mainly by China. This reflects a global trend in underdeveloped countries to eliminate poverty and raise the standard of living. Steel is the indispensable material for modernization. The rapid increase in steelmaking capacity triggered strains in the supply-demand balance. The resulting shortages in raw materials, energy and means of transportation contributed to raising prices. Furthermore, the increase in polluting emissions (CO2) created additional dangers to the environment. To minimize the ills of steel expansion, a "sustainable" rate of growth has been postulated. An effective method to make the expansion of steelmaking "sustainable" is by satisfying the engineering needs with less steel of higher (stronger) quality. Microalloyed (MA) steels are suitable as a replacement of commodity grade carbon steels. High strength and weight reducing potential of MA steels are derived from microstructural changes taking place during hot-rolling and subsequent cooling. Means for achieving maximum weight reduction at minimum cost are discussed in detail. By contributing to a "sustainable" growth rate of steel production, microalloyed steels fulfill a new role: they create economic value and wealth. To achieve global economic goals of underdeveloped countries, substitution may be a necessity, rather than an option.

Key words: microalloying, vanadium, nitrogen, strengthening mechanisms, substitution of carbon steel, sustainable growth, wealth formation.

1 The Age of Maturing of Microalloyed Steels

The second half of the 20th century represents a period of growth and maturing of HSLA (or microalloyed (MA)) steels. The "miracle" of microalloying in transforming a commodity grade C-Mn steel into a value-added HSLA steel excited the imagination of metallurgists world-wide. Beginning with the early studies on "pearlite-reduced" steels at BISRA (British Iron and Steel Research Association), there were during the next five decades countless international conferences on all five continents. Dealing mainly with ferrite-pearlite class steels, voluminous proceedings of these conferences represent a unique body of information on a single group of steels. The intensity of the expended R&D effort leads some experts to conclude that development and perfection of MA steels represents the most significant metallurgical achievement of the past century.

Two theoretical concepts laid foundation and provided guidance for the international research. First, an empirical equation of proportionality between the yield stress and the inverse square root of ferritic grain dimension provided a quantitative measure of the effect of microstructure on properties. This relationship, discovered by Petch, has shown that grain refinement is unique in its ability to increase both strength and improve toughness[1]. The necessity of using carbon for strengthening hot-rolled steel has been diminished. The second milestone was Pickering's method of quantifying the contribution of various strengthening mechanisms to the strength of ferrite-pearlite steels[2].

These two contributions changed the methodology of high strength steels development. Chemical composition was no longer the sole criterion defining properties. The combined effect of chemistry and processing parameters determines formation of a microstructure which controls the mechanical properties. Realization of the importance of grain refinement led to intensive studies on the evolution of austenite in the process of hot-rolling. The aim was to "condition" the austenite in such a way as to produce finest ferrite size. The three MA elements: Nb, Ti, and V, were found to have different effect on suppression of recrystallization during hot-rolling. The "recrystallization stop temperature" was highest for Nb and lowest for V addition. Brilliant paper by Fukuda has shown that austenite can be equally well "conditioned" by rolling either above or below the recrystallization stop temperature[3]. The low-temperature regime of rolling in the unrecrystallized region is termed Conventional Controlled Rolling (CCR). High-temperature regime of rolling fully recrystallized austenite is named Recrystallization Controlled Rolling (RCR).

The CCR was accepted for plate rolling, mainly because of data presented by Kozasu[4]. In his study, coarse grains of austenite produced finer ferrite when transformed from unrecrystallized than form recrystallized state. The CCR practice has serious shortcoming: high rolling loads and low productivity because of delays to reach low finishing temperature. Plates for line pipe represent one of major applications of this rolling practice.

In processing MA steels on a hot strip mill (HSM), excellent grain refinement is obtained by applying the RCR practice. This is possible because of short interpass time, preventing coarsening of recrystallized austenite. Lowering of the transformation temperature by accelerated cooling (AC) supplements the grain refining potential of "conditioned" austenite. The first lamellar cooling system on a 2 meters wide HSM was installed in mid-eighties by the Johns & Laughlin Steel Co. (J&L) in Cleveland, OH, and this technology of "controlled cooling" was instantaneously accepted world wide[5].

The J&L team, using the new AC system, achieved several successes in MA steels technology:

(a) The first hot-rolled strip of 550 MPa yield stress combined with excellent engineering properties[6].

(b) Reduction of anisotropy of properties by inclusion shape control, dispelling the "common wisdom" that a high YS/UTS ratio is responsible for limited transverse bendability[7].

(c) Use of nitrogen and vanadium, to maximize the effect of precipitation and to prevent aging[8].

The thin slab casting and rolling, an innovation perfected during the last decade of the past century, represents a breakthrough in the economics of hot-band technology. In-line processing from liquid steel to a marketable product, coupled with hot-charging, delivers lowest cost product, compared to traditional rolling practices[9].

In long products, use of MA was found to be particularly effective in medium-carbon forging steel. Strength was enhanced by precipitation of VN, and toughness was improved by small austenite grains, prevented from coarsening by finely dispersed TiN particles.

In heavy sections, grain refinement by hot deformation is difficult. Here the possibility of using intragranular nucleation of ferrite has been first reported by Nippon Steel researchers[10].

Intensive studies by world's scientists accumulated a detailed pool of knowledge on science and production technology of MA ferrite-pearlite steels. In spite of these advances, the total application of MA steels, modified mainly by Nb or V (single or in combination) is estimated to be in the range of 10 to 15% of the total steel production. Most frequently, the MA steels are used as a replacement of more costly, heat-treated alloy grades.

2 Sustainable Growth by Substitution

The beginning of the 21st century witnessed an unprecedented growth of steelmaking capacity and steel usage.

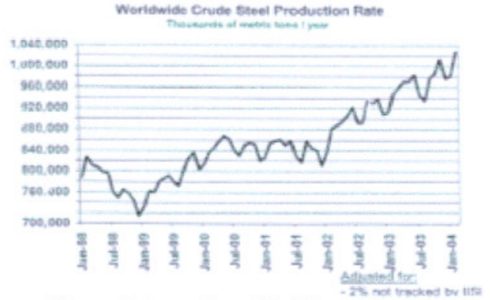

Figure 1: Annual worldwide steel production surpassed in 2004 one billion tons (IISI)

The benchmark of one billion tons annually was passed in 2004, and growth continues at a rate of 5 to 7%.

The main engine for growth is China. Production of steel is expected to reach here 350 million tons in 2005, about 30% of world's output.

The surge in steel consumption reflects the drive for accelerated modernization for the purpose of raising the living standards of the population. These goals are

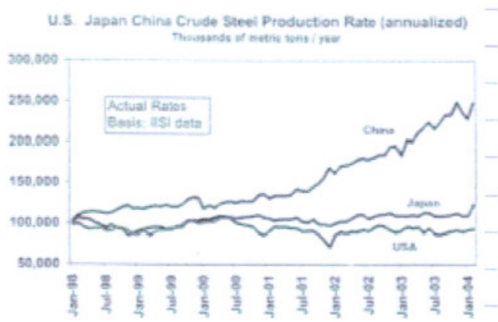

Figure 2 China is the main contributor to increase in steel production (IISI)

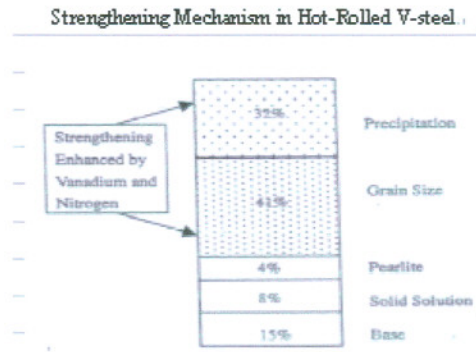

Figure 3 Grain refinement and precipitation hardening are the key strengthening mechanisms of HSLA steels.

similar for all developing nations. Advances in information technology accelerated the drive for economic emancipation: For that reason the explosive increase of steel production is not a cyclic phenomenon. It may persist for many decades to come.

The inevitable imbalance between supply and demand led to shortages of resources, steep price increases and alarming endangerment of the environment. To counteract these negative consequences, several measures have been considered to be able to maintain a "sustainable" growth rate. These include: conservation, recycling, use of low-energy processes, and exploration for new natural resources. The concept of "circular economy" envisions the enterprise being responsible not only for its economic success, but also for moderation in using resources, energy and be involved in environmental protection.

On this background, the possibility of satisfying engineering needs with less steel of better (stronger) quality appears promising[11]. The concept may be an important factor in facilitating a "sustainable" growth rate. It is not surprising that the idea of substitution is met with skepticism. For the producer, selling less steel suggests lower profits. The consumer, associates the use of a better quality product with higher cost. To change these negative perceptions, the weight reduction by substitution must be attained at low cost. This prerequisite is fulfilled when MA steel is substituted for commodity grade carbon (C-Mn) steel. The high strength of MA steel is derived from a change in microstructure during hot-rolling and subsequent cooling.

Almost 70% of the yield strength is due to two strengthening mechanisms: grain refinement and precipitation hardening.

To make the substitution economically attractive, the weight reducing potential must be maximized at lowest cost. This is achievable by optimizing the alloy design and the economics of processing.

Precipitation hardening is enhanced when the precipitation reaction in ferrite involves a high volume fraction of finely dispersed particles[12]. This requirement is satisfied by alloy design, aimed at a high degree of supersaturation of ferrite by MA element and the interstitials: C and N. Among the MA elements, vanadium is most suitable for this purpose; being highly soluble in austenite, virtually all vanadium is available for precipitation in ferrite[13]. As to the interstitial elements, nitrogen has the advantage of high solubility in ferrite. In fact, the amount of nitrogen in ferrite is the same as in austenite.

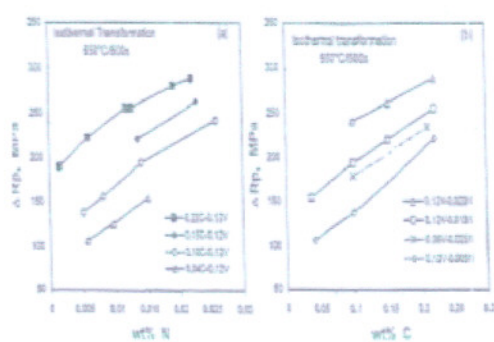

Figure 4 In vanadium steels, precipitation strengthening increases with the increase in of both nitrogen and carbon

The amount of carbon, on the other hand, may vary from 50 to 250 ppm, depending on the duration of austenite to ferrite transformation. In ferrite, vanadium forms vanadium nitride first. Carbon participates in the reaction after all nitrogen has been exhausted[14]. The high degree of supersaturation increases the driving force for particle nucleation and contributes to their small size. Decrease in the interparticle spacing enhances the strengthening contribution of precipitation.

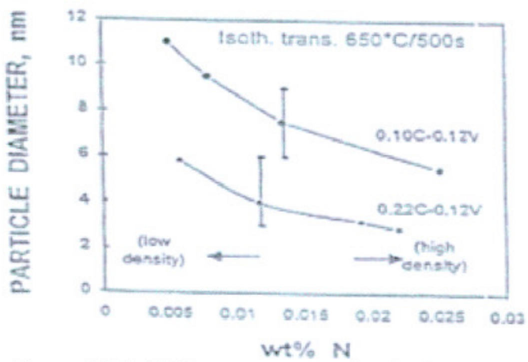

Figure 5 The higher supersaturation in nitrogen and carbon intensifies nucleation, produces smaller particles and increases strengthening

For these reasons alloy design utilizing vanadium and nitrogen offers a high and consistent precipitation strengthening.

The vanadium-nitrogen alloy system responds well to energy-friendly Recrystallization Controlled Rolling (RCR). Fine ferritic grain size (4-5 μm) is obtainable by rolling strip by the low-cost RCR practice[15].

Vanadium is also the MA element of choice for steel made by electric arc furnace (EAF) practice and for strip processed by thin slab technology[16]. Steel made in an electric arc furnace is high in residual nitrogen (70-100 ppm). Vanadium converts nitrogen from impurity into an alloy by forming vanadium nitride, simultaneously making steel non-aging. In hot-rolling by thin slab technology, the hot-charged slabs have coarse (over one mm) as-cast grains of austenite. The ease of recyrystallization of vanadium steels, indicated by low recrystallization stop temperature, facilitates grain-refinement and eliminates danger of mixed grains.

Because of these physico-metallurgical characteristics, the V-N steels are most suitable as an economically attractive substitute of carbon steels[17]. The use of V-N steel sheet having yield strength twice as high as carbon steel may reduce weight by about 30%.

A simplified cost comparison between MA and C-Mn steel is shown in Table 1, assuming a weight reduction of 25%. This means that 4 tons of C-Mn steels are replaced by 3 tons of MA steel.

Table 1 Advantages of MA Steel at a Substitute for C-Mn Steel (arbitrary units/ton)

	C-Mn Steel	MA Steel
Base	100	100
MA Element	---	15
Profit	20	40
Total Price	120	155
Profit	4x20=80	3x40=120
Material Cost	4x120=480	3x155=465

Using arbitrary cost units, the base cost of both steels is assumed as 100. The cost of MA addition is conservatively listed at 15. The profit postulated for C-Mn steel is 20 and for the value-added MA steel 40. The total cost of C-Mn and MA-steel is 120 and 155, respectively. In spite of selling less steel, producer's profit for MA steel is higher and the cost to the consumer is lower. This is a unique "win-win" situation, illustrates a new role for MA steel: creating an economic value.

It is of importance to note that the monetary value of one ton of Mn-C steel which was not made equals: 100-20=80 units. This amount has not been spent and is equivalent to wealth formation; this is a valuable contribution to the economy.

3 Path from Concept to Commercial Reality

Prospects for speedy realization of the concept of substitution are very promising in China. The "Iron and Steel Development Policy," issued recently (2004) by the National Development and Reform Committee (NDRC) provides a road map for a systematic implementation of substitution[18].

Specifically, Article 34 states that steel producers are encouraged to develop high strength and atmospheric corrosion resistant (weathering) steels to reduce weight and lengthen the life span of steel products. To reduce the steel consumption, the following projects are suggested: promotion of Grade III reinforcing bars (400 MPa YS), or of higher strength, high strength sheet and plate and heavy H-shape structures. To speed up the acceptance of new steel products, the construction departments are instructed to incorporate these new products into revised design specification and standards (Article 32). In this manner, the benefits of economical and resource saving products may become available without delay.

In compliance with the "Policy," the following projects may be initiated immediately:

(a) Resumption of full scale production of Grade III rebars as soon as the price of vanadium returns to commercially acceptable level.

(b) Initiation of steps, such as revised standards and design specifications, necessary for the utilization in construction of a stronger, Grade IV rebars (500 MPa YS). Rebars of this strength are in use in Europe. Use of Grade IV rebar will contribute to weight reduction of 30% or more, compared to 15% obtained for Grade III.

(c) Full advantage should be taken of high strength and low cost strip made by thin slab technology. New applications include cold formed structural shapes. The cold forming technology should be competitive to that available abroad (Sweden) [19].

(d) Production of high-strength atmospheric corrosion resistant (weathering) steels should be initiated, preferably by thin slab technology, as material for a new generation of light weight railroad cars, shipping containers, building components, etc.

(e) Improvements in heavy H-shaped structurals shall be accelerated by determining through research studies, the critical hot-rolling parameters optimal for intragranular ferrite nucleation.

(f) Simultaneously, a survey should be initiated to identify most promising large tonnage products suitable for substitution

An adequate availability of vanadium is a prerequisite for speedy expansion of substitution. The main source of V_2O_5 are vanadium bearing slags, a by-product of steel production form vanadium bearing titanomagnetite. These slags, accounting for 50% of world's V_2O_5 supply, are available from 6-7 steel plants, located mainly in S. Africa, Russia and China. They represent a combined annual tonnage of the order of 10-15 million tons. Looking into the future, an addition of one or two medium size steel plants, dedicated to both steel and V-bearing slag production, might suffice to support the expanding volume of V-steels.

Subtitution, i.e., replacement of inefficient carbon (C-Mn) steels by value added MA steels, creates a multitude of benefits. There are no technical or economic impediments which would prevent immediate sharing of these benefits. The rate of implementing substitution depends on the readiness of steel users to accept the idea of using less steel of better quality. The rate of acceptance may be influenced by promotion demonstrating both cost reduction and quality improvement. In this area, government may add special incentives or requirements, as was the case with the introduction of Grade III rebar.

4 The Role of Technology: Getting More for Less

The excessive steel usage may be reduced by satisfying engineering requirements with less steel of better (stronger) quality and that enables to maintain a "sustainable" growth rate. Furthermore, by replacing low-performance C-Mn steel with MA steel, significant economic benefits are created. These benefits are available to both steel producer and consumer. The steel producer is rewarded by higher profits, while the consumer pays less for the material, in addition to lower fabrication (welding) and transportation expenses. This creates a unique "win-win" situation.

Additional benefits resulting from reduced steel production include savings of capital, resources and energy as well as a decrease in polluting emission (CO_2), harmful to the environment.

The economic benefits derived from substitution are a direct result of the ability of MA steels to acquire their value (high strength and weight reducing potential) at a minimal cost equal to the cost of MA element addition. This characteristic has been discovered and perfected by expending an enormous amount of scientific and technological efforts. As a culmination of this

investment, MA steel has been created capable of replacing the C-Mn steel and simultaneously produce an economic value and contribute to wealth formation. This new role of microalloyed steel has a strong positive impact on economics. For that reason, MA steels are likely to play an important role in the current drive of developing countries to reach their economic goals.
The history of evolution and perfection of MA steels illustrates technology at its best: getting more for less.

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