Niobium-Bearing Steel Technological Developments for Long Products and Forgings

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INTRODUCTION

The technological development of value-added applications for niobium (Nb) microalloyed long products and forgings steels continue to increase globally meeting more demanding end user requirements. The global end user community is specifically seeking improved energy absorption behavior, improved fatigue life, better crack arrest capability, reduced component mass, and more efficient production with reduced emissions throughout the product life cycle. Within the forging sector, additions of microalloying elements affect the rate of grain growth during the heating of blanks, recrystallization parameters of deformed austenite, temperature of gamma-alpha transformation at cooling as well as the contribution to precipitation hardening of the ferrite constituent. Development of a seismic resistance resistant rebar, fine grain forgings and construction sections exhibiting better yield-to-tensile ratio consistency, improved energy absorption at low temperature and better weldability are described. Another rapidly expanding global niobium metallurgical sector involves both medium and high carbon long products. Micro additions of 0.005 to 0.020%Nb exhibit improved formability during manufacturing, uniform grain size as well as enhanced mechanical property performance compared with traditional non-Nb bearing treated medium and high carbon steels.

BACKGROUND INFORMATION

Long products in structural and automotive applications account for over 500 million tonnes of global steel production. Chemical and mechanical property requirements are quite diverse to accommodate the end user application. Nb-bearing steels are methodically being introduced in bars, shapes, forgings, wire rod, rail and rebar improving end user demands with stricter requirements compared to the traditional steels. These traditional steels have been applied for decades with relatively insignificant mechanical performance enhancements for the end user. The incorporation of Nb into numerous steel grades has transcended the traditional low carbon sheet and plate grades and has moved into value added medium and high carbon long products. For example, Nb is a key element in steel grades for eutectoid composition rail and prestressed concrete wire rod, engineering steels, carburized components, mechanical tubing for both energy and non-energy applications, antiseismic resistant reinforcing bar and forgings. The application of Nb-technology in medium and high carbon long products depends upon the design criterion of the end user. Often the customer may desire improved toughness, better fracture toughness, improved cyclic fatigue performance, more homogeneous grain size and microstructure. These mechanical property attributes are primary drivers and an increasing market trend demand within the long product global segment. On the processing side, with additions of Nb for carburizing and other heat treatment cycles can be shortened, thereby increasing throughput and productivity at a reduced cost.

Within the global rebar sector, demand for a better fatigue and antiseismic reinforcing bar has been developed incorporating Nb with congruent thermomechanical processing of a low carbon reinforcing bar at 500 and 600MPa strength levels. Such technological advancements incorporate niobium process metallurgy with sound and disciplined steelmaking and hot rolling practices and performance. It is important to leverage the attributes of niobium to obtain ultra-fine grain, homogeneous structural steel microstructures with superior mechanical properties. In addition, with the ever-growing concern regarding the environment and resource sustainability, the application of advanced high strength Nb-bearing steels for both long product and structural applications are shown to reduce resource usage and improve the carbon footprint. Recent Nb-microalloyed steel applications provide more efficient product designs, reduce steelmaking emissions and reduce overall energy consumption.

Microalloyed forging steels are being used in the hot forged condition without subsequent quenching and tempering resulting in manufacturing cost reductions. The high strength and exceptional toughness attributes are applied in numerous applications for automotive, truck and industrial machinery applications. The controlled forging of microalloyed steels has become a viable economical process for the manufacture of a variety of long product components. Ferrite grain refinement and precipitation hardening are the major micro-structural parameters to enhance the mechanical properties of these forged components. The evolution of microalloys (Nb, Ti, V and B) in forgings not only save energy through the elimination of heat treatment cycles, but offer other advantages over conventional heat treated steels in terms of inventory control, improved shape consistency and machinability, reduced processing time and overall better product quality. Another advantage of parts used in the as forged state is the ability to manufacture more complex-shaped parts that are difficult to make by the conventional quenching and tempering process due to the distortion problems resulting from very rapid cooling. The grain refinement of the microstructure with Nb is practically the only means available for increasing both strength and toughness without making appreciable composition changes which increase material cost.

NB EUTECTOID STEEL METALLURGY

The application of the MicroNiobium® Alloy Approach in carbon steel long product and plate steels enhances both the metallurgical properties and processability thereby reducing the operational cost per tonne by 10 to 15%. The MicroNiobium® Alloy Approach is applied in higher carbon steels exceeding 0.20% carbon. This Nb eutectoid metallurgy research focuses on application in both prestressed concrete wire rod and then cross applied to rail. The research study evaluates different Nb and Nb-V compositions from 0.020 to 0.120%Nb in AISI1080 steels for wire rod applications. Although the Nb solubility is limited in high carbon steels compared to low carbon steels, the optimized Nb content is defined based on experimental results. The optimized Nb content resulted in the best mechanical properties and related directly to the finer interlamellar pearlite spacing. Seven different eutectoid steel developmental chemistries were evaluated in this study in order to determine the effectiveness of Nb, V or a Nb-V combination on the pearlite interlammelar spacing, mechanical properties and drawability consistency. Based upon the optimum Nb chemistry, an industrial heat was then successfully produced and converted into pre-stressed concrete wire rod. This research and development resulted in the Nb optimization at 0.02% in 0.80%C eutectoid steel exhibiting superior properties compared to the traditional grade based upon both laboratory and industrial trials. [1] Table I below illustrates the laboratory compositions evaluated.

Table I. Chemical compositions of experimental heats

	S_0	V1	V2	VNB	NB1	NB2	NB3	NB4
C	0.829	0.778	0.776	0.781	0.811	0.770	0.805	0.791
Mn	0.756	0.707	0.731	0.730	0.760	0.635	0.736	0.723
Si	0.221	0.234	0.218	0.205	0.221	0.193	0.228	0.230
Al	0.004	0.003	0.002	0.002	0.005	0.002	0.008	0.005
Cr	0.144	0.138	0.152	0.150	0.152	0.124	0.156	0.157
Nb	0.002	0	0.002	0.021	0.023	0.038	0.087	0.119
V	0.002	0.092	0.053	0.050	0.003	0	0	0
N (ppm)	69	73	67	73	70	70	70	85

Laboratory ingots were welded onto the end of industrial billets of similar carbon grades and then hot rolled at an industrial operation into 11mm diameter wire rods following appropriate reduction and thermal practices for pre-stressed concrete (PSC) wire rod. The wire rods were characterized by optical microscopy, scanning electron microscopic (SEM) examination and tensile tests. The pearlitic interlamellar spacing was measured using the line intercept method with the SEM. The austenite grain size was measured utilizing the NFA 04-102 standard method. The hot rolled wire rods were then cold drawn in the laboratory. The mechanical behavior was investigated through tension and torsion tests after each drawing pass.

Mechanical Property Results of PreStessed Concrete Wire Rods

The microstructures of the produced wire rods were homogeneous and pearlitic for all of the experimental steels. Optical observation did not reveal any negative effects of the Nb addition on segregation, decarburization and microstructure homogeneity. The mechanical properties of the wire rods are shown in Table II.

Table II. Mechanical properties based on tensile tests [1]

Wire Rod Sample	Yield Strength 0.2% (N/mm^2)	Tensile Strength (N/mm^2)	Reduction of Area (%)
SO	627	1086	30.4
V1	733	1154	26.8
V2	719	1154	22.9
VNB	740	1169	38.0
NB1	648	1139	45.1
NB2	680	1102	41.4
NB3	666	1115	38.4
NB4	709	1150	35.8

Generally, the tensile strength levels are of the same order for the V-containing or Nb-containing steels, however, the Nb steel trend is a slightly lower yield strength. Nevertheless, all compositions exceeded the base steel S0 yield strength minimum of 627 N/mm^2 and the 1086N/mm^2 tensile strength. As expected, the combination of Nb+V exhibited the highest yield and tensile strength. The important attribute is the consistently higher % reduction of area for the Nb-containing grades compared to the V-containing grades. Review of the mechanical property data shows the best elongation with Sample NB1 which is the 0.02%Nb MicroNiobium Alloy design at 45.1% reduction of area. The yield strength, tensile strength and reduction of area is met as defined by SO in Table II. The mechanism of this optimization of the Nb concentration in this high carbon eutectoid steel is the refinement of the lamellar spacing. The Nb affects the diffusion rate of the C thereby delaying the pearlite transformation.

Interlamellar Spacing Measurements

Figure 1 illustrates the measurement of the interlamellar spacing for the various microalloy compositions.

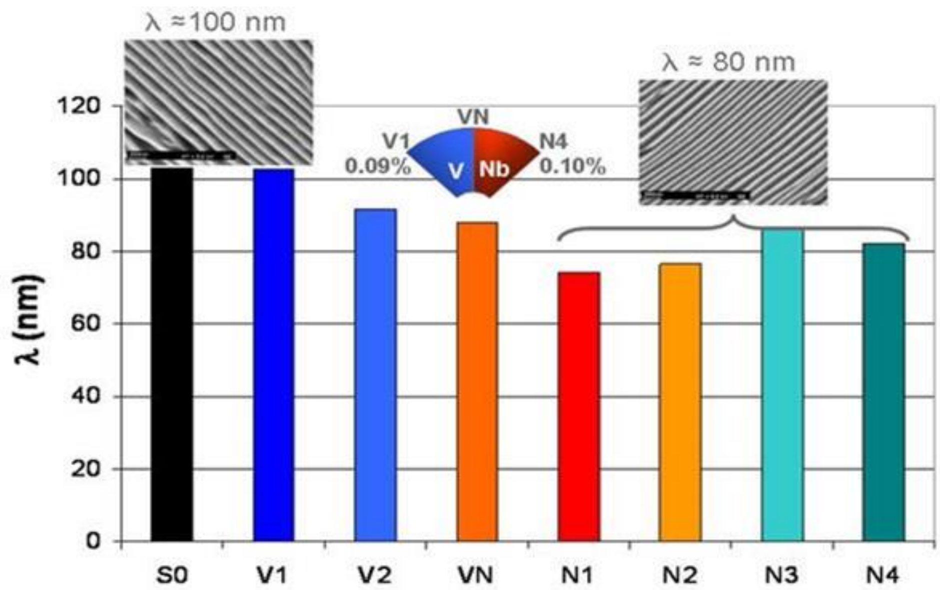

Figure 1. Interlamellar spacing of pearlite in microstructure of as rolled wire rod [2]

The refinement of the spacing is the finest at 72nm with 0.02%Nb directly linked to the best elongation result. The optimized composition of 0.02%Nb (N1 in Figure 1) exhibits nearly double the %RA. All Nb compositions met a minimum 30%RA. The relationship between finer interlamellar spacing with Nb compared to V and the higher %RA is depicted below in Figure 2 and 3.

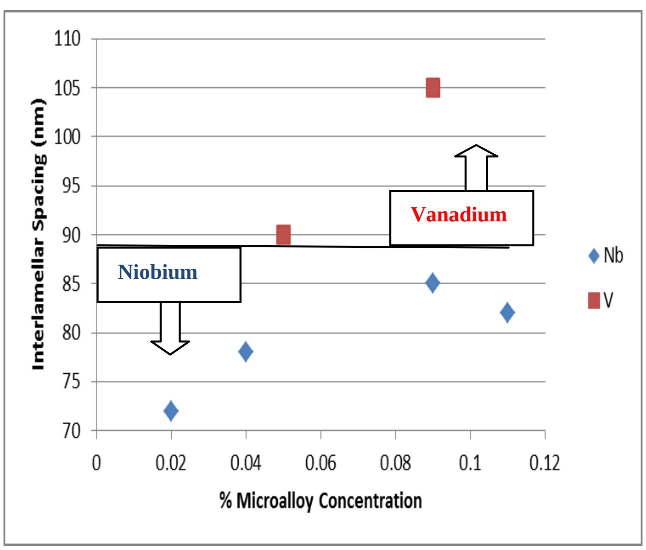

Figure 2. Interlammelar spacing vs. microalloy concentration

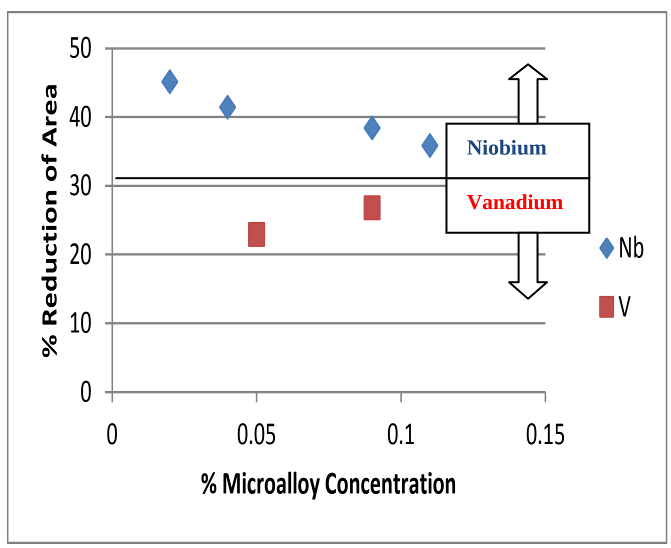

Figure 3. % Reduction of area vs. microalloy concentration

Figure 4 illustrates a high magnification micrograph of the industrially produced 0.80%C-0.02%Nb prestressed concrete wire rod with an interlammelar spacing of 72nm (standard material at 100-105nm spacing).

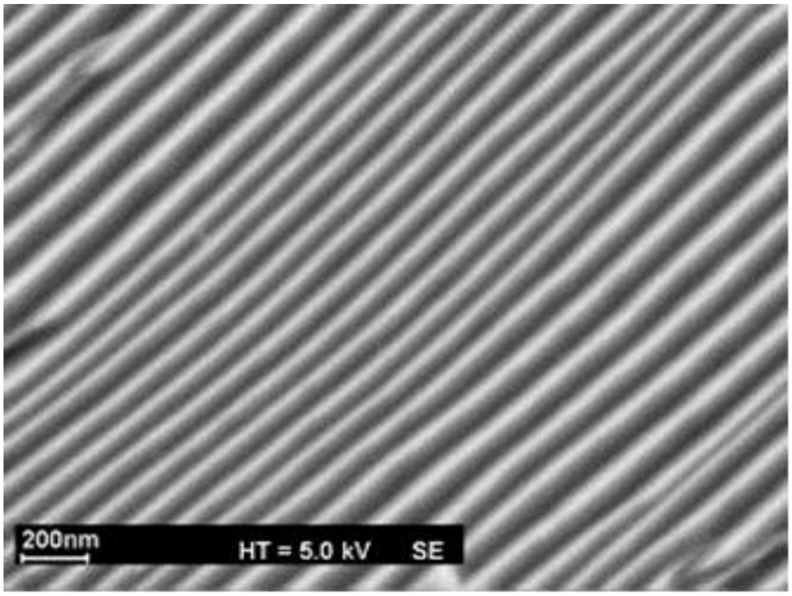

Figure 4. SEM micrograph of sample NB1 (0.023% Nb) with finest interlamellar spacing [1]

Mechanical Property Results of Eutectoid Rail Steels

The cross application of these positive results from the Nb-prestressed concrete wire application is now considered for eutectoid rail products. This application is especially important considering the end user requests for improved wear resistance, shelling resistance, ductility and better weldability for meeting modern track system requirements. With the role that niobium demonstrates in eutectoid steel wire rod providing a fine austenite grain size and fine interlamellar pearlite spacing, the same mechanism should apply to eutectoid rail steels. This mechanism was investigated at the start of the head hardening treatment even with a fairly wide range in the production parameters of time and temperature. The Nb-grain refining effect results in a finer pearlite colony size by reduction of the interlamellar spacing, which in turn leads to the prevention of rail head damage through the improvement in ductility.

A very important contribution to niobium-bearing rail steels was the development of Niobras-200 in Brazil [3] where a rail steel with 0.75%C, 0.8%Si, 1.0%Mn and 0.02%Nb was designed. Here niobium acted as a grain refiner, which resulted in a fine pearlite colony size as well. Subsequently, the rails have improved mechanical properties and possess good weldability. Niobras-200 is a high strength rail steel with a tensile strength of about 1100 MPa. It was developed specifically to utilise Brazilian resources and has proven to be a great success in heavy haul iron ore service. [3]

Niobium Mechanism in Heavy Haul Rail Steels

When the niobium content is low, the precipitates containing niobium predominantly appear in the cementite, which improved the toughness of heavy rail steel by refining the austenite grain size and pearlite lamellae distance. At 0.024%Nb, the finely dispersed precipitates containing niobium mainly occurred in the ferrite, which improved the toughness of heavy rail steel by pinning dislocations and inhibiting crack growth. As the niobium content further increases, both the quantity and size of precipitates containing niobium gradually increased. At niobium content > 0.073%, most precipitates containing niobium could not pin dislocations and inhibit crack growth because the precipitate size was too large. In the present study, when the niobium content was about 0.053%, the fracture toughness of heavy rail steel was the best. The maximum plane-strain fracture toughness was 49.88 $MPa \cdot m^{1/2}$. [4]

Niobium additions in heavy rail steel can form carbides or nitrides with the characteristics of high melting point, strong stability, good matrix-precipitate coherency, uniform dispersion throughout the matrix and spherical in shape. Fine dispersed carbide and nitride precipitates can pin austenite grain boundaries, thus growth of austenite grain is inhibited. Furthermore, niobium can improve the austenite recrystallization temperature and retard the recrystallization process, thereby refining austenite grain of heavy rail steel. But in this grade, when the niobium content is at elevated levels, niobium can promote austenite grain growth due to the large precipitate size. Precipitates which do not pin the boundaries as well, such as nitrides and carbides of vanadium, reduces the pinning of austenite grain boundaries, thereby leading to an increase of the grain boundary energy. In these rail steels, the optimization of niobium should balance the fracture toughness with the autenite grain size and interlamellar pearlite spacing. Based upon these considerations, in the present study, the content of niobium should aim 0.035% for heavy rail steel with an industrial Melt Shop Nb range of 0.030-0.040%. Figure 4 and 5 relate the rail fracture toughness and austenite grain size with the niobium content.

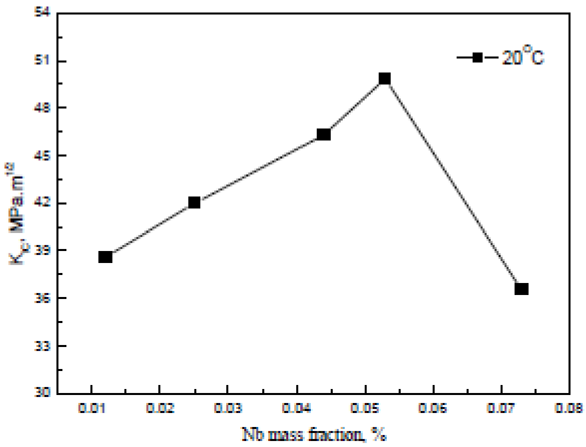

Figure 4. Fracture toughness and niobium content [4]

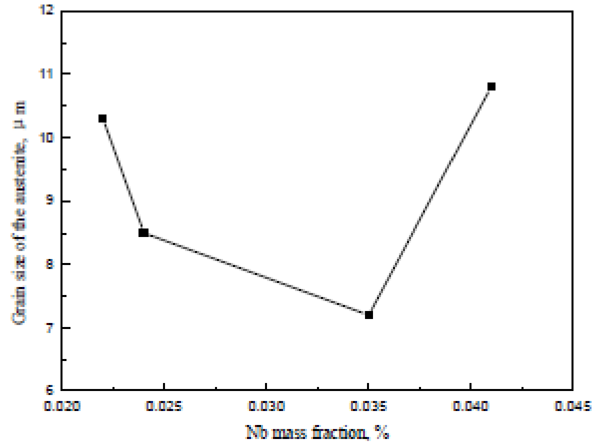

Figure 5. Austenite grain size and niobium content [4]

Bainitic Medium Carbon Rail Steels

Concurrent research into the development of bainitic medium carbon (0.35%C) as an alternative to eutectoid rails with improved fracture toughness is in progress. High performance steels mean strength levels greater than 1200 MPa and yet possess toughness, tribological properties, favorable responses to large strain rates, resistance to fatigue and are cost effective to manufacture. Carbide free bainitic steels can be used in such applications such as rail. [5]

High strength bainitic rail with 0.35% carbon has been produced on a commercial scale, and its characteristics were examined and compared with those of a high strength pearlitic rail steel. The resulting bainitic rail steel has a high tensile strength of 1420 MPa, and high elongation. Both fracture toughness and absorbed energy by U-notch Charpy impact test are twice as high as those of head hardened pearlitic rails as shown in Table III. [6,7]

Table III. Mechanical properties of developed bainitic rail steel

Steel Grade	Rm MPa	A %	K_{IC} MPa·m$^{1/2}$	U-notch Charpy Impact J(20°C)	Fatigue Strength MPa	Wear g/2hr
Bainite	1420	15.5	98	39	870	0.77
Pearlite	1300	13.5	43	20	750	0.76

The wear resistance of the above-mentioned fine pearlitic rail steels has proved to be satisfactory. However, with the current end user requirement for an extension of the rail life, rail surface damage by rolling contact fatigue has now surfaced as a new challenge. In order to resolve this new challenge, the applicability of some bainitic steels with Nb is a possible solution. Thus far, the bainitic rail steels have high tensile strength and high elongation. Both fracture toughness and absorbed energy are much higher than those of head-hardened pearlitic rails. The wear resistance is nearly the same as in head-hardened pearlitic rails. Very long life span before shelling is also observed. With the addition of Nb to these developed bainitic rails, it may be possible for heavy haul railroads to exhibit excellent performance over current experience.

GLOBAL NB ANTISEISMIC REINFORCING BAR DEVELOPMENT

Weldable and non-weldable reinforcing steel bar is one of the most important steel products widely applied in civil construction. The available strength levels of Nb-bearing rebar has been increased in 345, 390 and 490 grades. Traditionally, higher strength grades were produced with vanadium. However, recent niobium bearing steel developments combine clean steelmaking practices at the melt shop with selective accelerated and controlled cooling practices at the rolling mill to produce low carbon equivalent high strength and earthquake resistant reinforcing bars. The production practices from the melting stage through the crack-free continuous casting of the billets through the hot rolling and accelerated cooling are keys to maximize the niobium effectiveness when producing these high quality, high strength reinforcing bar grades. The compelling need for development of even higher quality rebar for seismic applications is driven by recent catastrophic earthquakes in Haiti, Japan, Peru and China. Therefore, research projects are in progress around the world with a focus on the development of a family of S500 and S600 grades with superior toughness, excellent low temperature energy absorption, fatigue resistance and less yield to tensile ratio variation. The traditional Tempcore® produced reinforcing bar with a tempered martensite shell and a pearlitic or bainitic core mixed microstructure. Successful high quality production of these higher strength-elongation steel grades, regardless of the microalloy addition type, will require changes in melting and hot rolling practices to consistently manufacture these value added S500 and S600 reinforcing bar grades for earthquake as well as typhoon resistant applications. [8]

The goal is consistent production of lighter-weight reinforcing bar products at a lower carbon equivalent with improved weldability, higher elongation and better toughness at a lower cost. Low carbon grades with microalloys of Nb, Ti and Mo and the judicious application of accelerated/controlled cooling with or without the Tempcore Process can result in improved toughness, fatigue resistance and weldability. With increasing raw material and energy costs, the effects of processing parameters such as reheating temperature and cooling rate after hot rolling to achieve improved mechanical properties can still result in significant savings. A lower total cost of production may be achieved through a low alloy low carbon chemistry with selective accelerated cooling and better control of reheat furnace temperatures. Three key elements that require strict control to improve ductility are discussed below. As there has been limited published research on the impact and toughness properties of rebar, some fundamental process metallurgy considerations should be incorporated into the production scheme to effectively manufacture S420, S500 and S600 seismic rebars. There is a need to reduce carbon levels of rebar to improve fatigue and fracture behavior in seismic regions. It is a two step process, first moving to 0.20%C and then to 0.10%C. The reduction of sulfur and phosphorous is imperative. Third, the grain refinement that results from the Nb addition is critical. Figure 6 captures these three critical success factors in designing and producing consistent high quality rebar with exceptional properties over the currently produced antiseismic rebars.

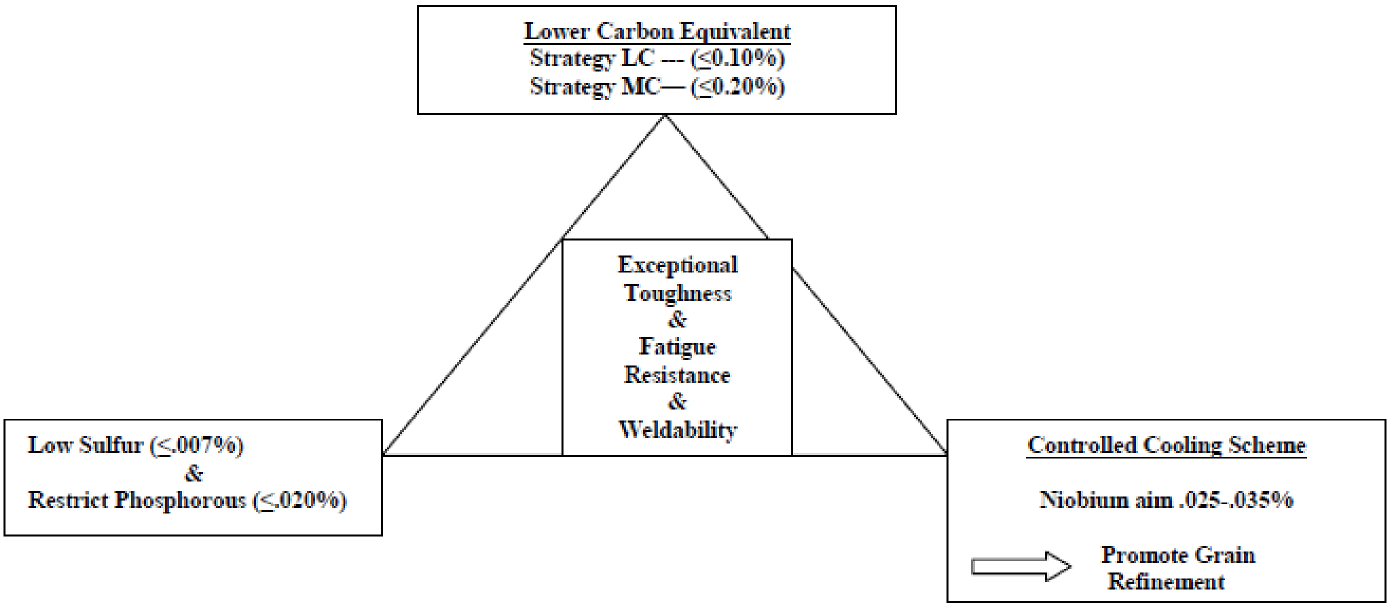

Figure 6. Ultra tough seismic rebar approach [8]

Reheat Furnace Process Metallurgy

Often overlooked is the role of the reheat furnace operation combustion conditions and its effect on final hot rolled rebar mechanical properties. Differences in yield and tensile strength and elongation result dependent upon the carbon level, microalloy composition and heating history. Just as accelerated cooling was introduced as a scheme to reduce alloy cost, so too does the scheme of reduced reheat and soak zone temperatures. Several furnace operational variables will significantly reduce the solubility temperature in practice by as much as 25 to 35°C. Variables such as billet size, push-out or drop-out rate, air-to gas ratios, excess O_2, furnace atmosphere affecting scale formation, and overall furnace efficiency all affect the heating behavior and ultimate kinetics of solubility of the micro-carbides. The furnace heat loss profile can also affect the kinetics. Such problems as improper refractory construction, heat loss through openings, poor fitting inspection doors, inadequately maintained skids, and entry and discharge door problems all negatively affect the kinetics of the solubility process. [9] The effects of improper heating and billet soaking can lead to the following variations in final rebar mechanical properties supplied to the end user:

1. Increased variability in yield strength within a rolling schedule

2. Variable yield-to-tensile ratios

3. Hard spots in rebar due to variation in volume fraction of martensite affecting cored properties and elongation

4. Overheating of the billets resulting in abnormal austenitic grain growth

Based upon mill trials, the effects of processing parameters such as reheating temperature and cooling rate after hot rolling on the mechanical properties can be significant. A lower total cost of production is achieved through a low carbon-low alloy composition with better control of reheat furnace temperatures and selective water or air cooling after exiting the final finishing stand [10]. The following reinforcing bar trials illustrates this concept. The chemical compositions are shown below.

Table IV. Chemical compositions

	C	Si	Mn	P	S	Al	Nb	V	N(ppm)	C_{eq}
0NB	0.249	0.47	1.19	0.023	0.002	0.040	-	-	65	0.554
5NB	0.249	0.51	1.22	0.024	0.002	0.042	0.051	-	79	0.565
5NV	0.249	0.51	1.26	0.026	0.003	0.036	0.050	0.045	71	0.569

$C_{eq} = (\%C) + (\%Si)/7 + (\%Mn)/5 + (\%Cr)/9$

The relationship between reheat dropout temperature and the effect on elongation is different dependent upon the microalloy design. Figure 7 and 8 shows the effects of reheating temperature on elongation (El) and yield point elongation (YPEI). [10]

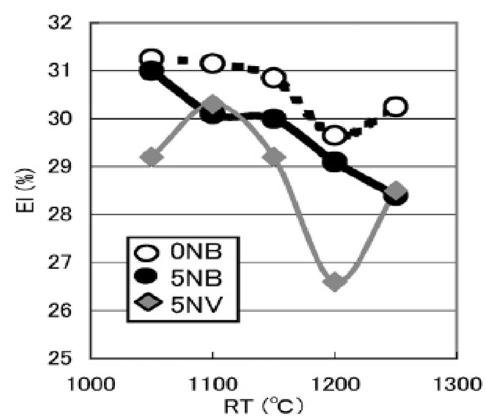

Figure 7. Elongation and Reheat Temperature

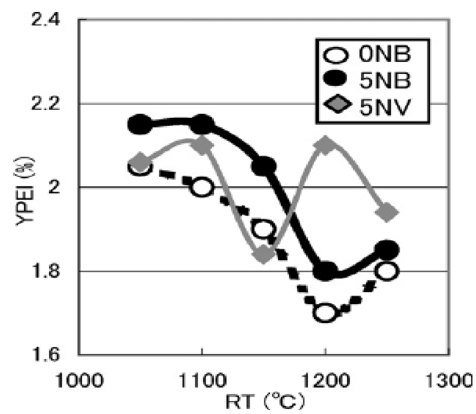

Figure 8. Total Elongation and Reheat Temperature

The elongation (El) decreases consistently with increasing reheat furnace temperatures for the 5NB (0.05%) chemistry whereas the 5NV vanadium-niobium (0.05%N%-0.045%V) combination exhibits extreme variability and an elongation trough at 1200°C which is a typical soak zone temperature for many steel producers. In the 5NB chemistry, the most consistent elongation is between 1100 and 1150°C which is the optimal soak zone temperature for both ductility and lower energy consumption (i.e. mmbtu per tonne). The 5NB shows the highest overall YPEI at reheating temperatures less than 1150°C. Optimization of the furnace temperatures between 1100-1150°C could provide civil engineers with a more consistent rebar with less elongation variability for design considerations. It is in the best operational interest of the mill to keep furnace temperatures below 1150°C for the following reasons: 1) better YPEI and El, 2) minimize overheating of steel leading to poor surface quality, 3) reduce energy consumption by 10-15% and 4) potentially less UTS/YS ratio variation. Generally, excessive soak zone temperatures tend to be a common universal operational problem globally.

Cooling Schemes

Cooling schemes directly affect the relationship between the UTS/YS ratio and percent elongation. The elongation can change by as much as 10% dependent upon the use of early cooling water or late cooling water as the bar exits the last finishing stand. The importance of the cooling strategy decision of early versus late cooling directly affects the transformation and the size of the ferrite pearlite core or ferrite bainite core and the thickness of the surface layer of tempered martensite. There is a tradeoff between tensile to yield ratio and elongation depending on the end user's specification. There is tremendous flexibility to achieve some excellent properties through this scheme since the application of water during and/or after rolling will significantly affect energy absorption properties.

AISI9259 MicroNb Coil Spring Application

Mechanical properties improvements with the addition of Nb in rebar and structural shapes has been cross applied to automotive structural components, such as coil springs. For example, a North American vehicle front suspension coil spring composed of 0.51%C with Mo-V-Nb was developed and commercialized with improved mechanical properties compared to conventional springs. A similar effect was observed as in rebar and other long product applications when adopting 0.035%Nb in a 9259 engineering alloy spring steel grade. The improved properties are attributed to the grain refinement, more homogeneous microstructure, microalloy carbonitride precipitate morphology and precipitate strengthening provided by Nb. The chemistry of the Nb-modified spring steel is shown below in Table V. [11]

Table V. Coil spring chemical compositions

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	N(ppm)
SAE9259	.61	.86	.014	.021	.78	.008	.008	.51	.008	.005	.002	55
V-SAE9259	.60	.81	.020	.017	.85	.007	.009	.51	.003	.100	.002	110
Nb-V-Mo SAE9259	.51	.69	.016	.020	1.31	.007	.012	.45	.040	.10	.035	120

The improvement in hardness at temper temperature has translated into increased strength, better fatigue endurance limits and good fracture toughness, thereby allowing for a lighter weight design coil spring. This Nb-V-Mo modified coil spring steel has resulted in the reduction in weight of a coil spring by approximately 15%, improved fatigue resistance by 12% and improved fracture toughness by 27% compared to the conventional 5160 or 9259 and/or the V-modified 9259.
The resultant Nb-V modified grade exhibits improved yield and tensile strength which translates into better cyclic fatigue life and improved fracture toughness. The adjusted steel chemistry, grain refinement, Nb-V(CN) precipitation strengthening and overall lower volume fraction of hard oxide inclusions results in the improved properties. This application illustrates the complimentary synergy between Nb and V in these higher carbon engineering tools steels. In actual operation, the Nb to V stoichiometric ratio has been reduced thereby lowering the cost of the V and Nb additions at 0.020% Nb. The fatigue and fracture toughness comparison of standard SAE9259 is compared to the Nb-modified SAE9259 in Figure 9 and 10 respectively. [11]

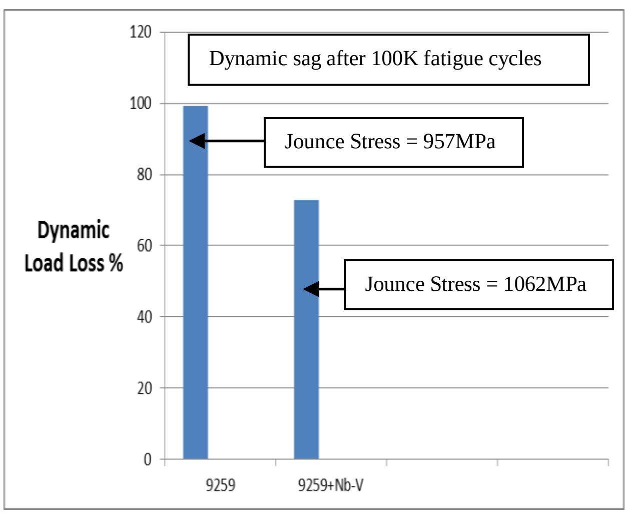

Figure 9. Fatigue dynamic load loss & Jounce stress

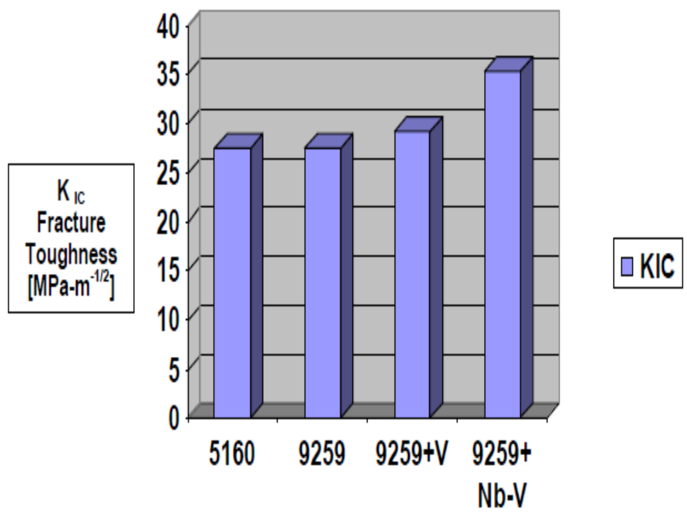

Figure 10. Fracture toughness

The resultant Nb-V modified grade exhibits improved yield and tensile strength which translates into better cyclic fatigue life and improved fracture toughness. The adjusted steel chemistry, grain refinement, Nb-V(CN) precipitation strengthening and overall lower volume fraction of hard oxide inclusions results in the improved properties. This application illustrates the complimentary synergy between Nb and V in these higher carbon engineering tools steels. In actual operation, the Nb to V stoichiometric ratio has been reduced thereby lowering the cost of the V and Nb additions at 0.020% Nb. [12]

AISI 1035 MICRONIOBIUM AND EFFECT ON PROPERTIES

The influence of reheat furnace soak temperature is also important in terms of fracture toughness behavior. In order to validate this effect, the micro addition of Nb to a 1035 steel grade (0.35%C-0.3%Si-1%Mn) was evaluated in relation to the yield strength, tensile strength and toughness. All properties improved, especially the Charpy impact properties which are markedly improved with a billet reheat temperature of 1100°C and controlled rolling practice as shown in Figure 11. Again, the influence of lower reheat temperature on desired final Nb precipitate size is critical to optimize toughness.

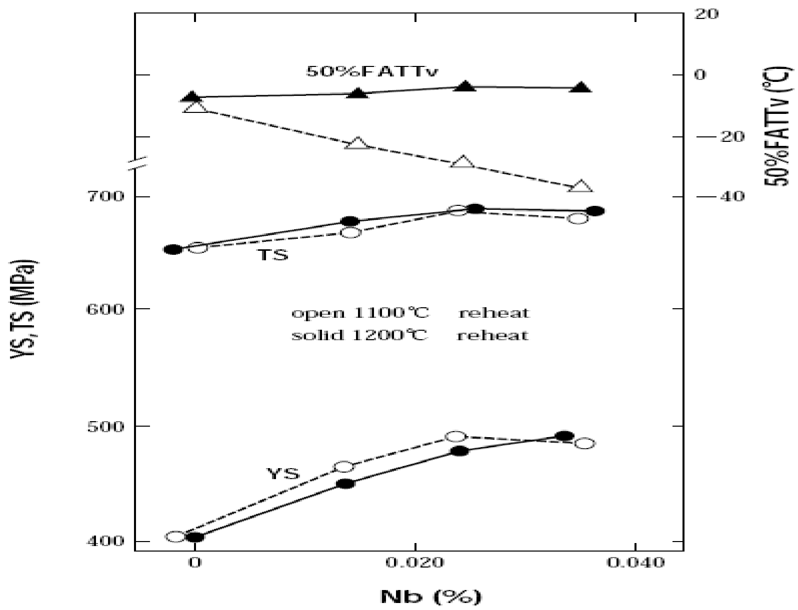

Figure 11. Effects of Nb on tensile and Charpy V notch impact properties of 1035 steel [13]

The process metallurgy reheat furnace control and consistency of the combustion assists greatly in achieving these excellent toughness properties. Since part of the Nb remains as a precipitate at this temperature, both grain refinement and precipitation occur and are complementary.

NB IN FORGED STEELS

Efforts to reduce energy costs in the hot forging process continue to be an important initiative for most forging companies. Through the application of microalloyed steels, 10-15% operational cost reductions may be achieved. Mechanical properties of microalloyed steels in the as-forged condition without heat treatment are comparable to those of quench and tempered steels. During the early stages of development of medium carbon microalloyed forged steels, the strength requirements were met easily and the toughness was initially lower. In contrast to quenched and tempered martensitic steels, the strength and toughness of microalloyed forging steels is obtained by its chemical composition and during the thermomechanical forging process. The microstructure after the forging process is generally ferritic-pearlitic. Therefore, the mechanical requirements can be provided by the strengthening mechanisms of grain refinement and precipitation hardening by microalloying elements. The precipitates offer grain size control through the pinning of grain boundaries with microalloying element carbonitrides control during the preheating and forging steps. On the other hand, the precipitation hardening is obtained by fine carbonitrides formed in austenite and especially in ferrite, which may cause a slight decrease in toughness of steels depending upon processing routes. [14,15] The recrystallization is inhibited by the pinning forces exerted by precipitates of microalloying elements Ti and V, or solute dragging effect due to segregation of alloying elements, especially Nb. [16-19]

The grain refinement of the microstructure is essentially the primary mechanism available for increasing both strength and toughness simultaneously without making significant and costly changes to chemical composition. In many forging operations, an attempt is typically made to refine the grain size by resorting to low temperature forging practices. However, this approach is often impractical because of increased forging forces and shortened die life. Considering that the major metallurgical feature of Nb microalloying is its grain refining effect and that of V microalloying is precipitation strengthening, the application of combined microalloying of Nb and V in the medium carbon non-quenched steels is a proven concept for the improvement of these forging steels. Through experimental research and actual production, these developed steels show better impact toughness while maintaining high strength levels. Figure 12 schematically shows the interrelationship the steel microstructure refinement through an optimum combination of chemistry control and forging process control in order to achieve both high strength and high toughness. [20]

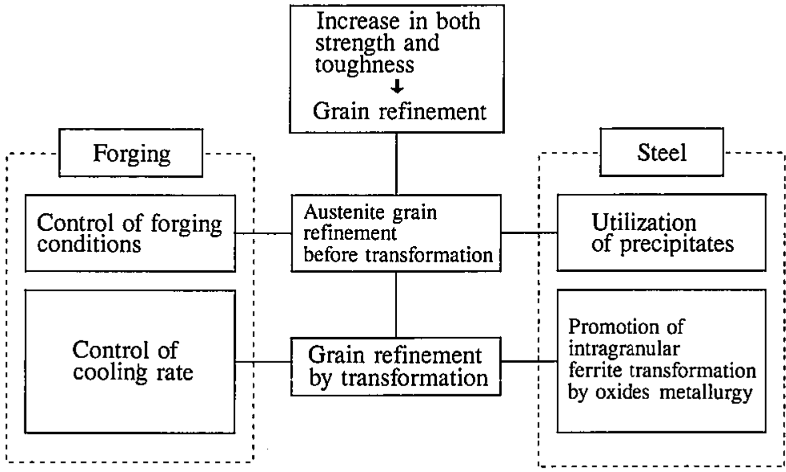

Figure 12. Strengthening and toughening of ferrite-pearlite steels [20]

A non-quenched steel grade for forgings and rolled products has been industrially developed and produced. The non-quenched steel grade is the 35MnVNb. In addition, a free-cutting steel grade 35MnVNbS has been derived and developed and put into industrial application. Many components like large diameter axles, gear racks are applied as 35MnVNb forgings and small diameter axles, and bevel gears have been applied as hot rolled bar products of 35MnVNbS. [21] In addition, a free-cutting steel grade 35MnVNbS has been derived and developed and put into industrial application. The Nb-V combined microalloyed steels 35MnVNb as forging steel are industrially produced and applied to large size axles, gear racks, and bolts. The free-cutting grade 35MnVNbS as hot-rolled long products with diameter 12-50 mm are applied to small size axles and bevel gears and the other is bevel gears of 32 mm in diameter used for electric powered tools. Table VI lists several forging steel compositions and Table VII presents the resultant mechanical properties for the Nb-V microalloyed medium carbon forging steels. [21]

Table VI. Forging steel compositions

Steel Sample No.	Chemical Composition (wt%)								
	C	Si	Mn	V	Nb	Al	N	P	S
1	0.46	0.31	0.81	0.10	-	0.049	0.0042	0.006	0.010
2	0.45	0.38	0.81	0.12	0.030	0.050	0.0043	0.006	0.010
3	0.39	0.59	1.42	0.10	0.050	0.052	0.0034	0.007	0.010
4	0.32	0.59	1.39	0.10	0.035	0.052	0.0051	0.006	0.010
5	0.24	0.59	1.39	0.11	0.040	0.052	0.0054	0.007	0.010

Table VII. Forging steel mechanical properties

Steel No.	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Reduction Area (%)	Charpy Energy at 20°C
1	445	780	20.5	46.7	66.6
2	485	810	21.3	49.2	72.5
3	540	855	19.6	59.7	114.6
4	510	785	22.0	62.7	150.9
5	470	710	26.2	66.6	198.7

For the Nb-V combination, the precipitation of V is enhanced by the presence of Nb. Results of TEM EDS analysis of the precipitate particles showed that the particles may be sole V, sole Nb or precipitate of both Nb-V. [22] Figure 13 compares the ductile to brittle temperature transition curves at similar V to Nb stoichiometric ratios at different carbon contents. The 0.39%C exhibits the best yield and tensile properties with an extended consistent Charpy plateau between 60-110°C.

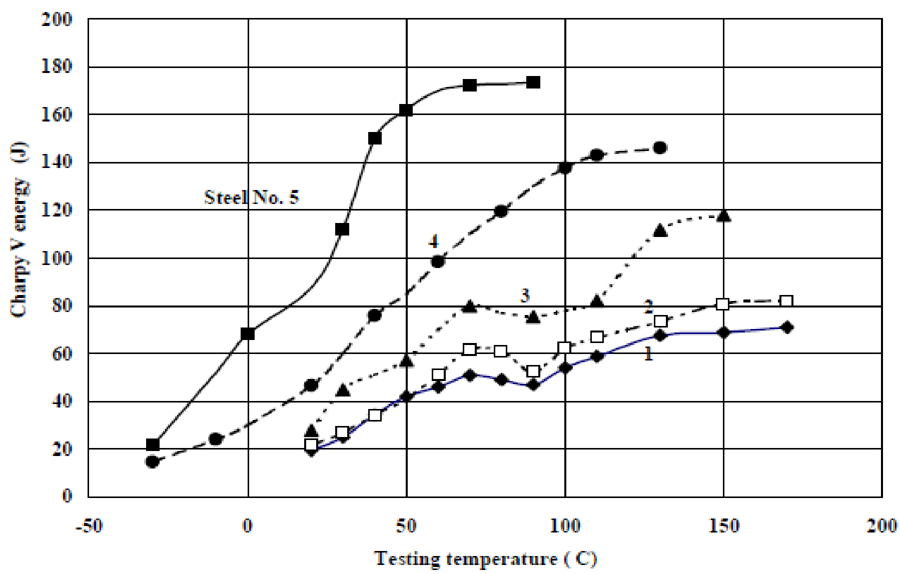

Figure 13. Ductile to brittle transition curves [21]

NB IN CARBURIZED STEEL LONG PRODUCTS

Recently, significant improvements in processes and controls have resulted in development of several Nb-bearing carburizing grades. The effects of heating rate on austenite grain growth and precipitate distribution in Ti-modified SAE 8620 steels with Nb additions of 0.02, 0.06 and 0.1 wt% were evaluated with pseudo-carburizing, *i.e.* without a carburizing gas, heat treatments characteristic of high temperature vacuum carburizing. Suppression of abnormal grain growth was correlated with the development of a critical distribution of fine NbC precipitates, stable at the austenitizing temperature. The susceptibility of Ti-modified 8620 steel to abnormal grain growth during pseudo-carburizing heat treatments at 1050°C increases with an increase in heating rate and a decrease in Nb content. In steels with 0.06 or 0.1 wt% Nb, higher densities of fine precipitates capable of suppressing abnormal grain growth develop at lower heating rates (10 to 20°C min_1) while at 145°C min_1 a coarser precipitate distribution develops that is less able to suppress abnormal grain growth. [23]

CONCLUSIONS

The application of niobium in medium and high carbon steel long products enhances both the metallurgical properties and processability and reduces the operational cost per tonne. The technological development of value-added applications for niobium (Nb) microalloyed long products and forgings steels continue to increase globally meeting more demanding end user requirements. The process and product metallurgical improvements relate to the Nb-pinning effect of the austenite grain boundaries and the refinement effect in pearlitic medium and high carbon steels. Considering the temperature variations observed during the reheating of the billets in an industrial operation, the metallurgical mechanism of the MicroNiobium® Alloy Approach retards austenite grain coarsening during reheat furnace soaking of the billet, slabs or shapes before rolling. In eutectoid prestressed concrete wire rods and rails, a finer prior austenite grain size translates into a finer interlamellar spacing in the pearlitic microstructure. For medium carbon carburized grades, Nb allows for increased carburizing temperatures, thereby reducing soaking time and operational cost. New Nb-modified medium and high carbon steel developments will continue at an accelerated pace.

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