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Production and Niobium Application in High Strength and Earthquake Resistant Reinforcing Bar

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Abstract

Weldable reinforcing steel bar is one of the most important steel products widely applied in civil construction. The available strength level of Nb-bearing rebar has been increased in 345, 390 and 490 grade. Although traditionally, higher strength grades have been produced with vanadium, recent development combining selective accelerated cooling practices and niobium have been successful in producing the 490 grade. The production practices from the melting stage through the crack-free continuous casting of the billets through the hot rolling and accelerated cooling practices are pivotal to successfully incorporating niobium into these high strength reinforcing bar grades. Current research is in progress with a focus upon development of a family of S500 and S600 grades with even superior toughness and elongation. Successful and high quality production of these higher strength-higher elongation grades, regardless of the microalloy addition type, will require disciplined melting and hot rolling practices to consistently manufacture these value added S500 and S600 reinforcing bar grades for earthquake and typhoon resistant applications.

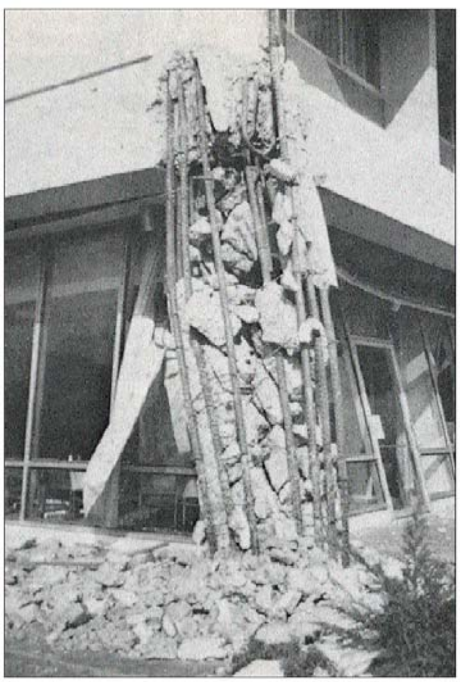
Introduction

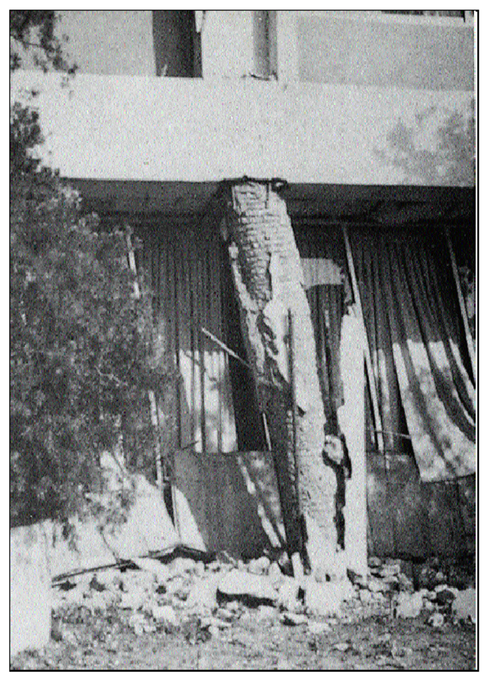
The market trend for an improved reinforcing bar in seismic and hurricane/typhoon regions will require new grades of reinforcing bar with exceptional properties not found in currently manufactured reinforcing bars. The next generation of Nb-bearing rebars is aimed at improved properties in such attributes as: 1) better toughness at lower temperature, 2) higher yield strengths for lower cross sectional area of structure, 3) higher elongations, 4) better weldability to reduce construction time, 5) improved heat affected zone (HAZ) toughness, 6) improved elevated temperature properties and 7) improved fatigue resistance. All of these properties are desired in both the weld and the base metal. Tighter process control during the melting, casting, billet heating and rolling is highly recommended if a steel mill expects to meet the demanding properties in seismic-prone environments.

Civil Engineering Materials Design Considerations

From a construction perspective, rebars should offer a good combination of high yield strength, good bonding with properly mixed concrete, easy bendability and good resistance to fire, corrosion and earthquake conditions. Some of the recent research into fire resistant steels for structural plate will be briefly presented in this paper as well since a similar niobium-steel process and physical metallurgy scheme may be considered for cross application in fire resistant reinforcing bars.

It should also be understood that the dynamic strength of the reinforcement provided by the rebars in concrete is only as efficient as the bond strength developed between the reinforcing steel bars and the surrounding concrete. The spacing between the rebars in the concrete column or beam is a critical design criterion that affects the rebar performance under loading. Figure 1 below illustrates the effect of this spacing consideration.





(a) widely spaced bars

(b) closely spaced bars

Figure 1. Effect of widely spaced rebar ties (a) versus closely spaced rebar ties (b)

These two columns from the same building show the remarkable difference the reinforcing bar spacing will have as the column deflects and fractures. The column on the left (a) with widely spaced ties, failed during an earthquake. The column on the right (b), with closely spaced spiral reinforcement, continued to carry loads even after an 18-inch lateral deflection [1].

The civil engineer aims to design for ductility. Concrete structural members will behave in a brittle manner without proper reinforcing bar properties and placement. Classically, as shown below in the load versus elongation curve in Figure 2 below, a brittle column or beam will deform a small amount before fracturing and lose its load carrying ability. Conversely, ductile columns or beams can carry loads even after deflection. The area under the curve indicates the structural beam or column's ability to absorb and then dissipate this energy.

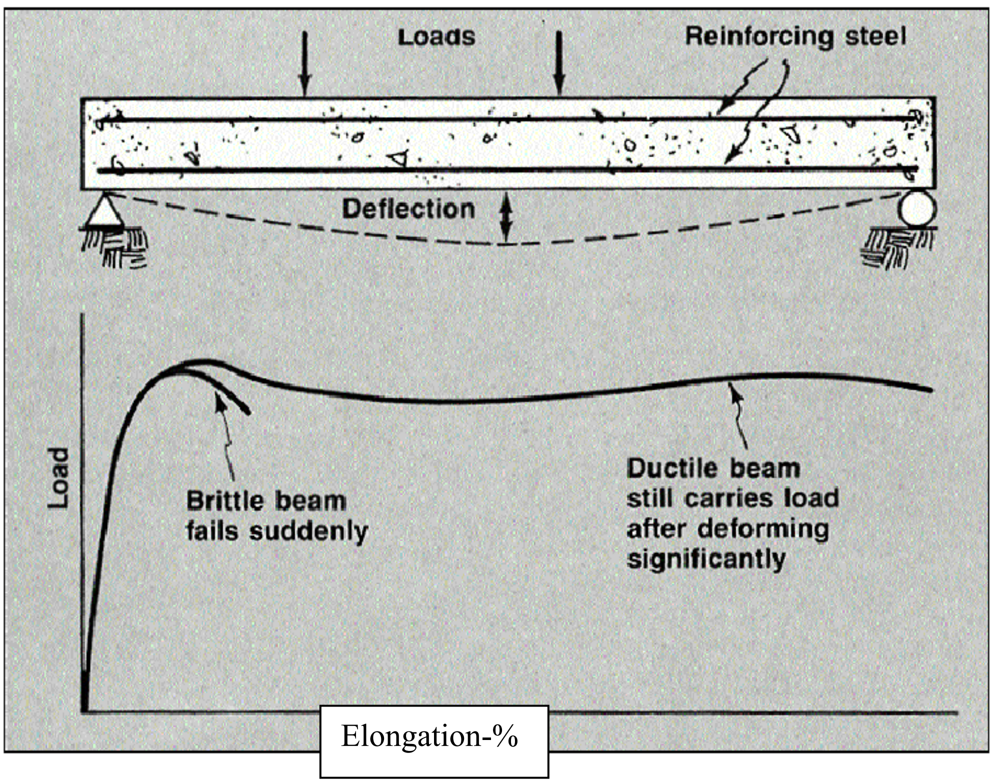


Figure 2. Load vs. deflection for brittle vs. ductile beam behavior [1]

Generally, if the civil engineer chooses to design a brittle structure, then three to five times earthquake loads specified by the civil engineering code is required. Therefore, it is more economical to design the structure with a highly ductile rebar materials assuring that both the individual columns and beams are ductile [1]. There is a metallurgical need to study more closely the stress-strain behavior and work hardening characteristics of various reinforcing bar chemistries and microstructures at different finishing temperatures and then correlate and their stress-strain behavior and performance under different strain rates, loads and fatigue cycles.

Generally, the yield strength specification is very important in terms of structural stability. The minimum elongation and Ultimate Tensile Strength/Yield Strength (UTS/YS) ratio provides a measure of the capacity for plastic deformation and is consequently, a safety factor against fracture. Furthermore, the carbon content and carbon equivalent, which is an indication of weldability and ductility, is generally between 0.25% and 0.51%.

As a result of the wide difference between the deformability characteristics, mainly modulus of elasticity and yielding of steel and concrete, the concrete develops tensile cracks. Major cracks can be avoided by using ductile mild steel and by improving the local bond all along the bar. The bond is improved by ensuring a non-smooth surface, that is, by providing ribs of certain profile and depth on the surface of the bars and by using deformed bars with ribs and ridges.

With the goal of producing lighter-weight reinforcing bar products at lower carbon equivalent for weldability, higher elongation and lower cost, alternative lower carbon grades of higher strength welded steel rebars need to be further been developed by applying microalloys of Nb, Ti and/or V and judiciously apply accelerated cooling through the "Tempcore Process" or combining alternative accelerated cooling practices with microalloys. With increasing raw material and energy cost, 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 may be achieved through a low alloy, lower carbon selective accelerated cooling approach with better control of reheat furnace temperatures [2].

Fundamental Niobium Metallurgy in Rebar

Niobium (Nb) can effectively influence the mechanical properties of steel in three ways: through grain size refinement during the thermomechanical hot forming, lowering the austenite (γ) to ferrite (α) transition temperature (Ar_3) and precipitation hardening. Grain refinement is the most effective mechanism that can simultaneously increase strength, toughness and ductility. Therefore, niobium is the most effective microalloying element, even when added at concentrations below 0.010%. In conjunction with the proper alloying technique and melting operation, the thermomechanical rolling and cooling patterns are pivotal in successfully achieving an optimal balance between strength and toughness.

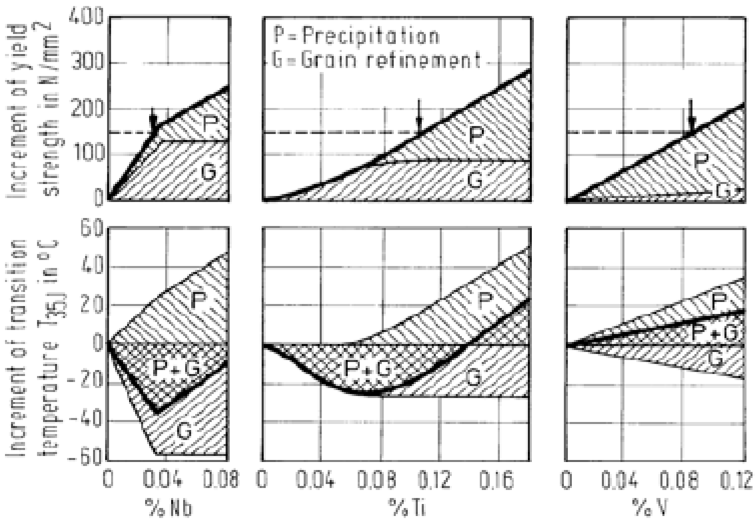


Figure 3. The contribution of microalloying elements to ductility and strength of 0.08%C, 0.90%Mn [2]

As a result of the grain-refinement mechanism of niobium, higher yield strengths, improved weldability and improved fracture toughness can be achieved through a lowering of the carbon content. This allows the alloy designer the opportunity to specify lower carbon-level steels to improve the toughness and weldability of the structure without sacrificing strength. An opportunity exists to study the niobium metallurgy and some of the grades applied to high strength pipeline and advanced high strength structural steel grades with lower carbon and microalloy systems for these demanding seismic applications.

The grain refining effect of Nb is mainly due to delaying or preventing recrystallisation in the last hot-forming steps. Flattened grains as well as a high dislocation density of the austenite enhance ferrite nucleation. By lowering the γ to α transformation temperature, Nb simultaneously enhances the ferrite nucleation rate and reduces the grain growth rate. This combined effect leads to a particularly fine grained transformation structure. In order to make optimum use of its metallurgical potential Nb has to be in solid solution through the appropriate reheating furnace temperature to dissolve Nb(C, N) precipitates before hot forming. The solubility for Nb(C,N) under laboratory conditions is given in Figure 4.

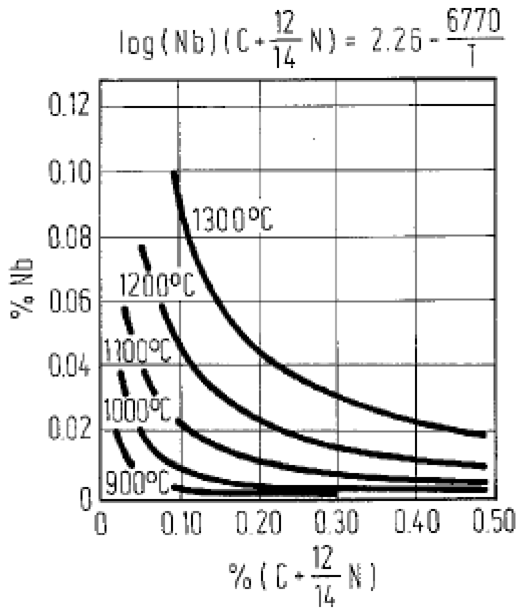


Figure 4. Solubility of Nb(C,N) [2]

It has been experienced in mill operations that 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 can 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 can negatively affect the kinetics of the solubility process.

The effects of improper heating and billet soaking can lead to the following variations in final rebar mechanical properties supplied to the end user:

- Increased variability in yield strength within a rolling schedule
- Variable yield-to-tensile ratios
- Hard spots in rebar due to variation in volume fraction of martensite affecting cored properties and elongation
- Overheating the billets and abnormal grain growth

Cost Effective Value Added Niobium Operational Optimization for Rebar Production

The successful implementation of a Nb-based structural steel product depends upon the optimization of the melting, lowering of melt carbon levels in the basic oxygen furnace (BOF) or electric arc furnace (EAF), control of oxygen levels during refining to minimize oxide inclusion formation, billet casting without edge cracking or segregation, and billet furnace reheating practices and proper thermal and draft reduction rolling schedules. These synergistic practices can produce the finest possible grain size. In several of the product applications discussed in this paper, grain sizes as fine as ASTM 10 to 12 are achieved through execution of the proper operational practices resulting in excellent low temperature toughness and good weldability [3].

The critical success factor for a steel producer is their ability to improve temperature uniformity through the billet thickness in the heating and soak zone of the reheat furnace. This minimizes cold billet ends and uniform heating through the z-direction of the billet which contributes to high mill loads upon threading, thereby significantly constraining the horsepower potential to finish at low temperatures. Essentially, the reheat furnace operation can be segmented into the following operational and maintenance parameters [4].

SLAB/BILLET REHEATING:

- Furnace operational parameters (i.e. air/gas, excess air, ramp heating, etc.)
- Standard operating practice (SOP) for heating procedures after mill delay
- Uniformity of slab or billet heating through-the-thickness and over slab length
- Skid Pipe vs. Walking beam considerations

MAINTENANCE CONSIDERATIONS:

- Combustion fans regularly-scheduled preventative maintenance
- Burner balancing
- Fan efficiency (which directly correlates to surface quality and abnormal austenitic grain growth)

COMBUSTION CONSIDERATIONS:

- Adjusting air to gas ratio as a function of carbon equivalent
- Monitoring nitrogen dioxide (NOX) and sulfur dioxide (SOX)
- Regularly-scheduled balancing of burners and orifices' mechanical condition

OTHER CONSIDERATIONS:

- Furnace instrumentation and calibration
- Furnace heating SOP by family of grade
- Furnace heating model adapted to Nb-grades

Implementation of these disciplined heating and furnace maintenance procedures is the key to rolling microalloy steels at lower finishing temperatures and reduced mill loads thereby reducing energy costs and improving rebar quality.

It is the author's recommendation that the additional manufacturing cost associated with the production of cleaner rebar steels and the increased furnace maintenance expense are more than offset by the increased productivity, reduced energy costs, internal and external quality benefits, improved mill discipline and better material utilization at the reinforcing bar end user.

Continuous Billet Casting of Nb-Bearing Grades:

The continuous casting of crack free Nb-bearing reinforcing bar grades is achieved through the application of appropriate casting practices at a given bar mill producer. Although beyond the scope of this paper, if billet cracking is experienced on Nb-bearing grades (or any other grades for that matter), it can typically be related to one or several of the following causes:

1) Heat transfer characteristics

- heat transfer of mold powder
- mould level control performance
- consistency of mold powder feed
- reduce secondary cooling water to keep billet corners above 900°C

2) Caster and mould design

- mold face taper
- oscillation mark depth and less crack depth relationship

3) Preventative maintenance issues

- cooling headers and nozzles (i.e. pressure and volume variations)
- water quality and temperature
- segment alignment
- roll gap and wear history

4) Melting and ladle temperature control

- hot ductility trough issues related to high sulphur
- ladle temperature stratification during teeming
- excess superheat (greater than 20°C)

5) Scarfing induced cracks

- inadequate standard operating practices
- inexperienced operators introducing cracks on high carbon equivalent materials

Nb-Bearing Reinforcing Bar for High Strength Applications

Formable and weldable high strength rebar is produced by fast cooling and/or microalloying.
The reheating furnace operation and combustion efficiency/effectiveness are a key reason for the successful substitution of Nb for V in billet sizes as small as 100x100mm to as large as 125mmx175mm. Again, the solubility curves are a guide, but the ultimate operational success lies in understanding the dynamics of the furnace operation and the appropriate Nb level to ensure dissolution. The resultant substitution effect has been as high as a 50–60% reduction in the microalloy levels when successfully substituting Nb (i.e.~.065%V replaced to ~.030Nb) [5].

Also, the low carbon content and strength increase by Nb alloying will give a good combination of high strength and excellent ductility, toughness and weldability.

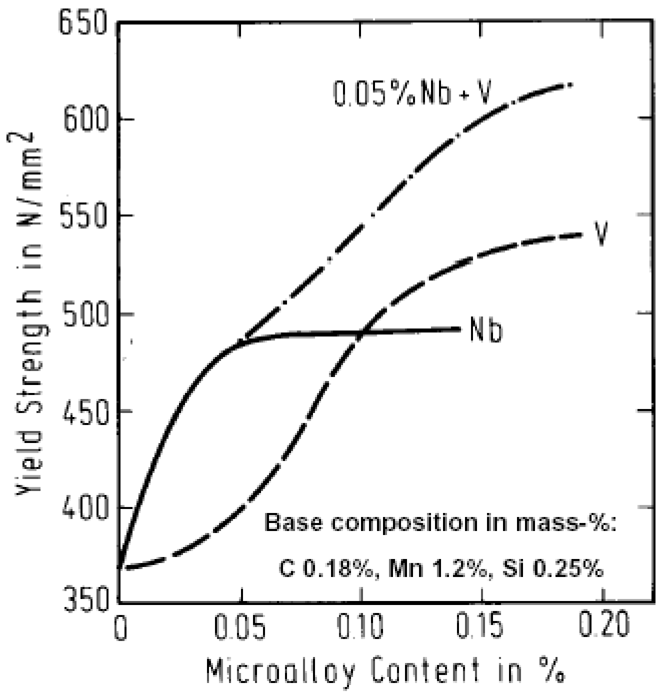


Figure 5. Yield strength of microalloyed ferrite-pearlite steel for rebar [6]

General High Strength Reinforcing Bar Guidelines:

Increased sizes of greater than 40mm in diameter, high yield strength (greater than 450MPa), and good weldability are required in concrete reinforcing bars. Microalloyed steels with vanadium have been traditionally used in rebar, but recently, the strong grain refinement effect of Nb has resulted in the increased development of Nb-bearing steels in concrete reinforcing bars for 500 and 600MPa strength levels. The addition of Mo offers some fire resistant properties that will be discussed later in this paper. The Tempcore process may be reduced or eliminated on the lower strength grades, resulting in reduced operating cost and increased productivity. For reference purposes, Table I below illustrates typical chemical compositions from 450 to 650 MPa rebars incorporating the Tempcore process.

Table I. Chemical compositions hot rolling conditions and resultant properties in reinforcing bars with Tempcore [7]

	C	Si	Mn	P	S	Al	Nb	V	Ti	N	FRT (°C)	BarΦ
B	0.17	0.44	0.99	0.020	0.009	-	-	-	-	0.008	~1050	20
D	0.13	0.38	1.45	0.016	0.003	0.028	-	-	0.016	0.006	1100~1150	16
E	0.12	0.40	1.46	0.020	0.003	0.025	0.024	-	0.019	0.009	1100~1150	16
F	0.08	0.26	1.40	0.014	0.006	0.031	0.033	0.032	0.011	0.007	1100~1150	16

	Y.S @ 600°C*	**T.S. @ 600°C***	**Elongation (%)**	**Y.S @ 700°C***	**T.S. @ 700°C***	**Elongation (%)**
B	550	630	23	NA	NA	NA
D	570	675	21	450	530	28
E	610	675	20	500	605	25
F	625	675	18	550	625	20

The comparison of steel D and E indicates that the Nb addition of 0.024% produced an increase in yield strength of 50MPa. In order to achieve 25 to 30% elongation properties, the Mo-Nb approach is being researched.

Nb-Bearing Reinforcing Bar for Earthquake Zone Steel Development

With the projected increased intensity and frequency of hurricanes, earthquakes and cyclones, there is a market demand to develop and then consistently produce S500 and S600 rebars with elongations of 25 to 30%. Civil engineers are requesting steelmakers to produce reinforcing bar at elongation levels approaching 30%. Microalloying with Nb and/or Mo offers the possibility to achieve 600MPa with elongations of 25 to 30% and an ultimate tensile strength to yield strength (UTS/YS) ratio of 1.28-1.30. In addition to a Nb or Nb/Mo chemistry, customized and disciplined quenching practices are of critical importance in order to successfully meet the needs of this demanding application.

The S500 and S600 rebar alloy design strategy involves: (i) lowered carbon equivalent to improve weldability, (ii) improved ductility and toughness, and (iii) achievement of good yield point elongation. Niobium is added at the 0.040 to 0.050% level to effect precipitation strengthening, improve grain refinement and enhance hardenability to compensate for the strength loss due to the reduced carbon and manganese levels. Additions of Mo in the 0.05 to 0.10% range will enhance hardenability in order to meet stringent earthquake applications and improve fire resistance, achieving elongations exceeding 25% (approaching 30%) consistently. Nb and Mo have a synergistic effect in achieving a ferrite and bainite core in place of the conventional ferrite and pearlite core with Tempcore. An alloying combination of Mo+Nb+Cr+Ni < 0.30%, C between 0.10-0.20% and Mn between 0.60-1.20% with specially designed coiling cooling conditions and low sulfur/low phosphorous should consistently meet

S500, and with further adjustments to rolling temperature and cooling, meet S600. This is an area of continuing research for this demanding application [8].

Fire Resistant Steel Development

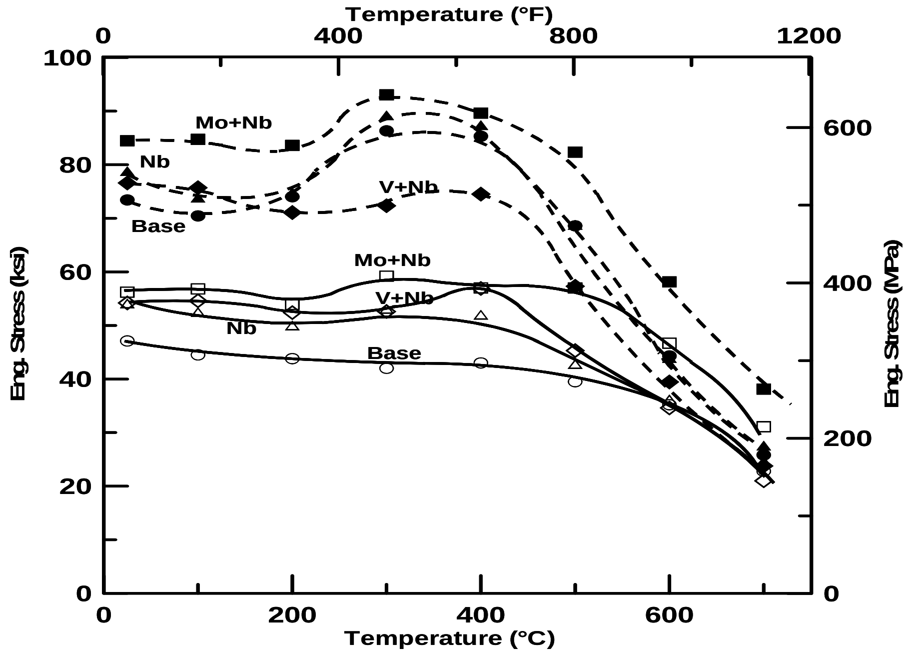
Fire resistant steel research has increased in the United States over the last decade with the intent of developing steel that retains high strength at elevated temperatures. There is no commercially available fire resistant plate or reinforcing bar grades produced within the United States. The goal of this research is to develop a Nb-Mo alloy design that will retain two-thirds of its yield strength at 600°C. Steel structures made from mild steel for fire resistant applications are protected from fire by applying a fire resistant coating or insulation, thereby adding to the construction cost. Currently, either the steel beams are encased with concrete or covered with a fire protective coating. Elimination of these fire protective layers would reduce construction costs by at least 10%. So, there exists an opportunity to offset the increased alloy cost by commercializing a high temperature beam design consisting of Nb-Mo or Nb-Cr-Mo specifically designed for fire resistant steel applications. The increased alloy cost would be more than offset by a reduction in project cost making for a more fire resistant steel structure.

Globally, Nippon Steel produces two grades of fire resistant steel plate steel, one containing Nb+Mo and one grade with Mo only. Thyssen Krupp is the only other producer basing their alloy design on FR30. Research has been performed comparing the elevated temperature behavior for some experimental chemistries shown in Table II and elevated temperature properties shown in Figure 6 [9].

Table II. Compositions of Experimental Fire Resistant Steels

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	Al	N
Base	0.11	1.16	0.018	0.013	0.19	0.25	0.08	0.17	0.02	0.004	0.001	0.002	0.010
Nb	0.10	1.06	0.005	0.031	0.27	0.39	0.16	0.09	0.047	0.001	0.021	0.003	0.016
Mo+Nb	0.10	0.98	0.008	0.028	0.30	0.38	0.15	0.10	0.48	-	0.017	0.004	0.010
V+Nb	0.08	1.13	0.005	0.030	0.27	0.32	0.11	0.13	0.036	0.047	0.021	0.003	-
Nippon I	0.11	1.14	0.009	0.020	0.24	-	-	-	0.52	-	0.03	-	-
Nippon II	0.10	0.64	0.009	0.050	0.10	-	-	-	0.51	-	-	-	-

Figure 6. Yield and tensile stress behavior at elevated temperature for experimental steels



The Mo+Nb alloy exhibits the strongest precipitation response over the temperature range of 250-550°C retaining two-thirds of its yield strength at 600°C. Following substantial secondary hardening up to 550°C, precipitate coarsening occurs making the precipitate less effective in pinning dislocations or stabilizing the microstructure. It is noted that again the elevated temperature strength of a Nb only alloy exceeds the strength of the Nb+V alloy composition, but only retains 50% of its yield strength at 600°C, not meeting the goal. Nevertheless, it is observed that small additions of .017%Nb exhibit a greater elevated temperature strength offsetting the influences of significant changes in the base microstructure at these temperatures [10].

Microalloying with niobium has been shown to enhance the elevated temperature properties of fire resistant (FR) steels, and variations in the thermomechanical processing schedules of a niobium containing structural steel have been evaluated. In particular, the thermomechanical processing strategy developed a ferrite substructure. By finish rolling within the warm working regime, it may be possible to generate a stable ferrite substructure capable of improving the elevated temperature strength of FR steels [11].

Nb-bearing Cryogenic Reinforcing Bars

The optimum application of Nb-microalloying is made through the controlled rolling process having a certain percentage of deformation in the region where the austenite does not recrystallize anymore. This situation leads to an elongated austenite grain. After the austenite/ferrite transformation to an extra fine ferrite grain occurs, the strength and toughness improve. Typical applications involve:

- Low service temperature down to -40°C in Arctic regions in Canada and Russia
- Concrete walls for underground LNG storage tanks with service temperature between – 100 to -125°C [12]

These concrete reinforcing bars for cryogenic applications have been produced by Sumitomo Metals using low carbon Nb-bearing steels [13]. This chemistry design provides another example of the low carbon-low residual-low sulfur approach. The developed steel A contains 0.09%C, 0.51%Si, 1.67%Mn, 0.012%P, 0.008%S, 0.059%sol Al, and 0.033%Nb. The conventional steel replaced was 0.23%C, 0.24%Si, 1.46%Mn, 0-.035%P, 0.018%S and 0.001%solAl. Table III shows the results of room low temperature tensile tests using full scale commercially produced reinforcing bars.

Table III. Low temperature tensile properties of cryogenic rebar

	150°C	**100°C**	**50°C**	**0°C**	**25°C**
Steel A Tensile Strength (MPa)	730	650	620	575	555
Steel A Yield Strength (MPa)	715	610	550	515	510
Steel A %Elongation	32	40	32	38	40
Steel S Tensile Strength (MPa)	745	665	640	570	545
Steel S Yield Strength (MPa)	650	525	410	350	345
Steel S Elongation	26	29	29	30	32

Steel A = newly developed steel Steel S = conventional steel

The steel is rolled with a finish rolling temperature in the metastable austenite region (approximately 750°C). The combination of low temperature finishing and low carbon- low sulfur chemistry improves the ductility of this material even at -200°C with the 50% FATT in the Charpy V test below -135°C with an ASTM grain size of 11-12. This material will meet all requirements for concrete reinforcing bars for LNG tanks [14].

Operational Implementation Considerations

With respect to the wide range of reinforcing bar diameters, even at the same strength level, operational experience has demonstrated that a vast number of carbon-microalloy chemistry combinations, rolling mill practices and mill configurations can meet demanding mechanical property requirements and product applications. Each mill is unique and hence, there is no universal solution for the chemical composition, melting practice, reheat furnace soak temperature, and hot rolling regime. Carefully controlled mill trials should integrate the actual melting, casting, furnace and rolling mill operational parameters and variations of the process into the final analysis and mechanical property results.

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