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SEISMIC AND FIRE RESISTANT NIOBIUM-MOLYBDENUM-BEARING LONG AND PLATE PRODUCTS

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Abstract

The compelling need for development of higher performance steels for seismic and fire resistant steel applications is driven by the recent catastrophic earthquakes and/or tsunamis in Haiti, Peru, China and Japan. Current research and development projects throughout the world are focused on the development of a family of niobium-molybdenum-bearing S500 and S600 grades of bars, beams and plates with superior toughness, fatigue resistance, fire resistance, seismic resistance, reduced yield to tensile ratio variation within a heat of steel and overall superior performance. The engineered nucleation and controlled growth of complex nano-co-precipitation, containing Nb and Mo, contribute significantly to a mechanism that results in enhanced performance under seismic and/or fire environmental conditions. The successful high quality production of these Nb-Mo steels with higher strength and elongation behavior may require slight process metallurgy adjustments to the melting and hot rolling practices to consistently manufacture and initiate the optimum precipitate size, distribution and volume fraction of (Nb,Mo)(C,N) in these value added earthquake/fire resistant grades. Rebar, long product and plate producers, who intend to supply these earthquake and fire resistant steels, should incorporate the successful process metallurgy strategies and operating procedures exercised today in producing advanced high strength and toughness steels for automotive, pipeline and critical structural applications, such as fracture-critical beams, forging quality bars, ship plate and pressure vessels.

Introduction

The market trend for improved reinforcing bar and structural steel beam or plate for seismic and hurricane/typhoon regions is driving the development of new grades of steels, with exceptional properties, not available in currently manufactured reinforcing bars and construction steels for challenging civil engineering designs. The next generation of Nb-bearing seismic and fire resistant construction steels requires 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, (7) improved seismic performance and (8) better fatigue resistance. All of these properties are desired in both the weldment and the base metal.

The successful production of value added seismic and fire resistant steels requires the application of melt shop and rolling mill practices that in some cases are similar to those used for value added automotive, pipeline and structural grades. Tighter process control during the melting, casting, billet heating and rolling is necessary in order to meet the demanding properties necessary in seismic-prone environments. These practices are often considered unnecessary in conventional long product production, however, the future generation of value added long products will demand changes in operational practices. Different control strategies are required for the production of these high quality construction steels. These strategies include lower residual element levels, scrap segregation, lower sulfur and phosphorous levels, adopting a low carbon approach, and control of nitrogen levels at the basic oxygen furnace (BOF) or electric arc furnace (EAF) and at the billet caster.

Every rebar and plate producer that will manufacture these value added S500 and S600 reinforcing bars and plates should thoroughly understand their process metallurgy variables so the new practices fit their specific steel grade compositions, residual levels, clean steelmaking and hot rolling operation. In addition to the control of nitrogen, hydrogen and oxygen levels, control of scrap residuals, such as copper, lead, antimony and tin, is also very important in order to achieve exceptional toughness in the S500 and S600 products.

Quite often, steelmakers attempt to produce microalloy grades with exceptional toughness at higher carbon levels (approaching 0.12 to 0.20%C) and high residual contents due to poor scrap segregation. These high carbon and high residual contents can lead to a variety of quality problems such as cracking, poor surface quality, segregation issues and low toughness [1]. A reluctance to lower the base carbon level and achieve strength through precipitation and grain refinement can result in high strength reinforcing bars lacking superior toughness. The metallurgical cleanliness of the scrap and effectiveness of scrap segregation and preparation are often an opportunity area to improve overall structural steel quality.

Civil and Materials Engineering Developmental Trends

From a civil engineering design perspective, a performance-based design approach is applied. Such an approach involves the development of damage resistant systems that involve; (1) seismic isolation systems, (2) energy dissipation systems and (3) self centering frames and walls. Significant progress has been accomplished in the ability to better predict the occurrence and intensity of future earthquakes; however, through the course of these design changes, materials have not changed. Therefore, the designers have embraced the possibility of incorporating both improved fire and seismic resistant materials in construction to better withstand earthquakes, typhoons and other catastrophic events, thereby minimizing structural damage and saving human lives. Also, the development of new fire resistant steels for construction is necessary since fires are often associated with seismic events.

Material Engineering Integrative Design

Specified materials for construction have not changed significantly over the past decade. The global structural steel market development, research and industrial implementation require a shift in the traditional metallurgical approach, especially with designs requiring seismic and fire resistance capabilities. Current challenges confronting structural and long product steelmakers are identical in nature to the challenges faced by automotive steel and pipeline producers in their development of advanced high strength steels over the last decade.

For example, during the evolution of pipeline steel development from X52 through X100, similar challenges existed, resulting in steelmaking and processing changes to successfully apply High Temperature Processing (HTP) to overcome these production and product quality challenges. Some, but not all, of this technology can be transferred to the production of structural Nb-bearing steels. Many of the designs currently applied in the construction of high strength pipelines are strain-based. Unique materials have been developed to assist the designers in assuring that the proper stress-strain behavior occurs during loading of pipelines. Interestingly, structural designers and fabricators also desire a more uniform and predictable stress-strain behavior of beams, rebars and construction plates under severe loading and both low and high-cycle fatigue loading. Although the chemistries and hot rolling schedules of these newly developed pipeline steels do not necessarily apply directly to some of these construction applications, there are many elements of the metallurgical mechanisms that will apply in various bridge and building designs.

A second opportunity for materials improvement involves fatigue and fracture performance behavior under seismic and/or elevated temperature conditions. There is very limited data on fatigue and fracture toughness of recently developed construction steels.

Nb and/or Nb-Mo Steels for Earthquake Zones and Fire Resistance Requirements

The development of seismic resistant rebar was initiated with the introduction of Nb to existing rebar grades. Increased sizes of reinforcing bars, at greater than 40 mm in diameter, high yield strength (greater than 450 MPa), with improved weldability, are required in concrete reinforcing bars for seismic zone construction. 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 450 to 550 MPa strength levels, improving ductility and toughness. The addition of Mo also offers improved fire resistant properties for an evolving market.

Currently a large quantity of rebar is produced with no microalloys, using the Tempcore process, however, ductility is reduced. The cooling scheme achieved through application of the Tempcore process with a Nb-Mo grade may be modified or eliminated in the lower strength grades, resulting in reduced operating cost and increased mill productivity. The Tempcore process is applied to reinforcing bars to increase the yield strength, but elongation, toughness and fatigue performance may be impaired due to the microstructure produced.

Fire Resistant Plate Steels

Fire resistant constructional steels have been commercialized in some parts of the world (China and Japan) and are being examined in the USA. Current activities are focused on development of specifications for testing of elevated temperature properties. Some material specifications and niche applications (e.g. high-rise building columns, structures where friable insulated coatings are undesirable) will follow. Selected metallurgical studies are reviewed, with a focus on Nb-containing steels that are intended to help understand the microstructure/property relationships that control fire resistant (FR) properties. Specific examples are cited which illustrate the apparent benefit of Mo in suppressing precipitate coarsening rates at elevated temperature, beneficial effects of microstructure refinement, microalloy precipitation, and warm working of ferrite on the FR properties.

Since structural steels usually maintain most of their strength at 350 °C (and indeed some steels may be stronger at 350 °C than at room temperature due to strain aging effects of interstitials), this high yield strength requirement is effective but conservative. Consequently a need developed to design and implement newer steels with improved yield and tensile strength properties at even higher elevated temperatures than 350 °C. The FR steels produced in Japan for the past several years guarantee a minimum yield strength at 600 °C that is 2/3 of the room temperature yield strength, i.e. having a minimum yield strength ratio of 2/3, and these developments have already stimulated implementation of FR steels in some niche applications. Some other design codes cite minimum yield strength ratios of 50% at 600 °C [2].

With the evolving demand for fire resistance, it became apparent that a Nb-Mo based structural steel design could also improve fire resistance at the same time. Therefore, it was decided to study various compositions focused upon fire resistance behavior. So, the need for fire resistance in construction steels, for high strength at elevated temperatures, was defined in the USA. Also, there are very limited commercially available fire resistant plates produced globally. Simultaneously, work is being performed in China at Baoshan Iron and Steel Company as a result of the increasing demand for high performance fire resistant structural steels for use in commercial building-type applications and a low Mo-Nb approach via TMCP has demonstrated acceptable high temperature strength [3].

Based upon the research and development within the USA, as well as other previous developments in Japan, specifically Nippon Steel [4], it was decided to create a task force within ASTM to study the possibility of writing an ASTM specification. At this time, an ASTM specification for FR steels has been written and will be balloted. To meet this requirement, a new fire resistant Nb-Mo structural steel grade is under development. Much of this work is the underpinning for development of the specification.

Experimental Nb-Mo Fire Resistant Steel Comparison

The goal of the current research is to further develop a Nb-Mo alloy design that will retain 2/3 of its yield strength at 600 °C. Table I compares the compositions to the commercially available Japanese FR steel plate.

Table I. Compositions of Experimental Fire Resistant Steels wt% [5]

	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	-
NSC I	0.11	1.14	0.009	0.020	0.24	-	-	-	0.52	-	0.03	-	-
NSC II	0.10	0.64	0.009	0.050	0.10	-	-	-	0.51	-	-	-	-

Figure 1 exhibits the superior elevated temperature properties of Nb-Mo plate steels compared to other ASTM A572 or ASTM A992 type construction steels.

The Nb + Mo steel exhibits the best high temperature performance. The strengthening mechanism involves the co-precipitation of (Nb,Mo)(C,N) in a fine dispersion of 3 to 5 nanometers diameter within the ferrite matrix. Figure 2 illustrates the co-precipitation of the (Nb,Mo)(C,N).

Basis for New ASTM FR Steel Specification

The diffusion of Nb and Mo at different carbon concentrations influences the precipitation kinetics. Initially, solute Nb and Mo will retard dislocation climb motion, dislocation recovery and grain boundary migration. However, as the temperature increases, the dislocations can become mobile at approximately 400 to 500 °C and, consequently, the yield strength reduces as exhibited in Figure 1. Finally as the fire ensues, the secondary precipitation of (Nb,Mo)(C,N) occurs and the traditional Ostwald ripening mechanism takes place. Figure 3 below illustrates the retardation of the dislocation climb.

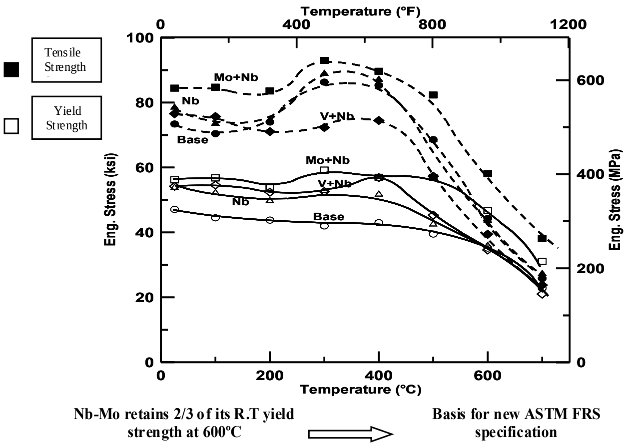

Figure 1. Yield and tensile strength vs. temperature (25-700 °C) for base, Nb, Mo+Nb and V+Nb alloys [5].

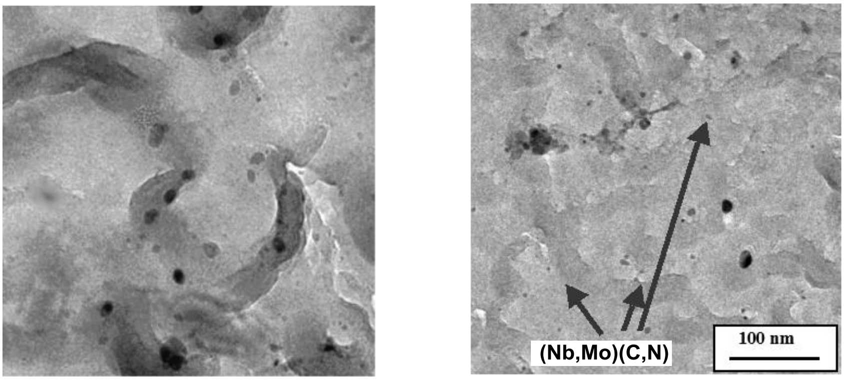

Figure 2. Co-precipitation of duplex (Nb,Mo)(C,N) precipitates in the ferrite matrix.

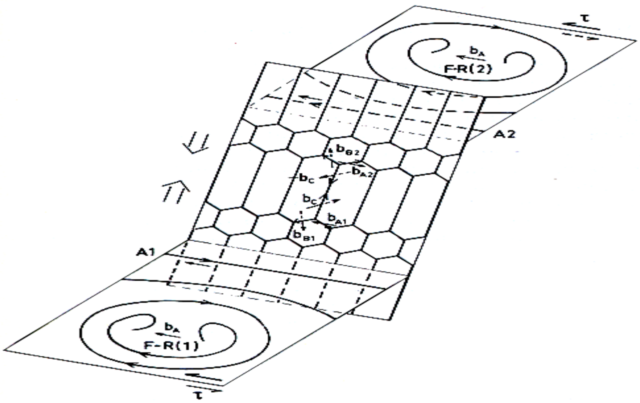

Figure 3. Retardation of dislocation motion during fire.

It is widely known that solute Mo and Nb have the effect of retarding the climb motion and recovery of dislocations as well as grain boundary migration. In low-carbon HSLA steel these solute elements retard dislocation recovery at temperatures up to 550 °C [6]. This can explain the moderate loss of strength of the Nb-added steel when heated in the range of 400-500 °C.

The important parameters of Nb-Mo production of FR steel plate, beams and rebar are:

- Through proper hot rolling thermal practices, create duplex 3-5 nm co-precipitates of (Nb,Mo)(C,N).
- The TMCP rolling process and appropriate finishing temperature must be controlled for a given Nb-Mo composition to assure both the proper size of the ferrite microstructure and the fine Nb-Mo precipitate distribution in the ferrite sub-structure.
- Secondary precipitation during fire.
- Clean steel process metallurgy at Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF) and Secondary Steelmaking.
- Reheating furnace practices and combustion control to drive nano-precipitation homogeneity in the final microstructure (i.e. the kinetics of the reaction).

Co-precipitation of Microalloy Carbonitrides

Extensive research is underway to study the synergistic effects of Nb,V, Ti and Mo in duplex and ternary combinations. The research-to-date is evaluating the precipitate size, shape, morphology, precipitate crystallographic structure, precipitate volume fraction, precipitate chemical stoichiometry and the coherency with the ferrite matrix. Figure 4 schematically illustrates the classical strain in the matrix dependent upon the degree of coherency between the precipitate and the matrix and illustrates the effect of soluble solute content on yield strength.

The diffusivity, mobility and solubility of the Nb, Ti, and V carbide forming elements will affect precipitate formation, volume and distribution. Depending upon the amount of interfacial distortion between the ferrite matrix and the precipitate, the amount of effective strengthening is determined, as shown in Figure 4. Also, the thermal practice during rolling and cooling after the last rolling stand affects the ferrite matrix grain size and the effective precipitate size, volume fraction and distribution and hence the resultant strength levels. The TMCP research relating the effect of different finishing temperatures and cooling on the Nb-Mo FR steel alloy composition is further discussed later in this paper.

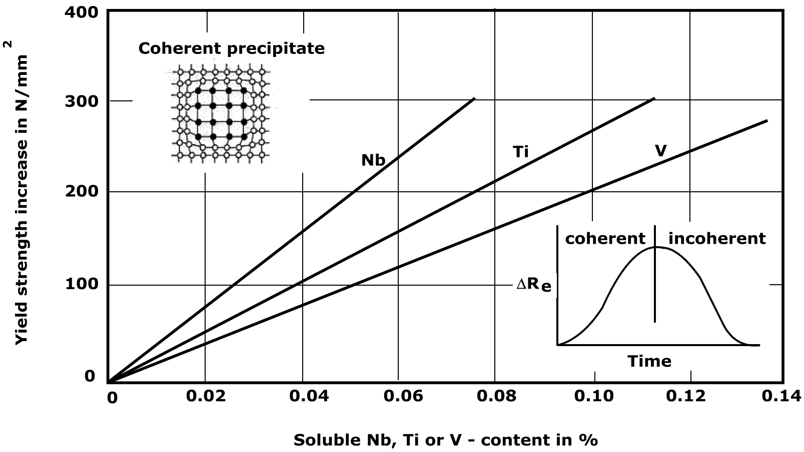

Figure 4. Effect of soluble solute content on increase in yield strength depending on coherency of precipitate with matrix and optimal time at temperature.

Since Mo delays the precipitation of NbC and obstructs Ostwald ripening, an increase in yield strength occurs during the fire [7]. Although the coarsening effect (i.e. Ostwald ripening) is well known, current Nb-Mo research is in progress to better understand the precipitate interaction with the matrix under elevated temperature conditions (i.e. simulation of actual fire conditions).

However, it is apparent in Figure 1 that the Nb-Mo combination results in the highest elevated temperature strength, retaining 2/3 of its room temperature yield strength up to 600 °C, thereby meeting the JIS and soon to be approved ASTM fire resistant steel specifications. Research will continue in order to gain a deeper understanding into the diffusion of Nb and Mo at different carbon concentrations and the influence on precipitation kinetics.

<u>Fire Resistant Steel in China</u>

A new, low Mo bearing FR steel design, containing Nb and other microalloy elements, has been commercially produced via the TMCP process. The new FR steel demonstrates acceptable high temperature strength and ambient temperature mechanical properties. The high temperature behavior of B490RNQ is better than that of Q345B for nominally the same room temperature strength level, by a remarkable margin as shown in Figure 5 [8].

Based upon the Chinese test results, molybdenum significantly improves the elevated temperature yield strength of steel. The steel microstructure is predominantly composed of ferrite, and a molybdenum addition of about 0.5% and 0.02% niobium are considered essential for FR steels with a tensile strength of 400 to 490 MPa. The addition of niobium to the base steel increases the elevated temperature yield strength by 20 MPa. The niobium addition reduces the ferrite grain size and increases the room temperature yield ratio by about 10% (the room temperature yield ratio is the elevated temperature yield strength at a given test temperature divided by the room temperature yield strength). The base composition of the developed FRS grade is shown below in Table II.

Fire resistant weathering steels (FRW) have been developed by Baosteel for many users for the construction of industrial buildings and civil architecture. Numerous welding tests, process evaluation and fireproof tests, carried out jointly with the relevant owners and engineering firms, have been completed. The results prove that these FRW steels can completely satisfy the users' requirements in terms of welding, shaping, earthquake resistance, fire resistance, weather resistance, and are considered the premium products among the constructional steels in China.

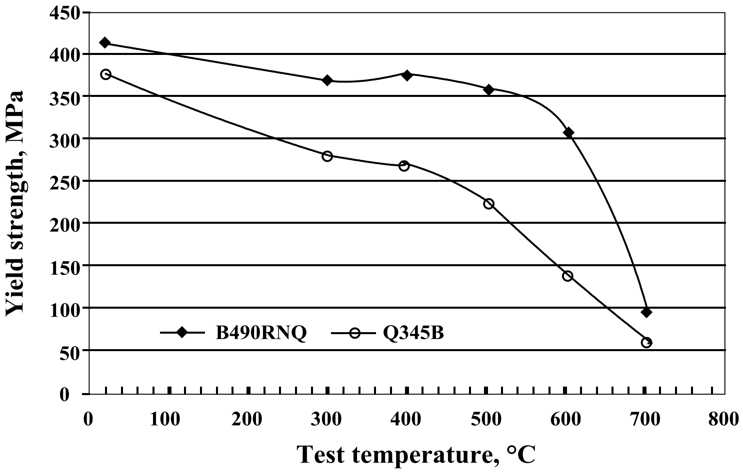

Figure 5. Comparison of elevated temperature yield strength properties of Q345 and B490RNQ FRS.

Table II. China FRS Composition (wt%) [8]

Steel	Base composition	Varied elements
A	0.12%C-0.25%Si-1.0%Mn-0.5%Cr	0.5%Mo
B	0.12%C-0.25%Si-1.0%Mn-0.5%Cr	0.02%Nb
C*	0.10%C-0.25%Si-0.9%Mn-0.5%Cr	0.5%Mo-0.02%Nb

* Steel C – Optimum Nb-Mo FRS composition

TMCP Considerations for FRS Plate Production

Thermomechanical processing laboratory simulations were developed to investigate the effect of finish rolling temperature on the room and elevated temperature strength of a Nb alloyed steel that might be considered for FR applications. Results suggest that finish rolling at low temperatures such as 650 °C can improve the elevated temperature strength of FR steel. This may be due to the presence of warm-worked ferrite generated from finish rolling at this temperature. The greater ability to maintain strength at elevated temperature may be due to the stability of the dislocation substructure that is created during warm working of the ferrite [9].

The constant-load test results illustrate differences between steels, with a Mo + Nb steel exhibiting better FR properties than comparative C-Mn, V, or Nb steels tested identically [10]. The good elevated temperature strength and creep properties are due to the high lattice friction stresses, which are the result of a very fine distribution of MC precipitates, Mo in solid solution, and a strong wave of secondary precipitation at approximately 650 °C. It is the lattice friction stress that maintains strengths up to 600 °C when grain boundary sliding initiates [11]. Nevertheless, it is observed that small additions of 0.017%Nb result in a greater elevated temperature strength offsetting the influences of significant changes in the base microstructure at these temperatures [12].

Thermomechanical processing of HSLA steels within the warm working regime of 0.4-0.6 T_m (where Tm is the absolute melting temperature) is known to produce a stable, recovered ferrite substructure [13]. The formation of a dislocation substructure in the ferrite occurs when the combination of strain and temperature allows sufficient dislocation motion and recovery to occur [14]. It has been shown that the presence of a bainitic microstructure can improve the elevated temperature strength of FR steels in comparison to a ferrite/pearlite microstructure [2,6]. Bainitic ferrite has some characteristics in common with recovered ferrite, specifically the presence of low angle boundaries. Therefore, it was decided to consider whether stable substructures may provide enhanced elevated temperature properties. Thermomechanical processing laboratory simulation cycles were developed and tested on a low Mo-Nb-Cu alloy to investigate the effect of finishing temperature on both the room temperature and elevated temperature strengths of a Nb-steel considered for FR applications. The composition of the rolled steel for the TMCP laboratory simulation is shown below in Table III.

Table III. Chemical Composition of FR Steel Used in TMCP Laboratory Simulation (wt%) [9]

C	Mn	P	S	Si	Cu	Ni
0.10	1.06	0.005	0.031	0.27	0.39	0.16
Mo	**Sn**	**V**	**Nb**	**Cr**	**Al**	**N**
0.047	0.011	0.001	0.021	0.09	0.003	0.011

TMCP Laboratory Rolling Simulation [9]

A schematic diagram of this processing experiment is illustrated below in Figure 6.

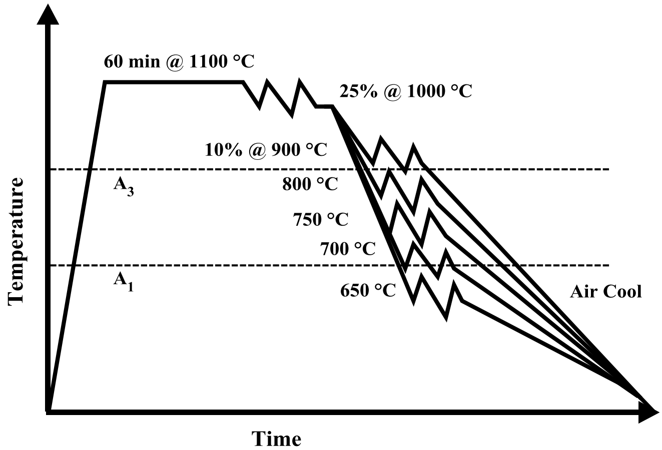

Figure 6. Schematic representation of the processing profile for study of effects of finishing temperature on fire resistant steel properties.

Room temperature tensile test results for the warm rolled experimental FR alloy are shown in Figure 7, as a function of finish rolling temperature. The results show that room temperature strength decreases with an increase in the finish rolling temperature of the FR steel. At the lowest finish temperature of 650 °C the highest yield and tensile strength values are observed, 424 MPa (61.5 ksi) and 574 MPa (83.3 ksi), respectively. As the finish rolling temperature increased into the two-phase region, the yield strength and tensile strength both decreased. During deformation at these finish temperatures there is a mixed microstructure of ferrite and austenite. At the highest finish rolling temperature of 900 °C, the microstructure consists entirely of austenite. Results show that the corresponding room temperature strength was lowest for this condition, probably because of the absence of warm worked ferrite grains and air-cooling to room temperature.

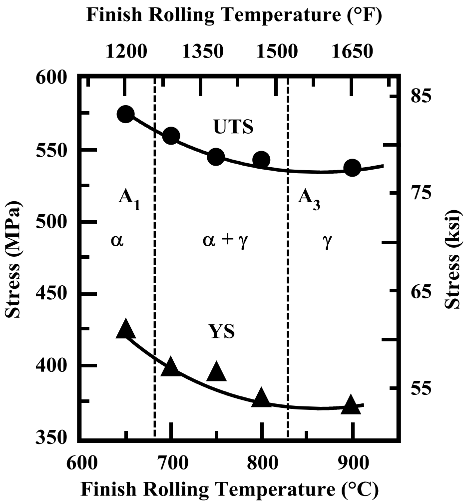

Figure 7. Room temperature yield and tensile strengths for FRS as a function of finish rolling temperature.

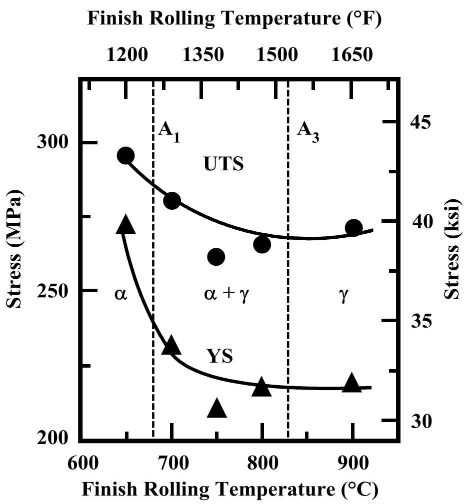

Figure 8. Elevated temperature (600 °C) yield and tensile strengths for FRS as a function of finish rolling temperature.

Elevated temperature mechanical property data at 600 °C for each finish rolling temperature are shown in Figure 8. The highest yield and tensile strength values are found to result from the lowest finishing temperature of 650 °C. The overall trend indicates that the highest yield and tensile strengths occur at the lowest finishing temperatures, presumably due to an increasing presence of warm worked ferrite. Intercritical rolling with higher finishing temperatures did not appear to increase the strength relative to austenitic rolling. The resulting elevated temperature strength ratio $YS_{600°C}/YS_{RT}$ and room temperature yield ratio YS_{RT}/UTS_{RT} were greatest for a finish rolling temperature of 650 °C, producing the highest 600 °C/RT yield strength ratio of 63%.

These results suggest that warm-working at low temperature may offer an attractive opportunity to increase the elevated temperature strength for FRS plate applications. Although this value does not surpass the JIS G 0567 standard of 66%, the rolling reduction was limited to 10% in the laboratory simulation. Also, because of these light reductions at very low rolling temperatures, adjustments to this low Mo-Nb composition are anticipated to easily meet the JIS standard.

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 with elongation levels approaching 30%. Microalloying with Nb and Mo offers the possibility to achieve 600 MPa strength levels with elongations of 25 to 30% and an ultimate tensile strength to yield strength (UTS/YS) ratio of 1.28-1.30 [15]. The S500 Nb grade with a 700 °C self temper has a 1.24 tensile to yield ratio compared to a 1.18 ratio for a Nb-V chemistry. Specifications need to include a tensile to yield ratio similar to ASTM A706 in North America for seismic applications. In addition to a Nb or Nb/Mo chemistry, customized and disciplined quenching practices are of critical importance in order to successfully meet the properties required for this demanding application.

The S500 and S600 rebar alloy design strategy involves; (1) lower carbon equivalent to improve weldability, (2) improved ductility and toughness, and (3) achievement of good yield point elongation. Niobium is added at the 0.020 to 0.035% level to promote 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% and approaching 30% consistently. Nb and Mo have a synergistic effect helping to achieve a ferrite and bainite core in place of the conventional ferrite and pearlite core obtained 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 coil 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 [16].

Niobium and molybdenum have a synergistic precipitation effect creating nano-precipitates, 5 to 10 nanometers in size, uniformly distributed throughout the matrix. The combination of grain refinement and nano-precipitation are significant factors in helping to achieve a finer ferrite and bainite core in place of the conventional ferrite and pearlite core with Tempcore [15]. The future seismic rebar recipe is an alloying combination of Mo + Nb, C between 0.10-0.20%, restriction of Mn to less than 1.00%, utilization of specially designed coil cooling practices and incorporation of low sulfur (less than 0.007%) and low phosphorous levels (less than 0.020% if possible). Such practices will significantly improve a given mills capability to consistently meet S500 property requirements, and with further adjustments to rolling temperature and cooling, meet S600 product requirements. As there has been limited published research on the impact and fracture 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. Three key elements that require strict control to improve ductility are illustrated in Figure 9.

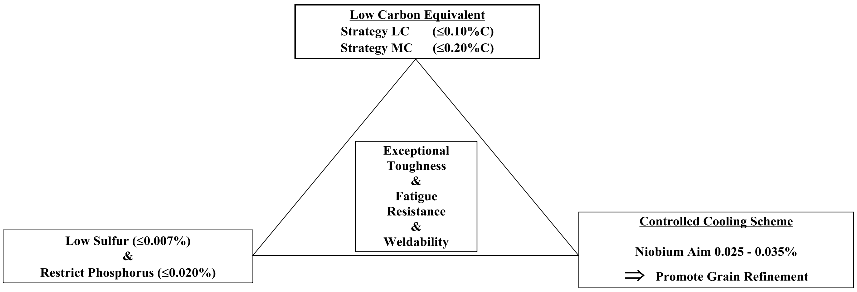

Figure 9. Ultra tough seismic rebar approach [17].

A lower total cost of production may be achieved through a low carbon-Nb alloy design incorporating the selective accelerated cooling approach in conjunction with better control of reheat furnace temperatures. For example, in comparing a Nb chemistry rebar with a V chemistry rebar, the Nb chemistry exhibits the more consistent elongation between 1100 and 1150 °C which is the optimal soak zone temperature for both ductility and efficient lower cost energy consumption (i.e. mmbtu per tonne). Reduced yield-to-tensile strength ratio variation is experienced as well with Nb-bearing versus V-bearing rebar when rolled with these thermal practices which offers quality improvements and reduced rejection rates [18].

<u>Nb-Mo EQR Rebar (Earthquake Resistant)</u>

The basic guidelines for designing this developmental Nb-Mo reinforcing bar are given in the Japanese Industrial Standard on Rolled Steel for Building Structures (JIS G3136-1994). The specification encompasses the mechanical property requirements as shown below in Table IV.

Table IV. Mechanical Property Requirements in JIS G3136-1994

Yield Strength (MPa) YS	Ultimate Tensile Strength (MPa) UTS	UTS/YS	Elongation (%)	Charpy @ 0 °C Joules
>325	>490	>1.25	>25	>27

Industrial heats of the Nb-Mo EQR chemistry nominally containing 0.14%C, 0.85%Mn, 0.25%Si, 0.024%Nb and 0.18%Mo were produced and evaluated. A variety of cooling practices were evaluated at various rebar diameters as shown below in Table V [19].

The Nb only and Nb-Mo grades of EQR exhibited excellent ductility (>36%) and a very high UTS/YS ratio (>1.24). The best balance of properties was obtained for the Nb-Mo combination with the partial water quenching cooling scheme as shown in Table VI.

Table V. Finish Temperatures (°C) by Size and Cooling Scheme

Thickness mm	80	62	47	35	25	18	12	Quenching Conditions
Nb-Mo 1	1070	1040	1010	990	950	890	800	AC
Nb-Mo 2	1070	1040	1010	990	950	890	825	AC
Nb-Mo 3	1070	1060	1050	1035	1020	990	950	Water cooling start at 730 °C
Nb-Mo 4	1070	1060	1050	1030	1015	1005	990	Water cooling start at 750 °C for few seconds and taken out

AC – Air Cool

Table VI. EQR Mechanical Properties [19]

Steel	Cooling Condition	YS (MPa)	UTS (MPa)	UTS/YS	Elong. (%)
Nb-Mo 1	AC	399	528	1.32	48
Nb-Mo 2	AC	386	532	1.38	46
Nb-Mo 3	WQ	533	780	1.46	37
Nb-Mo 4	PWQ	422	578	1.37	42
Nb	AC	400	500	1.25	48

AC – Air Cool

Summary

The future trend for successful development of higher strength FR steels and EQR S500 and S600 structural plate and bar grades will continue to incorporate Nb-Mo synergies for improved toughness performance at elevated temperatures. Seismic and fire resistant grades with Nb and Mo exhibit opportunities to increase toughness and maintain 2/3 of room temperature yield strength at 600 °C. The future for these grades is a dual Nb-Mo product as shown by the developments described in China, India, Japan and the USA. Further research and development activities are needed to transfer this Nb-bearing low carbon "clean steel" plate technology into the S500 and S600 value added long product structural sectors globally. The current fire resistant Nb-containing plate research provides a valuable foundation for the continuation of this development of a family of Nb-Mo chemistries which can be transferred to fire resistant and seismic resistant beam, rebar and plate research. Additionally, the civil and materials engineering communities need to collaborate more effectively to optimize structural design, tensile to yield ratio criterion and Nb-Mo bearing steel materials selection for fire and seismic resistant structural steel applications.

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