PRODUCTION AND APPLICATION OF

HIGH STRENGTH CONCRETE REINFORCING BAR

Alfredo Hey*, Helmut Weise**, William G. Wilson***

*Comision Nacional de Energia Atomica
Avda del Libertador 8250, 1429
Buenos Airea, Argentina

**Thyssen A.G.
Friedrich-Ebert-Str. 12
4100 Duisburg 13, West Germany

*** Consultant
820 Harden Drive
Pittsburgh, Pennsylvania 15229, U.S.A.

Abstract

Niobium has been used to strengthen high carbon (0.40% C) reinforcing bar for a number of years. Industry demands for improved bendability, toughness and weldability have prompted investigation of steels having lower carbon contents similar to the ranges used in traditional HSLA products.

The paper reviews specifications governing production of high-strength reinforcing bar and describes the important metallurgical considerations in applying niobium strengthening to bar-mill products.

Results are presented of numerous investigations conducted by the authors which illustrate the interplay between steel composition, bar size, reheating rolling and cooling conditions and their effect on final mechanical properties,

Introduction

In 1957, when high-strength, low-alloy steels (HSLA) were fist introduced, concrete reinforcing bar was commonly made from diverted heats that could not be used for any other purposes. Yield strengths were in the 40,000 ksi (276 MPa) range and the specifications for tensile strength, elongation and bending were not restrictive or demanding.

The steels produced for this application today have evolved as a result of demands first for higher yield strengths and later for improved bendability, better toughness for applications in seismic prone areas or in critical nuclear power station foundations and, more recently, because of the desire to weld without preheat.

The sequence of alloy development progressed through higher carbon contents, cold twisting, and eventually to microalloying. The microalloyed steels have undergone a secondary evolution through the application of rolling mill temperature control and on a limited basis the application of direct quenching on the run-out table. Details of this progression are contained in two papers presented at ILAFA conferences by Gray (1), (2).

The present paper reviews applicable specifications in North America and Europe and describes the benefits obtained from niobium additions to high carbon rebar. Recent efforts have focussed on the interplay of steel composition and rolling mill processing on the properties of relatively low carbon (0.15 to 0.25%) weldable niobium microalloy bar steels. These niobium containing steels are particularly applicable to specifications that require yield strengths in the 400-420 MPa (58-61 ksi) range.

Metallurgical Considerations

The basic metallurgical principles of high-strength, low alloy HSLA steels presented in this conference (3) are readily applied to the production of concrete reinforcing bar. However, the magnitudes of the various effects of the microalloys are affected by the relatively high carbon contents of the steels and the relatively high temperature processing regimes that are characteristic of most continuous bar mills.

The metallurgical characteristics of niobium which are most relevant to reinforcing bar and thus to discussions in this paper include the following:

(a) Solution and precipitation rates of niobium carbide and nitride in austenite under the prevailing heating, cooling and rolling conditions. These factors control the instantaneous composition of the austenite. Solubility data developed for low carbon steels can be used to predict the behavior of high-carbon steels but we should caution that since carbon reduces the activity of niobium, simple extrapolation will tend to overestimate the stability of niobium carbide.

(b) The effect of niobium in preventing austenite grain growth and in retarding austenite recrystallization, particularly at low rolling temperatures.

(c) The reduction in austenite decomposition temperature (transformation temperature) when niobium remains in solution from the reheating temperature.

(d) Precipitation strengthening potential in ferrite. This is proportional to the niobium remaining in solution prior to the austenite-ferrite transformation and is maximized at austenite-ferrite transformation temperatures which yield the smallest precipitate sizes.

The instantaneous composition of the austenite has a predominant effect on these processes and it is helpful to develop a perspective of the effects of steel composition and thermal and deformation sequences on precipitation behavior. Using the data of Narita (4) it is sometimes useful to construct equivalent solubility diagrams (5) for the various precipitating species, Figure 1. While these diagrams take no account of potential non-linearity at high carbon contents (for NbC) they can be used to indicate the relative importance of AlN, NbN, NbC, etc. At normal mini-mill nitrogen contents (<0.010%) Figure 1 suggests that niobium carbide is the predominant precipitate in high-carbon reinforcing bar.

Based on this assumption the temperature of solution has been calculated for steels with 0.05 percent niobium and various combinations of carbon and manganese, Table I.

Table I. Temperature [F (C)] of Solution of NbC at Various Carbon & Manganese Contents for a Steel Containing 0.05 Percent Niobium.

Carbon	No Mn Correction	.60% Mn	1.0% Mn	1.4% Mn	1.80% Mn
.15	2105 (1151)	2143 (1173)	2133 (1167)	2121 (1160)	2101 (1149)
.20	2164 (1184)	2212 (1211)	2206 (1207)	2199 (1203)	2187 (1197)
.25	2212 (1211)	2267 (1241)	2265 (1240)	2263 (1239)	2258 (1237)
.30	2253 (1234)	2313 (1267)	2315 (1269)	2316 (1269)	2319 (1271)
.35	2287 (1253)	2345 (1290)	2359 (1293)	2364 (1296)	2373 (1300)
.40	2318 (1270)	2391 (1310)	2398 (1315)	2407 (1319)	2421 (1327)
.45	2346 (1285)	2423 (1328)	2434 (1334)	2445 (1340)	2465 (1351)
.50	2372 (1300)	2454 (1345)	2467 (1352)	2481 (1360)	2501 (1374)

In North America, reinforcing bar mills generally use reheating temperatures of 2400–2500 F (1316-1371C), with a finishing temperature of 2000 F (1093C) and above. Because of higher energy costs, European mills use reheating temperatures of [2010-2280 F (1100–1250C)] and lower finishing temperatures [1780-1930 F (970-1050C)]. Within these temperature ranges Table I can be useful in rationalizing some of the results observed.

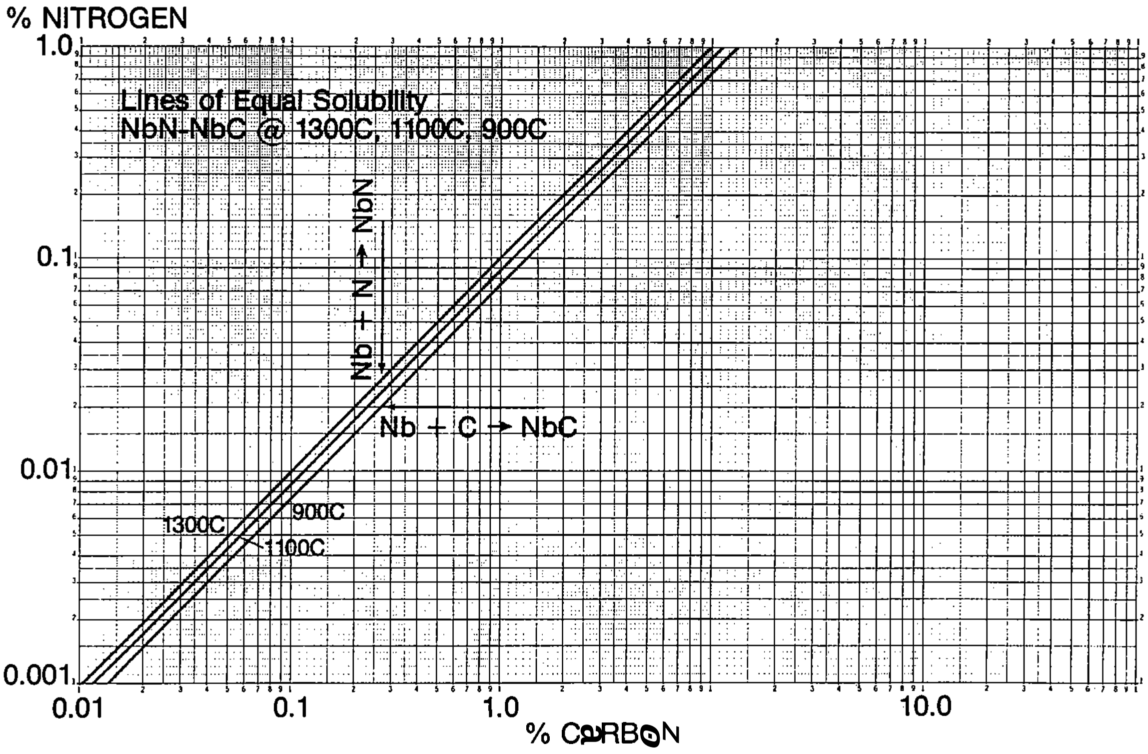

Figure 1. Lines of equal solubility (LES) for NBC and NbN at three temperatures.

Briefly, high reheating temperatures lead to complete dissolution of NbC which will allow grain growth to occur. The coarse grain sizes and niobium in solution will lead to lower transformation temperatures (3) (higher "hardenability") and possibly higher strength. However, if the γ to α transformation temperature is too low, NbC will not precipitate except on aging. Since strain induced precipitation of NbC is a possiblity during rolling, it follows that lower finishing temperatures (smaller bar sizes) will tend to produce higher austenite-to-ferrite transformation temperatures. This interplay of instantaneous austenite composition, grain size and cooling rate determines final mechanical properties.

The effect of niobium in increasing yield strength shows a plateau at between 0.03-0.06 percent niobium (3) depending on steel composition (vanadium and molybdenum tend to increase the effective niobium) and rolling schedule. A 0.20-0.30 percent carbon 1.30 percent manganese steel containing 0.04 percent niobium rolled to 25 mm bar normally has a yield strength of 60-65 ksi (41.4-44.9 MPa) which seems to be the practical upper limit for strength in the C-Mn-Nb system. Higher yield strengths require additions of vanadium, lower temperature rolling and water cooling, either used singly or in combination. Alternatively, extra low-carbon steel of the Mn-Nb-B type might be considered for yield strengths up to 70-80 ksi (48.3-55.2 MPa) when steelmaking technology permits (8).

Specifications and Practices

Property objectives for high-strength reinforcing bar are compiled in the list of specifications from North America and Europe in Table II.

Reinforcing bar that is to be fabricted without welding (North America)

For the smaller bar sizes 11.9 mm (#4) to 22.2 mm (#7) that will not be welded or which have high preheat requirements, the strength and ductility requirement shown in Table II can be achieved with combinations of carbon, manganese, and residual Cr, Cu, Mo, etc. from the scrap charge. Nevertheless, in larger diameter bar, it is common practice in North America to lower the carbon content in some cases to 0.44 percent max. and in others to as low as 0.35 percent max. Microalloying additions of about 0.02 percent niobium then provide the additional strengthening with an accompanying improvement in bendability.

Heating temperatures used in many of the mini-mills in North America where most reinforcing bars are produced are in the range 2350/2450 F (1288/1343 C) and finishing temperatures tend to be in the 2000/2100 F (1093/1149 C) range. The temperatures of solution of niobium carbide for the typical niobium and carbon ranges discussed above (1.00% manganese) are shown in Table III. When the mini-mill heating and finishing temperatures are compared with the solution temperatures, it can be concluded that all niobium should be in solution prior to rolling, but that deformation of the bar should take place below the solution temperature resulting in strain-induced precipitation of NbC particles which refines austenite grain size and possibly gives precipitation strengthening. Rolling mill processing of this type of steel is straight forward and the grain size reduction gives a simultaneous improvement in strength and ductility. The reliability of this method for producing 60 ksi (414 MPa) yield strength, large diameter bar has resulted in its adoption by several manufacturers in America. Typical results from four producers are shown in Table IV.

Table II. Weldable High-Strength R Steels European and North American Standards

State	Standard Number	Yield Strength N/mm^2 (ksi) mm	Chemical Composition (Ladle Analysis)
Austria	Onorm B 4200	420 (60.9) 500 (72.S) 600 (87.0)	To be found out by Certification Tests
Belgium	NBN A 24-302	400 (58.0) 500 (72.5)	C max. 0.25% C + Mn/6 max. 0.45%
Denmark	DS 13080	420 (60.9) 560 (81.2)	C max. 0.28%
Federal Repubic of Germany	DIN 488 (Revised)	420 (60.9) 500 (72.5)	C max. 0.22%
France	NF A 35-016 A 35-018	 400 (58.0) 500 (72.5)	C max. 0.22% Si max. 0.50% C + Mn/6 max. 0.45%
German Democratic Republic	TGL 1253001	 400 (58.0) 410 (59.5) 490 (71.1)	C max. 0.29% Si max. 0.50% Mn max. 1.55% C max. 0.60%
	TGL 12530108	410 (59.5) 490 (71.1)	C max. 0.26% Si max. 0.55% Mn max. 1.10%
Great Britian	BS 4446	410 (59.5)	C max. 0.25%
Netherlands	NEN 6008	400 (58.0) 500 (72.5)	C max. 0.27%
Sweden	SIS 142165 142168	 400 (58.0) 600 (87.0)	C max. 0.28% Si max. 0.60% Mn max. 1.60%
Euronorm	80 (Revised)	400 (58.0) 500 (72.5)	C max. 0.24% C + Mn/6 max. 0.45%
U.S.A.	706	414 (60.0)	C max. 0.30% Mn max. 1.30% CE max. 0.55%
U.S.A.	615**	414 (60.0) 276 (40.0)	None Specified

$$*CE = \%C + \frac{\%Mn}{6} + \frac{\%Cu}{46} - \frac{\%Ni}{20} - \frac{\%Cr}{10} \frac{\%Mo}{50} - \frac{\%V}{10}$$

** Weldable Only with Preheat

Table III. Temperature of Solution of Niobium Carbide (T*) and Levels for a 1.00 Percent Manganese 0.02 Percent Niobium Steel

.35 Carbon = 1158 C (2116 F)

.40 Carbon = 1176 C (2149 F)

.45 Carbon = 1192 C (2178 F)

$$*T\ ^\circ K = \frac{-7900}{\log(\%C \times \%Nb) - 3.42}$$

Table IV. Mechanical Properties of 25 mm dia. (#8) Niobium Containing Reinforcing Bar (Non-Weldable Grade).

	Composition - Weight Percent								Yield Strength	UTS
Plant	C	Mn	Si	Nb	Cr	Cu	Ni	Mo	MPa (ksi)	MPa (ksi)
No. I	0.35	1.45	0.30	0.03	-	-	-	-	>490 (71.0)	>540 (78.3)
No. 2	0.32	1.25	0.24	0.24	0.12	0.30	0.09	-	450 (65.3)	680 (98.6)
No. 3	0.31	1.30	0.30	0.05	-	-	-	-	470 (68.2)	690 (100.0)
No. 4	0.39	0.94	0.25	0.023	0.13	0.28	0.13	-	476 (69.1)	741 (104.5)

Weldable Microalloyed Strengthened Reinforcing Bar

For the past several years the International Standards Organization (ISO) has been preparing recommendations covering the strength, ductility and weldability of rebar. A working group of members of this organization has presented a document entitled "Draft Guide for Welding and Weldability of Concrete Reinforcing Steel," which has not been adopted at this time. The basic premise is that weldable rebar should be "weldable without precautions" (no pre-heat or post-heat when using rutile electrodes), and that a tension test incorporating the weld should be the normal test procedure, with the maximum allowable carbon set at 0.24 percent. The specifications summarized in Table III show that compliance with this proposed standard is not uniform. Generally, steels with carbon contents less than 0.22 percent are classified as "weldable" which with higher carbon contents they are classified as "weldable with precautions." The standards for the latter steels contain welding instructions with regard to welding procedures and necessity for testing bends of cross welds.

The American Society for Testing Materials (ASTM) specification (A 706) for weldable bar is not nearly as restrictive as the proposed ISO standard with respect to carbon (0.30% max.), but it is much more restrictive with respect to welding, requiring pre-heat of at least 50 F (10 C) for 25.4 (#8) diameter bar.

In addition, electrodes for shielded metal arc welding must be of the low hydrogen variety.

Investigations conducted in the 1970's (9) (10) by the authors show that niobium containing steels may be capable of meeting the proposed ISO standards for strength and weldability (max. 0.24% carbon-aim 0.22 carbon) and yield strength greater than 400 MPa. Results of various trials are summarized in Tables V and VI.

Heating and finishing temperatures are not known for the Table V data. Because the yield strengths of the heavier bars (32 and 40 mm) from heat 11529 are lower than for the other two heats in this trial, it is suspected that they were rolled with a non-optimum rolling schedule.

The mechanical properties of steels rolled in a second trial are shown in Table VI. Heating and finishing temperatures for the various bar diameters, as well as the temperatures at which all niobium carbide should be in solution, are shown in Figure 2. The results presented in Table VI are arranged in order of increasing niobium content. The first three heats Nb IV, III and I in Table VI have an optimum combination of composition and rolling practice for the 20 mm - 40 mm sizes. The data on heating and finishing temperature relative to NbC solution temperature shown in Figure 2, indicate that the heating temperatures for both heats Nb III and Nb IV were either above or close to the computed solution temperatures for all bar sizes. The finishing temperatures are sufficiently lower than the solution temperature so that strain induced precipitation of NbC should occur thus giving austenite grain refinement and simultaneously balancing they to α transformation temperature. These results confirm that niobium containing steel, when processed correctly with respect to composition, heating and finishing temperatures will develop uniform properties over a wide range of bar sizes.

The results for Steels Nb II and V in Table VI and Figure 2 suggest that part of the NbC remained undissolved at the heating temperature. The undissolved particles tend to act as nuclei for reprecipitation during rolling - thereby limiting the strengthening potential of the steel. Higher reheating temperatures or a further reduction in carbon content are required to maximize the precipitation strengthening potential of the 0.048 - 0.056 percent niobium content.

The yield strengths of the 10 mm bars from heats Nb III, Nb II and Nb V are adequate to satisfy 400 - 420 MPa strength requirements, whereas, the yield strength of heat Nb IV is marginal. It is noteworthy that the yield strengths of the 10 mm bars are not as high as those of the 20 mm bars from the same heats. Whereas their tensile strengths tend to be higher, it is suspected that for the cooling rates and transformation temperatures of 10 mm bar complete precipitation of niobium carbide would not occur and the yield strengths would thus be lower than anticipated. This possiblity when combined with the ability of unprecipitated niobium to produce bainitic microstructures and thus continuous yielding (no yield point plateau), gives rise to the apparently anomulous decrease in yield strength with decreasing bar size.

Table V. Mechanical Properties of Niobium Containing Weldable Reinforcing Bar.

Heat No.	Bar Size mm	Bar Size (1/8th)	Yield Strength MPa (ksi)	Tensile Strength MPa (ksi)	Elongation Percent	C	Mn	si	Nb	CE
21324	20	No. 6	479 (69.5)	649 (94.2)	22.0	0.216	1.18	0.31	0.0464	.432
	25	No. 8	480 (69.6)	643 (93.2)	16.8					
	32	No. 10	442 (64.1)	627 (90.9)	20.7					
	40	No. 12	449 (65.1)	616 (89.3)	16.7					
11513	20	No. 6	480 (69.6)	618 (89.6)	21.8	0.16	1.17	0.33	0.0627	.380
	25	No. 8								
	32	No. 10	444 (64.3)	614 (89.0)	19.3					
	40	No. 12	445 (64.5)	593 (85.9)	20.7					
11529	20	No. 6	456 (66.1)	587 (85.1)	24.0	0.15	1.24	0.21	0.0383	.382
	25	No. 8	453 (65.7)	590 (85.5)	20.3					
	32	No. 10	401 (57.6)	550 (79.8)	22.5					
	40	No. 12	410 (59.5)	560 (81.2)	20.9					

C.E. (ASTM 706)

Table VI. Mechanical Properties of Niobium Containing Weldable Reinforcing Bar.

Heat No.	Bar Size mm	(1/8th)	Yield Strength MPa (ksi)	Tensile Strength MPa (ksi)	Elongation Percent	C	Mn	Si	Nb	C.E.
Nb IV	10	No. 3	390 (56.6)	642 (93.2)	20.7	0.22	1.24	0.28	0.031	.446
	20	No. 6	459 (66.6)	678 (98.4)	15.9					
	25	No. 8	452 (65.6)	651 (94.4)	16.9					
	32	No. 10	450 (65.3)	633 (91.9)	20.0					
	40	No. 12	463 (67.1)	625 (90.6)	17.0					
Nb III	10	No. 3	432 (62.6)	680 (98.6)	19.2	0.27	1.23	0.35	0.034	.498
	20	No. 6	483 (70.0)	714 (103.5)	17.2					
	25	No. 8	467 (67.7)	700 (101.5)	14.3					
	32	No. 10	485 (70.3)	658 (95.4)	19.8					
	40	No. 12	465 (67.4)	651 (94.4)						
Nb I	10	No. 3	490 (71.1)	655 (95.0)	20.5	0.29	1.06	0.30	0.035	.493
	20	No. 6	477 (69.1)	688 (99.7)	19.6					
	25	No. 8	475 (68.8)	681 (98.7)	18.9					
	34	No. 10	460 (66.7)	639 (92.6)	20.0					
	40	No. 12	450 (65.3)	619 (89.9)	18.9					
Nb II	10	No. 3	462 (67.0)	607 (88.0)	25.5	0.21	1.13	0.32	0.048	.416
	20	No. 6	479 (69.4)	649 (94.1)	19.8					
	25	No. 8	472 (68.4)	640 (92.9)	18.2					
	32	No. 10	427 (61.9)	571 (82.8)	22.4					
	40	No. 12	423 (61.3)	576 (83.5)	21.5					
Nb V	12	No. 37	465' (67.4)	627 (90.9)	20.6	0.21	1.25	0.35	0.056	.438
	20	No. 6	476 (69.0)	690 (100.0)	18.2					
	25	No. 8	478 (69.3)	665 (96.4)	20.5					
	32	No. 10	412 (59.7)	572 (82.9)	23.4					
	40	No. 12	409 (59.3)	558 (80.9)	23.0					

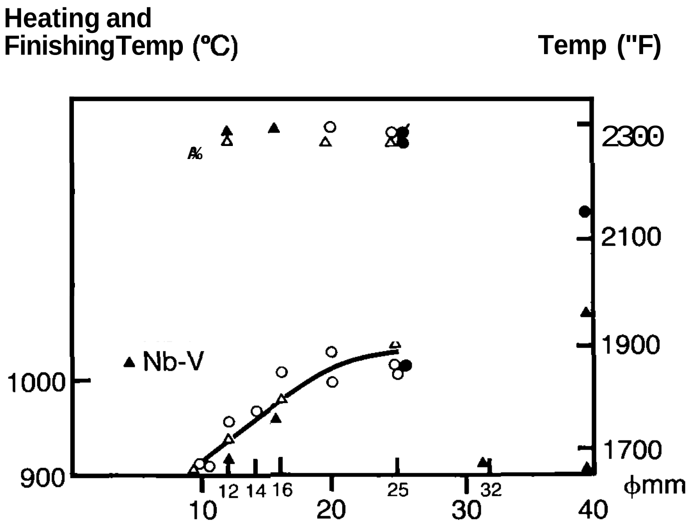

Figure 2. Heating 'and finishing temperatures of weldable reinforcing bar.

Additional results have been obtained from cooperative rolling trials on steels melted to conform to ASTM A 706 [41.4 MPa (60 ksi)] when rolled with conventional North American reheating and rolling practices. All bars meet the yield strength and elongation requirements of ASTM A706 with the highest yield strengths being obtained at the highest carbon equivalents Table VII. In mills where reheating temperatures were very high [2500 F (1371 C)] if not excessive, the low carbon equivalent steels had relatively low yield strengths, Table VIII. The results presented in Table VIII were obtained using a reheating temperature of 2450-2500 F (1343 - 1371 C). The computed NbC solution temperature for the steel (Steel 1, CE = 0.44%) is 2200 F (1204 C). Thus all niobium would be in solution and severe austenite grain coarsening would occur. The high reheating temperature results in a correspondingly high finish rolling temperature (no strain-induced precipitation of NbC) which combined with the coarse austenite grain sizes to produce very high "hardenability" conditions (low transformation temperatures) thus producing bainitic microstructures and preventing NbC formation during cooling (7).

Reheating of the air-cooled bars to 1200 F (650 C) effected a stress relief and simultaneously produced the expected precipitation hardening increment, Table VIII. Since the economics of reinforcing bar production do not allow consideration of expensive reheating treatments, it is necessary to balance reheating, rolling and cooling conditions for each steel composition to ensure that optimum strengthening is obtained in the as-rolled condition.

Stress-strain curves for a steel similar to Steel 1 in Table VII before and after stress relief treatment (tempering) are presented in Figure 3.

The "round house'' continuous yielding stress strain curve which results in a low yield strength for the steel in the "as rolled" condition and low yield strength-tensile strength ratio, changes to a conventional curve with a definite yield point when the steel is tested in the stress relieved condition. The low yield strengths and low yield strength-tensile strength ratios of the smaller bars produced from heats Nb IV, III, Table V, may be rationalized in terms of their cooling rates, and thus transformation and yielding behavior.

Table VII. Effect of Carbon Equivalent on Reinforcing Bar Intended to Meet ASTM A706

Steel 1

Composition		Bar Size mm	#	Yield Strength ksi, (MPa)		Tensile Strength ksi, (MPa)		Elongation Percent	Comments
C	0.21	16	5	69.0	(476)	86.7	(598)	18	--
Mn	1.23	29	9	64.5	(445)	94.5	(652)		Stress relieved 1200 F (644 C)
Si	0.20	32	10	60.7	(419)	87.4	(603)	16	--
Nb	0.046	35	11	65.4	(451)	91.4	(630)	16	--
CE =	0.44	44	14	60.4	(417)	82.2	(567)	20	--

Steel 2

Composition		Bar Size mm	#	Yield Strength ksi, (MPa)		Tensile Strength ksi, (MPa)		Elongation Percent	Comments
C	0.27	13	4	68.5	(472)	92.3	(629)	17	--
Mn	1.02	22	7	63.7	(439)	93.3	(644)	13	--
Si	0.21	25	8	63.3	(436)	82.5	(582)	15	--
Nb	0.049	29	9	65.8	(454)	85.6	(590)	18	--
CE =	0.463	32	10	66.9	(461)	87.1	(601)	19	--
		35	11	64.1	(442)	86.5	(597)	18	--

Steel 3

Composition		Bar Size mm	#	Yield Strength ksi, (MPa)		Tensile Strength ksi, (MPa)		Elongation Percent	Comments
C	.31	13	4	72.0	(496)	98.0	(676)	17	--
Mn	1.31	16	5	72.0	(496)	97.7	(674)	17	--
Si	0.20	25	8	70.3	(484)	96.2	(663)	21	--
Nb	0.050	29	9	67.0	(462)	93.0	(641)	15	--
CE =	0.54	32	10	70.0	(483)	94.2	(650)	16	--
		35	11	68.9	(475)	93.9	(648)	20	--

Table VIII. Effect of Aging on the Mechanical Properties of 29 mm (#9) Low Carbon Reinforcing Bar*.

Condition as Rolled	Sample No.	Tensile Properties LYP ksi (MPa)	UTS (ksi (MPa)	Elongation Percent
Max. Reheating Temp. 2500 F (1371 C) Reheating Time 77 min.	1	48.0 (331)	91.5 (631)	15
	2	--	91.5 (631)	16
	3	43.0 (296)	92.0 (634)	15
	4	41.5 (286)	90.5 (624)	16
	5	47.5 (328)	92.0 (634)	15
Aged (Tempered) 120 F (649 C) 1 hr.	1	65.5 (452)	94.5 (652)	16
	2	63.5 (438)	94.5 (652)	17

*C .21 (Steel 1 in Table VII)
Mn 1.23
Nb 0.049
CE = 0.44

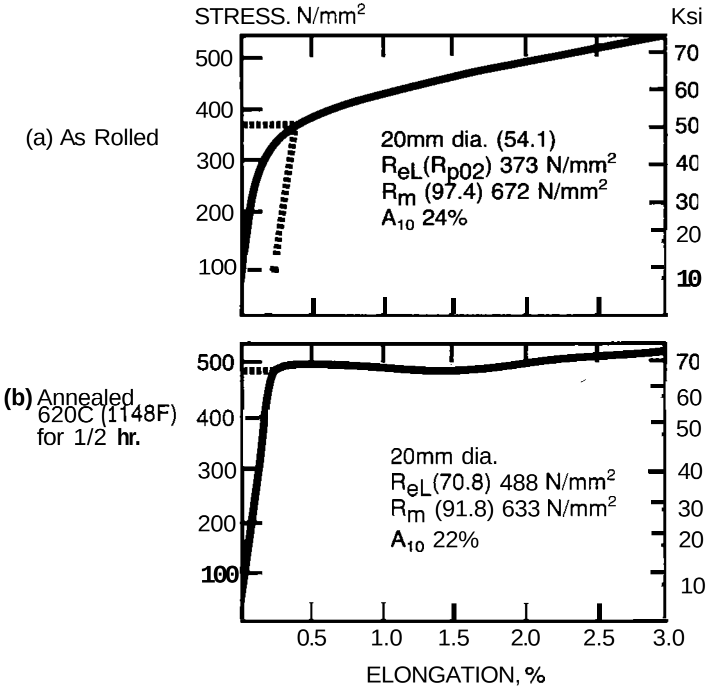

Figure 3. Effect of stress relief on the stress strain behavior of bars rolled from a high 2500 F (1371 C) reheating temperature.

Additional data presented in Table IX indicate that apparently minor variations in heating and rolling practice can have a significant impact on yielding behavior. The bars in Group A were heated to the same temperature in the soak zone, but the total reheating time was about twice as long as that for Group B -- probably long enough that all NbC was taken into solution with the extra time in the soak zone 2425 F (1329 C) resulting in excessive grain growth. The increase in hardenability probably prevented precipitation of NbC during cooling after rolling and produced bainitic microstructures. This, in turn, prevented development of the yield point in two of the Group A bars and a much lower yield strength in the third bar.

Further confirmation of the possibility of suppression of precipitation of NbC in low carbon niobium containing bar was obtained in a multi-plant rebar rolling investigation. The steel investigated had the following composition, in weight percent:

C	Mn	Si	Cr	Ni	Cu	Nb
0.15	1.42	0.45	0.09	0.12	0.19	0.025

Using standard heating and rolling practices, only one set of bars 12 mm (#4) in diameter exceeded the 60 ksi (414 MPa) yield strength requirements in the "as rolled" condition. After the bars were annealed at 1166 F (630 C), the bars from four out of five participating companies had yield strengths that exceeded 60 ksi (414 MPa) in diameters ranging from 12 mm to 32 mm (#4 - #10). However, it must be reemphasized that additional heat treatments of this type are not a commercially acceptable solution to this problem.

In order to produce as-rolled yield strengths of at least 60 ksi (414 MPa), it will be necessary to exercise a modest degree of control of the heating and rolling practice.

The results developed to date by the authors illustrate the following basis for selecting reheating and rolling conditions:

1. It is desirable to get most or all of the niobium into solution.

2. The reheating temperature should not be so high that the superheat over the NbC solution temperature causes excessive grain growth.

3. The rolling temperatures should be sufficiently low to produce some strain-induced precipitation, thereby producing grain refinement and optimizing hardenability.

The terms of the basic solubility equation may be rearranged to facilitate appropriate calculations as follows:

$$T_{\text{complete solution Nb}}\ (^\circ K) = \frac{-7900}{(\log(\%C \times \%Nb) - 3.42}$$

It is strongly recommended that future rolling schedules be designed using these guidelines.

When heating temperatures are lowered to a level that insures the attainment of yield strength objectives, care must be exercised, mainly in North America, so that mill loads do not become greater than mill capabilities. The approach of gradually reducing heating temperatures should enable operators to determine their mills' capabilities in this direction. It is anticipated that increasing cost of fuel for billet reheating will accelerate trends toward lower heating temperatures.

Table IX. Variation in Me Properties of 35 mm (#11) Bar with Variation in So Conditions Prior to Rolling

Reheating Conditions**	Sample No.	Tensile Properties: Yield Strength ksi (MPa)	Tensile Properties: Tensile Strength ksi (MPa)	Elongation Percent
Group A				
Total time in furnace 2 hr. 34 min. Preheat 2200 F (1204 C)	1	*ND (-)	89.7 (619)	17
Heat 2400 F (1316 C)	2	57.7 (398)	89.4 (617)	--
	3	ND (-)	89.4 (617)	--
Group B				
Total time in furnace 1 hr. 15 min. Preheat 2250 F (1232 C)	1	66.3 (457)	91.0 (628)	18
Heat 2400 F (1316 C)	2	63.5 (438)	91.7 (632)	14
Soak 2425 F (1329 C)				

* ND = Not Detectable

** Furnace temperatures not billet temperatures

Direct Quenching After Rolling

This technology is now being practiced both in Europe and South America for the production of weldable bar. The concept is relatively old and is simply to substitute increases in cooling rate obtained from water quenching for increases in hardenability from alloying. Investigation conducted in Argentina under the direction of one of the authors, (A. Hey), illustrates application of the approach to reinforcing bar. The steel studied had the composition

C	Mn	Si	Nb
0.19	1.33	0.34	0.023

The equation used to calculate NbC solubility proposed by Narita with a correction for 1.40 percent manganese when suitably rearranged indicates that, with this composition, the temperature for complete solubility of both niobium and carbon is 1984 F (1085 C). Thus the heating temperature used [2210 F (1210 C)] was sufficiently high to take all niobium and carbon into solution.

In order to control finishing temperature, the bars were delayed prior to the penultimate pass when the surface temperature ranged from *1922* F *(1050* C) to *1778* F *(970* C). The internal temperature is likely to be higher than the surface temperature at this stage. In any event, this holding temperature is sufficiently high that most of the niobium and carbon will remain in solution. The final two passes which reduced the billet to *31.7* mm (#10) with a *35* percent reduction in cross section were attained with a wide range of finishing temperatures. The kinetics of precipitation of NbC with rolling reductions of this order are indicated in the paper by DeArdo et al (3). They showed that it would take approximately *20* to *30* seconds to precipitate 50 percent of the NbC that could be precipitated. The last two rolling passes and entry into the cooling device that were used in this investigation fall into this time frame.

The yield strengths of the bars produced with air and water cooling are shown in Figure *4*. The yield strength of the air-cooled bars increases slightly from the *60* ksi *(41.4* MPa) level at a finishing temperature of *1742* F *(950* C) to approximately *68* ksi *(469* MPa) as the finishing temperature approached *1472* F *(800* C). However, the strength of the water-cooled bars increased rapidly from *65* ksi *(449* MPa) to *74.0* ksi *(522* MPa) as the finishing temperature decreased from *1742* F *(950* C) to *1562* F *(850* C). The rapid increase in strength in the water cooled bars may be explained by reference to a typical diagram (Figure *5).* The shape of the cooling curves is a function of cooling rate. Therefore, if the curves initiate from lower and lower temperatures, they will intersect the CCT curve in regions representing microstructures that are stronger (close to the left hand portion of the diagram) such as the acicular and martensitic microstructures.

With the rolling procedures used by Hey, it was predicted that at least half the niobium would be in solution when the bars entered the water cooling chamber. As previously stated, niobium in solution would increase the hardenability of the steel (lower the transformation temperature and move the nose of the CCT curve to the right) which would permit more latitude in finishing temperature and cooling rate to achieve the desired strength.

A number of European rebar producers are also using water cooling of reinforcing bar after rolling for the same metallurgical reasoning used by Hey.

The use of niobium in bars quenched from the rolling temperature will simplify production of high-strength steels. The increase in hardenability obtained with niobium in solution permits more latitude in finishing temperatures and cooling rates to achieve specified yield strengths. It should be noted that the grain refining action of the niobium under such circumstances detracts from hardenability, but the overall balance is for an increase in hardenability. In the absence of the niobium, rapid cooling rates from precise finishing temperature will be required with increasing likelihood of formation of poorly tempered martensitic structures that may lead to inadequate ductility.

Data from trials of another coauthor, (H. Weise), illustrate the effectiveness of niobium in increasing the strength of directly quenched bars, Table X.

The relative simplicity of the water delivery device, Figure *6*, suggests that water cooling will find increasing acceptance in bar mills.

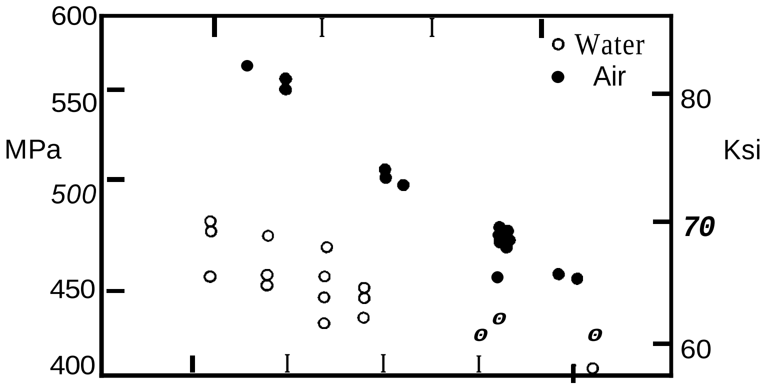

Figure 4. Yield strength of 31.7 mm dia. weldable reinforcing bar, air-cooled or water quenched affter rolling.

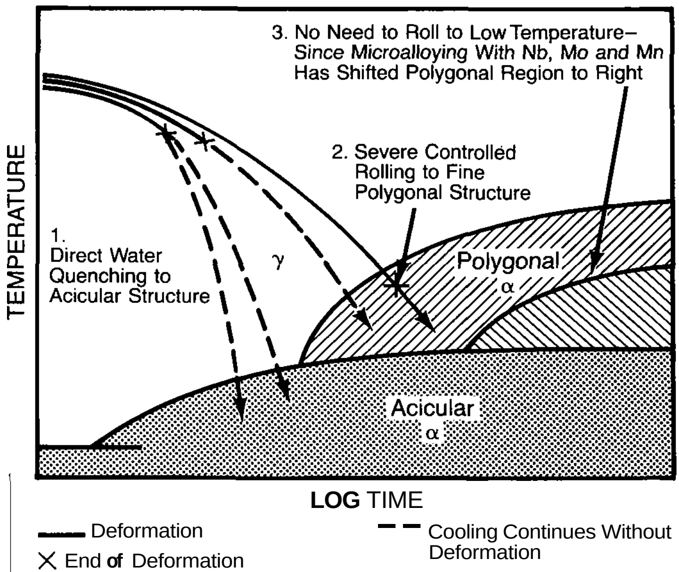

Figure 5. Continuous cooling transformation diagram.

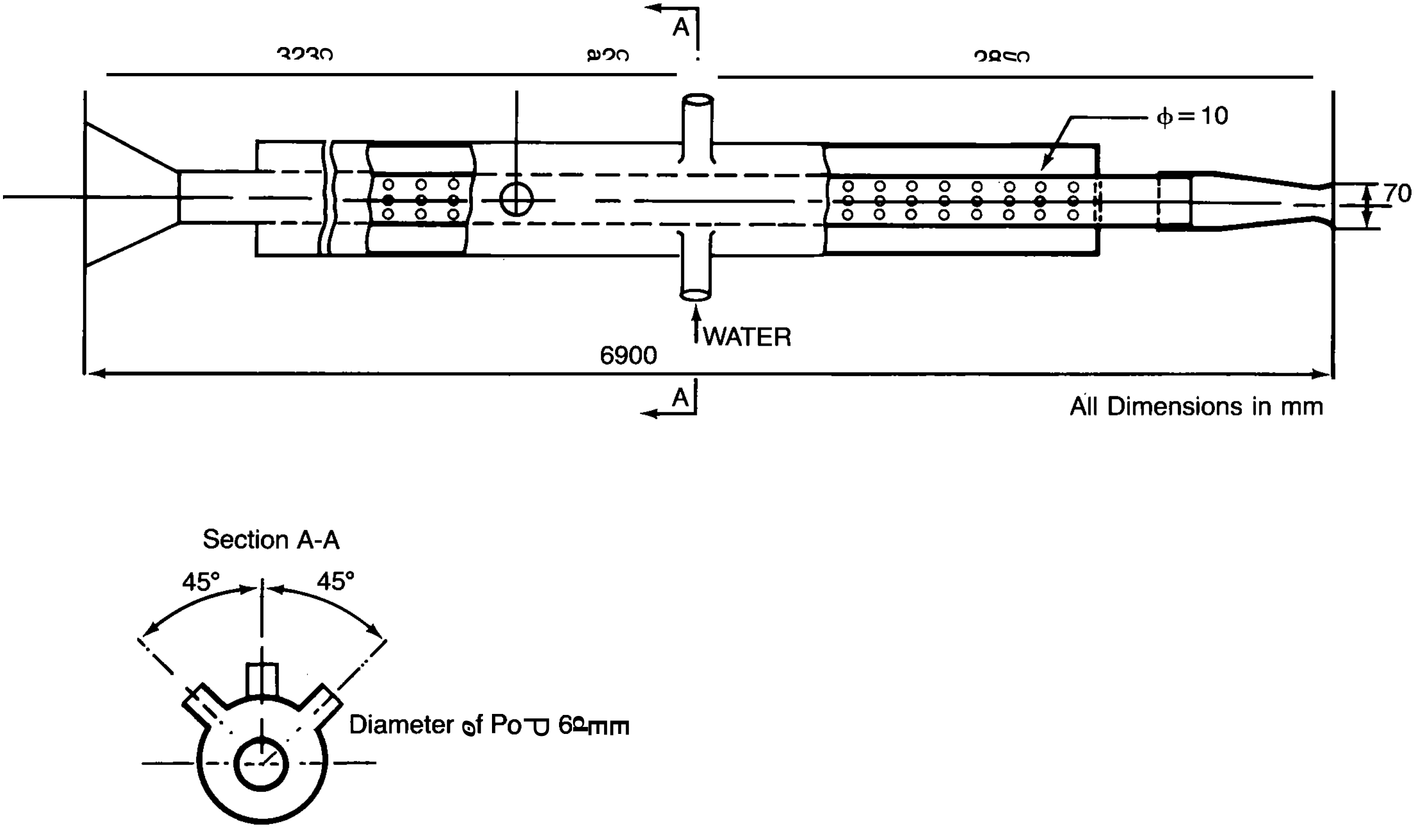

Figure 6. Water-cooling device for reinforcing bar.

Table X. Mechanical Properties of 20 mm dia. Weldable Reinforcing Bar Direct Quenched* from the Rolling Mill.

Chemical Composition, wt. %				Mechanical Properties		
				Yield Strength ksi (MPa)	Tensile Strength ksi (MPa)	Elongation % Gage length = 10 d
C	Mn	Si	Nb			
0.19	1.10	0.03	NONE	66.7 (460)	80.5 (555)	22
0.17	1.28	0.66	0.05	79.0 (545)	90.2 (622)	17

* Reheating temperature 2012 F (1100 C)
Finishing temperature 1832 F (1000 C)
Temperature after existing water 1202 F (650 C)

Discussion

A large portion, if not a majority of the reinforcing bar produced in Europe, is either made to be "weldable" or "weldable with precautions." In addition, Europeans take a realistic attitude toward welding of bars perpendicular to each other (cross splices). They realize that if welding is being done on a job that such welded splices will be made. Therefore, they have devised tests to demonstrate that these splices are safe. The tests devised include bends of the larger bar at the splice that do not break, and tensile tests of the welded bars (fracture is not permitted at the weld). Table XI is a summary of the present German standards covering such welded connections.

In North America most reinforced concrete structures are built according to the American Concrete Institute (ACI) Code 318. This code dictates that splices which are necessary during construction of concrete structures should be either the conventional laped splices or they may be achieved by mechanical or welded connections. For mechanical connections, reinforcing bar produced to ASTM specification 615 may be used. Any of these hot forged, or threaded connections must provide a joint that when tested in tension has an ultimate strength 1.25 times the yield strength of the rebar from which it is made. There is increasing use of mechanical splices in heavy bars because there is not enough room in many structures to accommodate the volume of steel necessary to make a satisfactory lapped joint.

If weldable rebar (ASTM 706) is to be used, the welded joint must meet the same strength requirements as the mechanical splices i.e. the tensile strength of the joint shall be a minimum of 1.25 times the yield strength of the bars used to make the joint. Tack welds of two bars perpendicular to each other (cross splices) are discouraged because the carbon content of bars made to either ASTM 615 or 706 is sufficiently high that brittle microstructures may result.

Although specifications for the manufacture of weldable reinforcing bar and accompanying strength requirements of the welded joints have been in existence in North America since 1974, production of rebar to meet ASTM 706 has been almost non-existent. It is hoped that with a better understanding of the basic principles and practices that production of this type of steel will increase.

Table XI. German Standard Governing Weldable Rebar.

Test Requirements for Welded Joints Fixed in German Standards DIN **488** and DIN **4099**

Test /Type of Joint	Overlap Weld	Butt Weld	Cross Weld
Tensile Test	Minimum tensile strength corresponding to specified value or **90%** of unwelded bar.		
	....		Elongation A_{10} after fracture min. 10% resistance welding: Min. 8%, if fracture in the weld.
Bend Test	---------------	Diameter of mandrel: 5d for d 6 12 mm 6d for *12* < d < **18** mm 8d for **18** < d < **28** mm No fracture, incipient cracks have to be contained within the bar, crossweld: bending of the bar with the bigger diameter, d = bar diameter.	
Shearing Test	....		Shearing Load $S = p \times R_e \times F_e$ (N) p = **0.3** for Load Bearing Joints **0.2** for Tack Welds R_e = Characteristic Strength F_e = Nominal Cross Section

Conclusions

(a) The metallurgical fundamentals governing the production of concrete reinforcing bar are no different from the ones governing the production of other high strength low alloy steels.

(b) Because the carbon content of reinforcing bar is generally higher than other HSLA steels, the heating temperature may be higher and finishing temperature may also be higher. These fundamental principles are more pertinent to the production of reinforcing bar than flat rolled HSLA steels. Heating temperatures greatly in excess of the solution temperature are detrimental.

(c) To obtain optimum mechanical properties, a portion of the rolling schedule must be conducted below the solution temperature of NbC.

(d). The use of niobium strengthening is an effective method of producing high strength reinforcing bar that can be welded. For yield strengths up to **60** ksi ***(41.4*** MPa) and bar sizes up to ***30-40*** **mm,** niobium can be used alone if heating, rolling, and transformation temperatures are properly controlled. For higher yield strengths or larger bar sizes, niobium may be used in conjunction with vanadium or with water cooling. Alternatively, niobium may be added as an effective strengthener of *0.400.45* percent carbon steels to achieve strength levels of 790 MPa ***(71.0*** ksi) but these should not be fabricated by welding.

References

1. J. M. Gray, "Use of Niobium in Concrete Reinforcing Bar Steels - A Review", ILAFA Conference, Lima, Peru, Sept. 21-25, 1975.

2. J. M. Gray, "Rolling of HSLA Concrete Bar and other Niobium Containing Steels", ILAFA Conference, Buenos Aires, Argentina, May 9-15, 1976.

3. A. J. DeArdo, et al., "Basic Metallurgy of Niobium in Steel", Niobium 81, Nov. 1981, San Francisco, California, U.S.A.

4. K. Narita, "Physical Chemistry of the Groups IVa (Ti, Zr), Va (V, Nb, Ta) and the Rare Earth Elements in Steel", Trans. ISIJ, Vol. 15, 1975.

5. S. R. Keown, and W. G. Wilson, "Prediction of Precipitate Phases in Microalloy Steels Containing Nb, C, N and Al", International Conference on Thermomechanical Processing of Microalloyed Austenite. To be published by TMS - AIME.

6. D. B. McCutcheon, et al., "Mechanically Expanded Steelform Pipe". Trans. Mechanical Working and Steel Processing Conference, Vol. 18, 1980, ISS - AIME.

7. J. M. Gray, Technical review presented to NW Project Metallurgical Task Force, Dallas, Texas, Jan. 18, 1972, published as Molycorp Application Report 7201, 1972.

8. P. Matrepierre, J. Rofas-Vernis and A. Wyckaert, "HSLA Steels in Bar and Wire Applications". Paper to be presented at forthcoming ASM Conference entitled "Technology & Application of HSLA Steels". Philadelphia, PA, October 1983.

9. H. Weise, "Weldable High-Strength Steels for Reinforcing Bars". Proc. Microalloying 75 Union Carbide Corp., 1977.

10. Private communication, A. Hey, Comision Nacional de Energia Atomica.