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MICROSTRUCTURES AND PROPERTIES OF CONTROLLED ROLLED AND ACCELERATED COOLED MOLYBDENUM-CONTAINING LINE PIPE STEELS

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ABSTRACT

Modern plate production techniques involving controlled rolling below the Ar_3 temperature and, more recently, the development of equipment for interrupted accelerated cooling after rolling have made it possible to simultaneously reduce the alloy content of line pipe steels while maintaining their strength-toughness balance. Several investigations have been conducted at the Climax Laboratory for the purpose of using these processing methods to develop cost effective steels with strengths sufficient for X-70 to X-80 arctic grade line pipe.

Arctic grade X-70 line pipe properties were achieved by intercritical rolling and air cooling a 0.08% C-1.5% Mn-0.15% Mo-0.04% Nb steel. X-80 strength was obtained in steels containing 0.08% C-1.65% Mn-0.3% Mo-0.055% Nb and 0.08% V. The microstructures observed in these air cooled steels consisted of mixtures of polygonal and acicular ferrite, martensite-austenite (M-A), and various ferrite-cementite aggregates that could be classified as pearlite or upper bainite. Strength was found to increase as finish rolling temperature decreased, and as total percent reduction below the Ar_3 temperature increased.

With the use of interrupted accelerated cooling, improvements in strength and toughness were observed even though finish rolling temperatures were at or above the Ar_3 temperature. For cooling rates of 5 to 15 C/s (9 to 27 F/s) and stop cooling temperatures of 500 to 600 C (930 to 1110 F), the Mo-Nb steels exhibited X-75 strength levels, while the Mo-Nb-V steels achieved strengths considerably in excess of those required for X-80 applications. In addition, significant improvements in transverse ductility and notch toughness were observed compared to intercritically rolled and air cooled steels. The microstructures ranged from ferrite + pearlite to mixed ferrite + bainite + acicular ferrite + M-A constituent. No significant effects of finish rolling temperature or stop cooling temperature were observed over the ranges investigated. The processing variable which influenced properties the most was cooling rate.

INTRODUCTION

Modern steel plate processing techniques involving controlled rolling into the ferrite plus austenite field[1-3] and, more recently, the development of interrupted accelerated cooling after rolling[4,5] made it possible to simultaneously reduce the alloy content of line pipe steels while maintaining a superior strength-toughness balance. This paper summarizes the results of several investigations in which these processing methods were employed to develop cost effective steels for Arctic grade line pipe in the X-70 to X-80 grade range.

The approach was to employ two base compositions--one for X-70 and the other for X-80 line pipe--and to vary the molybdenum content and processing conditions for each. The X-70 type steels nominally contained 0.08% C, 1.55% Mn, 0.25% Si, 0.04% Nb and 0% to 0.25% Mo, while the nominal composition of the X-80 type steels was 0.08% C, 1.65% Mn, 0.25% Si, 0.055% Nb, 0.08% V and 0% to 0.30% Mo. Two types of processing were studied, with the final plate thickness being 19 mm (0.75 in.) in all cases: one type was controlled rolling and air cooling (CR-AC) and the other was interrupted accelerated cooling (IAC).

EXPERIMENTAL PROCEDURES

MELTING AND FORGING - Twelve laboratory steels were prepared as 30 kg (65 lb) heats by induction melting in an argon atmosphere and chill cast in steel molds on copper bases. The compositions of the steels are given in Table 1. The small titanium addition was to inhibit austenite grain growth by forming small TiN particles. The ingots were press forged at 1230 C (2250 F) to slabs 84 to 104 mm (3.3 to 4.1 in.) thick preparatory to rolling.

ROLLING - The slabs were reheated and rolled to 19 mm (0.75 in.) plates using a variety of rolling schedules, presented in Tables 2 and 3. Temperatures were monitored at mid-thickness by embedded thermocouples. The plates were air cooled after rolling to the schedules in Table 2, while accelerated cooling to an intermediate temperature was employed after most of the schedules in Table 3. The accelerated cooling was achieved by

Table 1 - Steel Compositions

Steel No.	Climax Heat No.	Element, wt. %											Calculated	
		C	Mn	Si	Mo	Nb	V	Ti	Al	N	P	S	C.E.[a]	Ar_3, C (F)[b]
Controlled Rolled and Air Cooled (CR-AC)														
(X-70 Mo-Nb)														
1	P2715	0.083	1.56	0.18	0.16	0.041	-[c]	0.014	0.044	0.0050	0.008	0.006	0.38	770 (1418)
	P2785	0.080	1.51	0.16	0.16	0.040	-	0.022	0.067	0.0046	0.011	0.004	0.36	775 (1427)
(X-80 Mo-Nb-V)														
2	P3006	0.080	1.66	0.08	0.30	0.053	0.079	0.015	0.044	0.0048	0.011	0.006	0.43	763 (1405)
	P3007	0.078	1.70	0.09	0.30	0.055	0.082	0.016	0.038	0.0049	0.011	0.006	0.44	760 (1400)
	P3008	0.080	1.69	0.09	0.30	0.055	0.080	0.017	0.046	0.0049	0.011	0.006	0.44	760 (1400)
Interrupted Accelerated Cooled (IAC)														
(Mo-Nb)														
3	P3005A	0.080	1.60	0.25	-	0.040	-	0.017	0.058	0.0042	0.009	0.004	0.35	770 (1418)
4	P2899	0.081	1.52	0.29	0.10	0.038	-	0.009	0.041	0.0042	0.009	0.005	0.35	775 (1426)
	P2998	0.081	1.55	0.28	0.10	0.039	-	0.017	0.070	0.0044	0.011	0.008	0.36	772 (1422)
	P2999	0.080	1.55	0.25	0.11	0.039	-	0.011	0.057	0.0040	0.010	0.007	0.36	772 (1422)
5	P2896	0.081	1.59	0.28	0.16	0.039	-	0.011	0.072	0.0043	0.010	0.005	0.38	769 (1416)
	P2897	0.081	1.55	0.27	0.15	0.038	-	0.013	0.068	0.0045	0.009	0.006	0.37	772 (1422)
	P2898	0.081	1.55	0.27	0.15	0.038	-	0.012	0.066	0.0043	0.010	0.005	0.37	772 (1422)
6	P3003A	0.080	1.60	0.28	0.20	0.039	-	0.017	0.069	0.0042	0.010	0.004	0.39	768 (1414)
7	P3005B	0.079	1.59	0.26	0.25	0.041	-	0.016	0.047	0.0040	0.010	0.005	0.39	769 (1415)
(Mo-Nb-V)														
8	P3004A	0.080	1.62	0.26	-	0.053	0.078	0.016	0.068	0.0044	0.009	0.004	0.37	768 (1415)
9	P3004B	0.079	1.62	0.26	0.10	0.055	0.082	0.016	0.057	0.0046	0.010	0.004	0.39	768 (1415)
10	P3000	0.080	1.64	0.26	0.15	0.052	0.082	0.015	0.051	0.0048	0.010	0.007	0.40	765 (1410)
	P3001	0.080	1.69	0.28	0.15	0.051	0.082	0.014	0.046	0.0042	0.011	0.005	0.41	762 (1403)
11	P2903	0.080	1.69	0.27	0.20	0.051	0.076	0.013	0.058	0.0059	0.010	0.006	0.42	761 (1402)
	P3003B	0.080	1.66	0.28	0.20	0.055	0.074	0.022	0.063	0.0040	0.010	0.004	0.41	764 (1406)
12	P2912	0.077	1.66	0.28	0.30	0.054	0.073	0.012	0.044	0.0044	0.012	0.005	0.43	763 (1405)
	P2913	0.081	1.68	0.27	0.30	0.055	0.074	0.014	0.043	0.0054	0.012	0.006	0.44	761 (1402)
	P2902	0.082	1.68	0.28	0.30	0.052	0.076	0.013	0.067	0.0047	0.010	0.006	0.44	761 (1402)

[a] $C.E. = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5}$

[b] From Kawasaki formula: $Ar_3(°C) = 910-273C-74Mn-5Cu-16Cr-56Ni-9Mo$ (ref. 3).

[c] - = None added and not analyzed.

Table 2 - Hot Rolling Data for X-70 Mo-Nb Steels and X-80 Mo-Nb-V Steels in CR-AC Study

Rolling Schedule	Temperatures, C (F)				Accumulated Reductions, %		
	Slab Reheat	End of Roughing	Beginning of Finishing	Final Pass	≥1040 C (≥1900 F)	≤900 C (≤1650 F)	≤Ar_3
X-70 Mo-Nb Steels							
A				760 (1400)	41.3	68.1	16.7
B				745 (1375)			31.8
C	1150 (2100)	1040 (1900)	855 (1575)	730 (1350)			43.2
D					51.5	62.3	10.0
E					47.1	65.4	20.0
F					42.7	68.1	30.0
X-80 Mo-Nb-V Steels							
G	1220 (2225)			730 (1350)	42.9	62.5	32.4
H				720 (1325)			
I				705 (1300)			
J				690 (1275)			
K	1150 (2100)			705 (1300)			
L	1220 (2225)	1050 (1925)	900 (1650)		35.7	65.0	16.0
M					38.7	63.2	40.0
N					40.2	62.3	24.3
O				690 (1275)			
P				675 (1250)			
R	1150 (2100)						

Table 3 - Processing of 19 mm (0.75 in.) Plates in IAC Study

Rolling Schedules for Mo-Nb Steels

Pass No.	Entry Temperature, C (F) Schedule A	Entry Temperature, C (F) Schedule B	Exit Thickness, mm (in.)	% Reduction per Pass
0	1150 (2100)	1150 (2100)	88.9 (3.50)	(Initial)
1	1105 (2025)	1105 (2025)	81.3 (3.20)	8.6
2	1080 (1975)	1080 (1975)	70.6 (2.78)	13.1
3	1040 (1900)	1040 (1900)	59.7 (2.35)	15.5
4	885 (1625)	855 (1575)	49.3 (1.94)	17.4
5	870 (1600)	845 (1550)	40.4 (1.59)	18.0
6	855 (1575)	830 (1525)	33.5 (1.32)	17.0
7	845 (1550)	815 (1500)	27.9 (1.10)	16.7
8	830 (1525)	800 (1475)	22.9 (0.90)	18.2
9	800 (1475)	770 (1420)	19.1 (0.75)	16.7

Rolling Schedules for Mo-Nb-V Steels

Pass No.	Entry Temperature, C (F) Schedule C	Entry Temperature, C (F) Schedule D	Exit Thickness, mm (in.)	% Reduction per Pass
0	1220 (2225)	1220 (2225)	88.9 (3.50)	(Initial)
1	1175 (2150)	1175 (2150)	81.3 (3.20)	8.6
2	1135 (2075)	1135 (2075)	71.1 (2.80)	12.5
3	1095 (2000)	1095 (2000)	61.0 (2.40)	14.3
4	1050 (1925)	1050 (1925)	50.8 (2.00)	16.7
5	900 (1650)	870 (1600)	41.9 (1.65)	17.5
6	870 (1600)	845 (1550)	34.3 (1.35)	18.2
7	845 (1550)	815 (1500)	29.2 (1.15)	14.8
8	815 (1500)	790 (1450)	24.1 (0.95)	17.4
9	790 (1450)	765 (1410)	19.1 (0.75)	21.1

Cooling After Rolling (See Tables 5 and 6)

Nominal Cooling Rates, C/s (F/s)......Air Cool, 5(9), 15(27)

Nominal Stop Cooling Temperatures, C(F)......600 (1110), 500 (930)
(All plates air cooled from stop cooling temperature.)

immersion quenching in an agitated bath of a polymer quenchant. The cooling rate was controlled by the polymer concentration and by the rate of agitation. At the desired stop cooling temperature, the plate was removed from the quench tank and air cooled. The actual cooling rates and stop cooling temperatures were read from curves made for each plate with a strip chart recorder.

METALLOGRAPHY - Metallographic specimens from the center of each plate were mounted and polished on a longitudinal face. Significant variations in the proportions of microconstituents occurred only in plates from the IAC study. Therefore, approximate percentages of the microconstituents were estimated for each plate in the IAC study using an optical microscope and restricting the examination to the 10 mm (0.4 in.) thick region at the midthickness where the tensile and impact specimens were taken. Representative micrographs were taken from selected plates with a scanning electron microscope (SEM) to clarify some details not resolved by the optical microscope. For the SEM micrographs, the specimens were etched in a picral-nital solution, and a gold-palladium coating was vacuum deposited on the specimen to improve the contrast and resolution.

TENSILE AND IMPACT TESTING - Duplicate tensile tests were performed on transverse specimens from the midthickness position of each plate. The specimens were of a cylindrical, threaded design, with a gauge length equal to four times the diameter. In a few noted exceptions the gauge length was five times the diameter. The tests were performed on a hydraulic tensile machine at a strain rate of $5x10^{-5}$ s^{-1} to 1.5% strain, and at $8.3x10^{-4}$ s^{-1} thereafter to fracture. Total elongation was measured from reassembled broken specimens.

Full size Charpy V-notch specimens from the midthickness position of each plate were tested in duplicate at -20 C (-4 F). For the Mo-Nb steels in the CR-AC study and all the plates in the IAC study, an additional eight impact tests were performed over an appropriate range of temperatures to determine the full ductile-brittle transition curve.

RESULTS AND DISCUSSION

The experimental results are presented below in relation to the two types of processing studied:

1. Controlled Rolling and Air Cooling (CR-AC).
2. Interrupted Accelerated Cooling (IAC).

MICROSTRUCTURES - The microstructures of the X-70 0.15% Mo-Nb steels in the CR-AC study were all basically similar, consisting of non-lamellar pearlite and bainite in bands in a polygonal ferrite matrix, and a trace of the martensite-austenite (M-A) constituent as isolated islands. The polygonal ferrite matrix contained a fraction of grains having a deformation substructure produced by finish rolling below the Ar_3 temperature. The amount of substructured ferrite varies with the total reduction below the Ar_3 and how far the finish rolling temperature is below the Ar_3.

In the X-80 0.30% Mo-Nb-V steels the predominant phase again was polygonal ferrite, much of it substructured from the defotmation imparted below the Ar_3 temperature. These steels contained more bainite and less non-lamellar pearlite than the 0.15% Mo-Nb steels, and there was no banding. Also, the amount of M-A constituent is greater in the 0.30% Mo-Nb-V steels. The effect of increasing total reduction below the Ar_3 temperature from 24% to 40% is illustrated in Figure 1. It can be seen that the amount of deformation substructure in the ferrite increased with increasing reduction below Ar_3.

Microstructural changes in the plates from the IAC study are summarized in Table 4. As would be expected, the basic effect of accelerated cooling was to suppress the formation of polygonal ferrite and thereby promote the formation of the lower temperature transformation products bainite, acicular ferrite* and martensite. The molybdenum additions also helped to promote the substitution of the higher strength constituents for the lower strength polygonal ferrite. Typical examples of the microstructural change produced by rapid cooling are presented in Figure 2 for Steel No. 5, the 0.15% Mo-Nb steel, and in Figure 3 for Steel No. 12, the 0.30% Mo-Nb-V steel. Examples of the various microconstituents are labelled. In some cases a clear distinction between non-lamellar pearlite and bainite could not be made because there was nearly continuous range (spectrum) of morphologies between the two constituents. This problem is more academic than practical because the major increases in strength effected by IAC processing are not caused so much by bainite formation as by the introduction of large amounts of the acicular ferrite structure interspersed with small islands of M-A constituent, denoted by (AF + M-A) in Table 4.

In most cases throughout the present studies it was not possible to obtain a meaningful measurement of ferrite grain size because there were usually too many extraneous boundaries present, associated with substructures in deformed ferrite or in acicular ferrite. However, ferrite grain sizes were quite fine, and were estimated to be between ASTM 12.5 and 13.5.

STRENGTH AND IMPACT TOUGHNESS - Transverse tensile and Charpy V-notch impact properties were used to evaluate the plates. Specifically, the ultimate tensile strength and Charpy energy at -20 C (-4 F) were emphasized because these parameters are involved in proposed line pipe specifications in the Soviet Union where many pipeline construction projects are in progress. All of the properties are summarized in Tables 5, 6 and 7.

CR-AC Study - All of the controlled rolled and air cooled plates were finish rolled below the Ar_3 temperature. As a result, a significant part of the strength of these plates was due to the deformation substructure and

*It should be noted that acicular ferrite (AF) is the same as the matrix phase of upper bainite, with the only difference being that the high-carbon constituent is M-A instead of bainitic cementite. That is the reason why AF is always listed in Table 4 as being associated with M-A, viz. (AF + M-A).

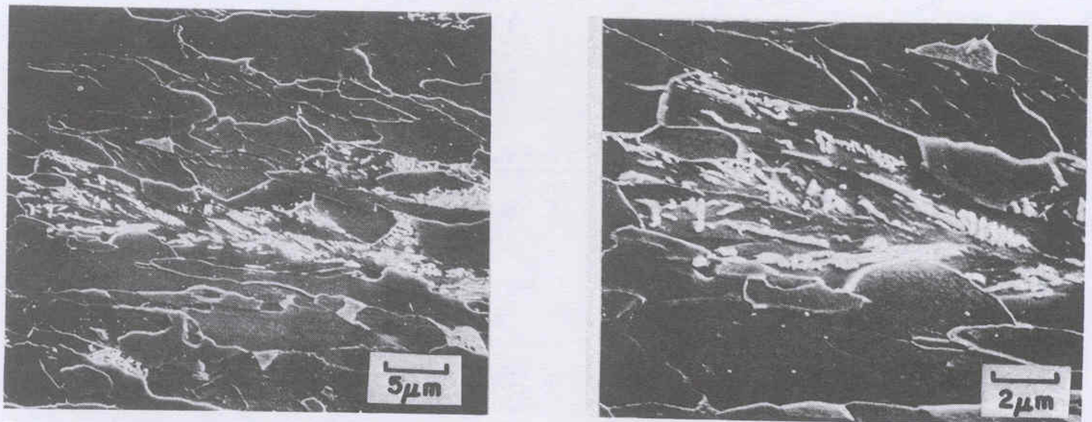
Table 4 - Summary of Metallographic Observations in IAC Study

Steel No. (% Mo)	Nominal Cooling Rate, C/s (F/s)	Range of Observed Microconstituents,[a] Approximate %
		Mo-Nb Steels
3 (0% Mo)	Air Cooled	Banded P + PF
	15 (27)	60% PF + P + B
4 (0.10% Mo)	Air Cooled	Banded (P + NLP + B) + PF
	5 (9)	70%-80% PF + NLP + B
	15 (27)	25%-75% PF + (AF + M-A) + B
5 (0.15% Mo)	Air Cooled	Banded (NLP + B) + PF
	5 (9)	60%-80% PF + NLP + B + (AF + M-A)
	15 (27)	10%-50% PF + (AF + M-A) + B
6 (0.20% Mo)	Air Cooled	Banded (NLP + B) + PF + M-A
	15 (27)	5% PF + B + (AF + M-A)
7 (0.25% Mo)	Air Cooled	Banded (NLP + B) + PF + M-A
	15 (27)	5% PF + (AF + M-A) + B(Tr.)
		Mo-Nb-V Steels
8 (0% Mo)	Air Cooled	Banded P + PF
	15 (27)	30% PF + (AF + M-A)
9 (0.10% Mo)	Air Cooled	Partially Banded NLP + PF + B(Tr.)
	15 (27)	10% PF + B + (AF + M-A)
10 (0.15% Mo)	Air Cooled	Partially Banded (NLP + B) + M-A
	5 (9)	40%-50% PF + B + (AF + M-A)
	15 (27)	0%-5% PF + (AF + M-A) + B(Tr.)
11 (0.20% Mo)	Air Cooled	Partially Banded (NLP + B) + PF + M-A
	5 (9)	15%-40% PF + (AF + M-A) + B
	15 (27)	Tr.-10% PF + (AF + M-A) + B (Tr.)
12 (0.30% Mo)	Air Cooled	PF + NLP + B + M-A
	5 (9)	20%-40% PF + (AF + M-A) + B
	15 (27)	0-5% PF + (AF + M-A) + B

[a]PF = Polygonal Ferrite
AF = Acicular Ferrite
B = Bainite
P = Pearlite
NLP = Non-lamellar Pearlite
M-A = Martensite-Austenite Constituent
(Tr.) = Trace

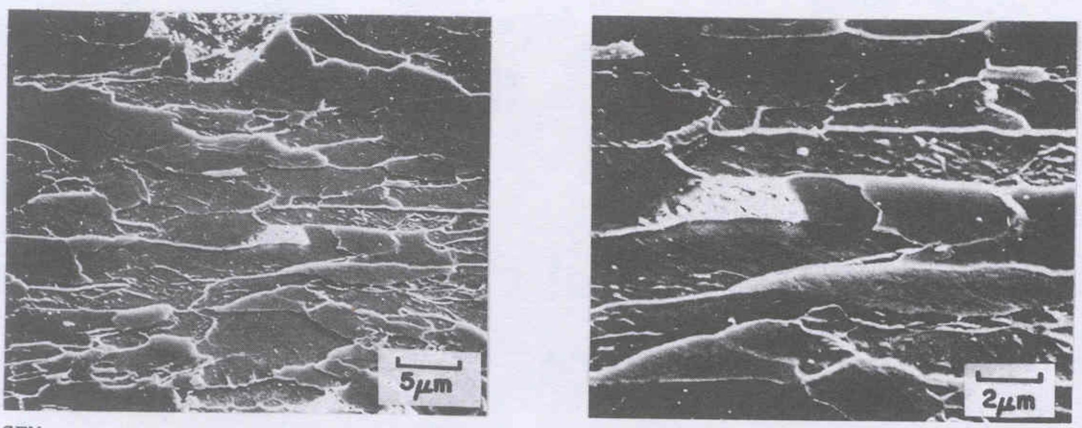
SEM X2000 SEM X5000

(a) 24.3% Total Reduction below Ar_3 Temperature



SEM X2000 SEM X5000

(b) 32.4% Total Reduction Below Ar_3 Temperature



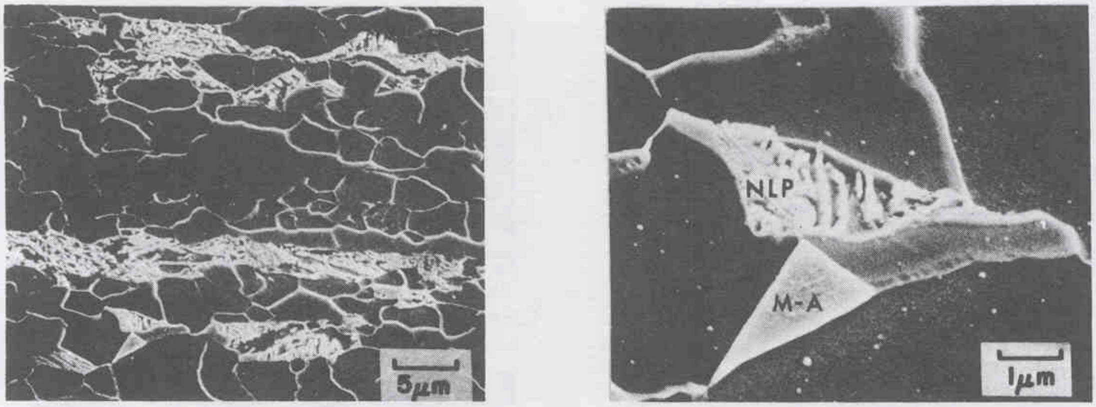
SEM X2000 SEM X5000

(c) 40.0% Total Reduction Below Ar_3 Temperature

Fig. 1 - Effect of total reduction below Ar_3 on the microstructure of 19 mm (0.75 in.) plates of 0.30Mo-0.055Nb-0.080V steel (No. 2) finish rolled at 705 C (1300 F) and air cooled.

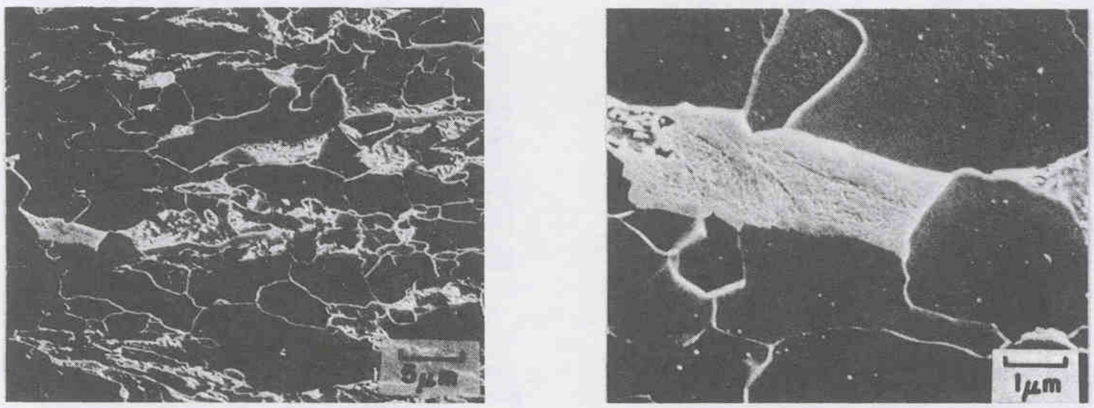
PF = Polygonal Ferrite
NLP = Non-lamellar Pearlite
AF = Acicular Ferrite

B = Bainite
M-A = Martensite-Austenite



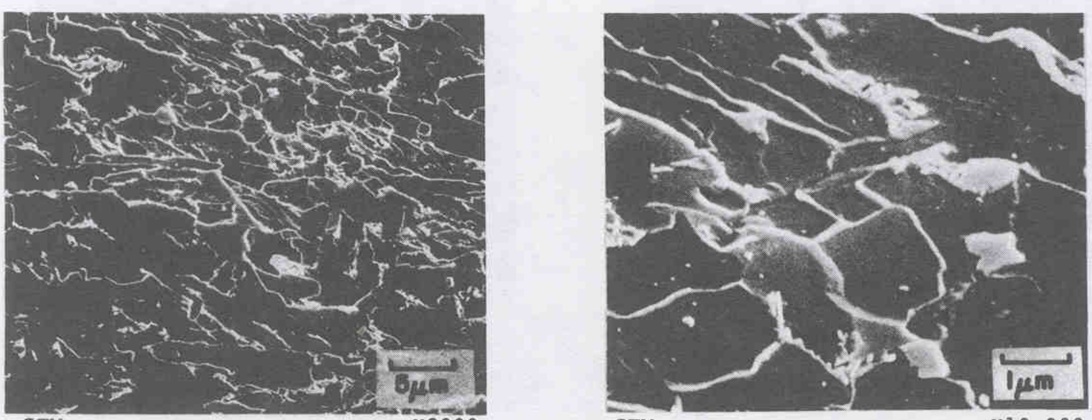
SEM X2000 SEM X10,000

(a) Air Cooled from Finish Rolling Temperature



SEM X2000 SEM X10,000

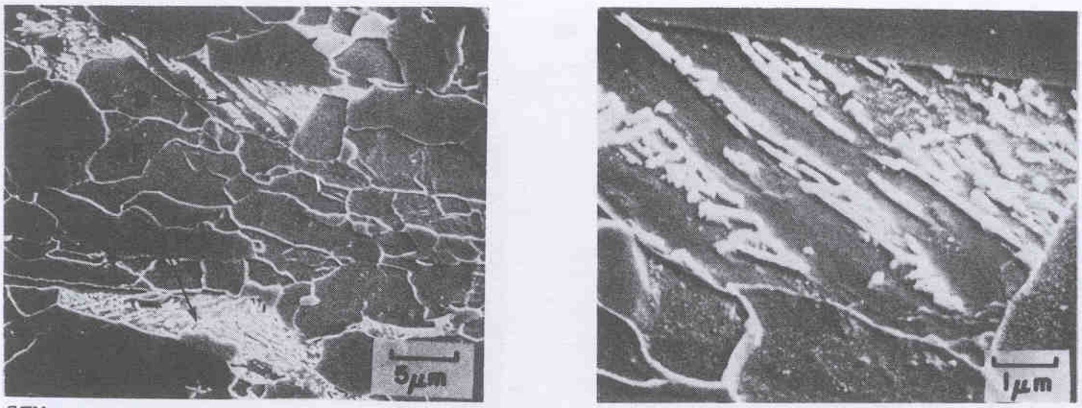
(b) Cooled at 5 C/s (9 F/s) to 500 C (930 F), Air Cooled



SEM X2000 SEM X10,000

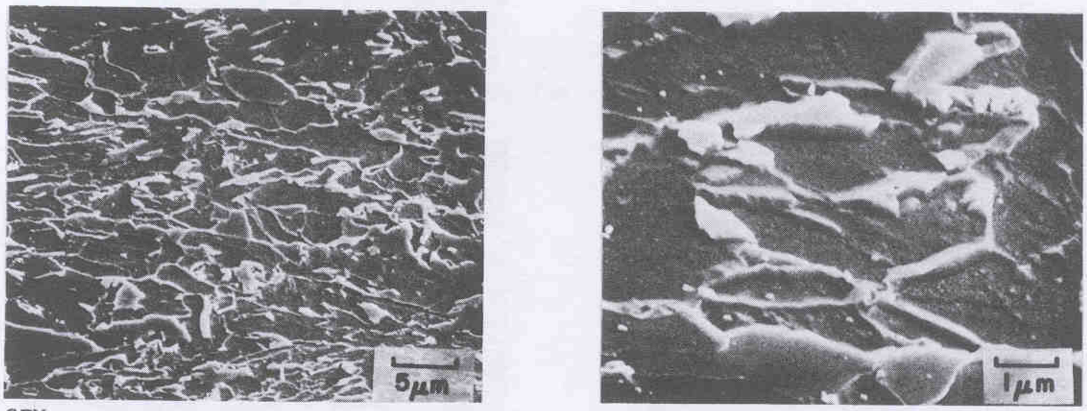
(c) cooled at 15 C/s (27 F/s) to 500 C (930 F), Air Cooled

Fig. 2 - Effect of IAC on Microstructure of 19 mm (0.75 in.) plates of 0.15Mo-0.04Nb steel (No. 5) finish rolled at 770 C (1420 F).



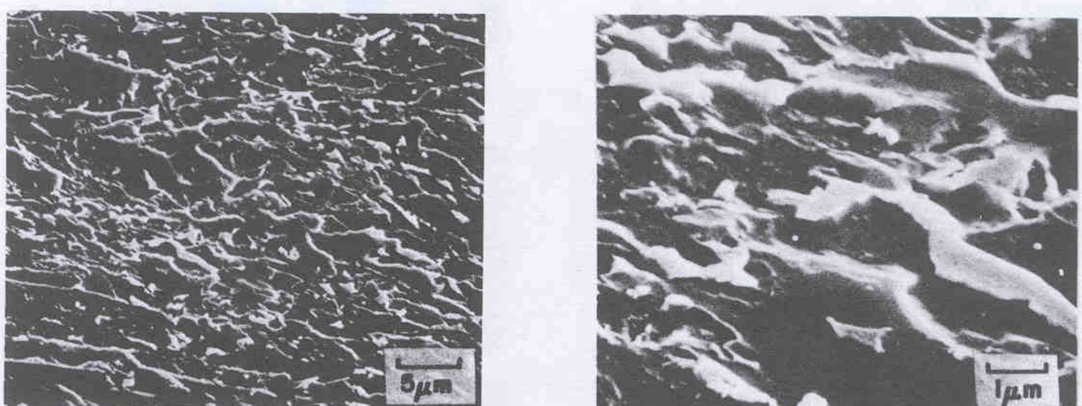
SEM X2000 SEM X10,000

(a) Air Cooled from Finish Rolling Temperature



SEM X2000 SEM X10,000

(b) Cooled at 5 C/s (9 F/s) to 500 C (930 F), Air Cooled



SEM X2000 SEM X10,000

(c) cooled at 15 C/s (27 F/s) to 500 C (930 F), Air Cooled

Fig. 3 - Effect of IAC on microstructure of 19 mm (0.75 in.) plates of 0.30Mo-0.055Nb-0.075V steel (No. 12) finish rolled at 765 C (1410 F).

Table 5 - Summary of Rolling Data and Transverse Properties[a] of X-70 Mo-Nb Steels and X-80 Mo-Nb-V Steels in Cr-AC Study

Steel No.	Climax Heat No.	Rolling Sched.[b]	Slab Reheat Temp., C (F)	Finish Rolling Temp., C (F)	Total Red. at or below Ar_3, %	Yield Strength, MPa (ksi) 0.2%	Yield Strength, MPa (ksi) 1.5%	Tensile Strength, MPa (ksi)	YS/TS Ratio	Total Elong. in 4D, % in 25 mm (1 in.)	Red. of Area, %	Charpy V-Notch Impact Data: Energy @ -20 C (-4 F), J (ft-lb)[c]	Charpy V-Notch Impact Data: 50% Shear FATT, C (F)
(X-70 Mo-Nb Steels)													
	P2715	A	1150 (2100)	760 (1400)	16.7	524 (76.1)	510 (74.0)	582 (84.5)	0.90	27.0	70	111 (82.0)	-95 (-140)
	P2715	B	1150 (2100)	745 (1375)	31.8	515 (74.8)	508 (73.8)	599 (86.9)	0.86	26.0	67	120 (88.5)	-85 (-120)
1	P2715	C	1150 (2100)	730 (1350)	43.2	550 (79.8)	548 (79.6)	631 (91.6)	0.87	24.0	66	112 (82.5)	-85 (-120)
	P2785	D	1150 (2100)	730 (1350)	10.0	524 (76.1)	ND[d]	585 (85.0)	0.90	22.4[e]	72	144 (106)	-95 (-140)
	P2785	E	1150 (2100)	730 (1350)	20.0	528 (76.6)	ND	590 (85.7)	0.89	22.2[e]	68	144 (106)	-85 (-125)
	P2785	F	1150 (2100)	730 (1350)	30.0	533 (77.3)	ND	614 (89.1)	0.87	22.0[e]	69	132 (97.0)	-75 (-105)
(X80 Mo-Nb-v Steels)													
	P3006	G	1220 (2225)	730 (1350)	32.4	527 (76.5)	552 (80.1)	662 (96.1)	0.80	24.5	65	129 (95.0)	
	P3006	H	1220 (2225)	720 (1325)	32.4	564 (81.9)	585 (84.9)	681 (98.9)	0.83	22.5	65	103 (76.0)	
	P3007	I	1220 (2225)	705 (1300)	32.4	577 (83.8)	617 (89.6)	696 (101.0)	0.83	23.0	67	97.0 (71.5)	
	P3006	J	1220 (2225)	690 (1275)	32.4	590 (85.6)	629 (91.3)	701 (101.8)	0.84	20.8	65	75.9 (56.0)	
	P3007	L	1220 (2225)	705 (1300)	16.0	555 (80.5)	595 (86.3)	672 (97.6)	0.82	24.9	70	112 (82.3)	
2	P3007	N	1220 (2225)	705 (1300)	24.3	548 (79.6)	581 (84.3)	670 (97.3)	0.82	25.0	73	123 (90.5)	ND
	P3007	M	1220 (2225)	705 (1300)	40.0	589 (85.5)	635 (92.2)	706 (102.5)	0.83	21.5	63	94.2 (69.5)	
	P3008	O	1220 (2225)	690 (1275)	24.3	586 (85.0)	632 (91.7)	699 (101.5)	0.84	22.8	69	84.8 (62.5)	
	P3008	P	1220 (2225)	675 (1250)	24.3	626 (90.9)	668 (96.9)	729 (105.8)	0.86	21.8	66	95.3 (70.3)	
	P3008	R	1150 (2100)	675 (1250)	24.3	579 (84.0)	618 (89.7)	690 (100.2)	0.84	23.4	67	105 (77.5)	
	P3008	K	1150 (2100)	705 (1300)	32.4	566 (82.1)	606 (87.9)	677 (98.3)	0.84	24.8	68	120 (88.3)	

[a] 19 mm (0.75 in.) plates.
[b] See Table 2 for rolling schedule data.
[c] Avg. values from duplicate tests.
[d] ND = Not determined.
[e] Elongation in 5D, % in 50 mm (1.97 in.).

Table 6 Summary of Cooling Data and Transverse Properties of Mo-Nb Steels[a] in IAC Study

Steel No.	Climax Heat No.	Rolling Schedule	Cooling from Rolling: Rate, C/s (F/s)	Cooling from Rolling: Stop Temp., C (F)	Yield Strength, MPa (ksi): 0.2%	Yield Strength, MPa (ksi): 1.5%	Tensile Strength, MPa (ksi)	YS/TS Ratio	Total Elong. in 4D, % in 25 mm (1 in.)	Red. of Area, %	Charpy V-Notch Impact Data: Energy @ -20 C (-4 F) J (ft-lb)[c]	Charpy V-Notch Impact Data: 50% Shear FATT, C (F)
3 (0% Mo)	P3005A	A	Air Cooled		441 (64.0)	434 (63.0)	517 (75.0)	0.85	36.0	78	241 (178)	-90 (-130)
	P3005A	A	21.1 (38.0)	465 (870)	548 (79.5)	542 (78.7)	622 (90.3)	0.88	27.5	77	188 (139)	-100 (-150)
4 (0.10% Mo)	P2899	A	Air Cooled		468 (67.9)	460 (66.7)	530 (76.9)	0.88	36.3	74	157 (116)	-105 (-155)
	P2899	B	Air Cooled		504 (73.1)	493 (71.6)	556 (80.7)	0.91	32.5	71	125 (92.5)	-100 (-150)
	P2998	A	5.7 (10.3)	600 (1110)	514 (74.6)	515 (74.8)	606 (87.9)	0.85	30.5	73	179 (132)	-95 (-135)
	P2998	A	6.3 (11.3)	515 (960)	509 (73.9)	508 (73.7)	608 (88.2)	0.84	32.3	76	206 (152)	-105 (-155)
	P2998	B	5.7 (10.3)	605 (1120)	524 (76.0)	528 (76.6)	613 (89.0)	0.85	28.8	72	178 (131)	-80 (-110)
	P2999	B	4.6 (8.3)	510 (950)	527 (76.5)	512 (74.3)	590 (85.6)	0.89	31.0	71	142 (105)	-100 (-150)
	P2999	A	15.5 (27.8)	600 (1110)	528 (76.6)	524 (76.1)	621 (90.1)	0.85	29.5	70	124 (91.5)	-95 (-140)
	P2899	A	15.4 (27.7)	535 (995)	556 (80.7)	557 (80.9)	636 (92.3)	0.87	25.9	74	152 (112)	-80 (-110)
	P2999	B	17.6 (31.8)	595 (1100)	539 (78.3)	528 (76.6)	617 (89.5)	0.87	28.5	69	121 (89.0)	-95 (-140)
	P2899	B	16.4 (29.5)	490 (910)	541 (78.5)	557 (80.9)	644 (93.4)	0.84	27.4	75	172 (127)	-110 (-165)
5 (0.15% Mo)	P2898	A	Air Cooled		472 (68.5)	460 (66.8)	547 (79.4)	0.86	38.1	74	168 (124)	-100 (-150)
	P2897	B	Air Cooled		511 (74.2)	502 (72.8)	566 (82.1)	0.90	31.5	69	116 (85.5)	-105 (-160)
	P2898	A	6.9 (12.4)	590 (1095)	495 (71.9)	490 (71.1)	583 (84.6)	0.85	33.5	69	190 (140)	-105 (-155)
	P2897	A	6.2 (11.2)	500 (930)	506 (73.4)	513 (74.5)	606 (88.0)	0.83	32.7	72	123 (91.0)	-110 (-165)
	P2896	B	6.2 (11.2)	595 (1100)	505 (73.3)	500 (72.5)	603 (87.5)	0.84	31.9	73	148 (109)	-100 (-150)
	P2896	B	5.9 (10.6)	490 (910)	522 (75.8)	524 (76.0)	619 (89.9)	0.84	31.2	73	156 (115)	-105 (-160)
	P2897	A	21.3 (38.3)	560 (1040)	539 (78.3)	551 (80.0)	649 (94.2)	0.83	28.0	71	137 (101)	-110 (-165)
	P2897	A	16.0 (28.8)	520 (970)	553 (80.3)	563 (81.7)	648 (94.1)	0.85	26.6	71	123 (90.5)	-95 (-135)
	P2896	B	15.6 (28.1)	605 (1120)	561 (81.4)	564 (81.9)	643 (93.3)	0.87	27.6	70	159 (117)	-100 (-145)
	P2896	B	20.9 (37.6)	430 (810)	553 (80.3)	577 (83.8)	655 (95.0)	0.85	24.8	70	132 (97.0)	-110 (-165)
6 (0.20% Mo)	P3003A	A	Air Cooled		448 (65.0)	446 (64.7)	566 (82.1)	0.79	32.5	69	214 (158)	-90 (-130)
	P3003A	A	15.8 (28.5)	500 (930)	539 (78.2)	548 (79.5)	652 (94.7)	0.83	28.3	71	176 (130)	-95 (-140)
7 (0.25% Mo)	P3005B	A	Air Cooled		426 (61.9)	429 (62.3)	566 (82.1)	0.75	32.0	74	250 (184)	-85 (-120)
	P3005B	A	17.6 (31.8)	495 (920)	555 (80.6)	586 (85.1)	662 (96.1)	0.84	27.0	73	224 (165)	-100 (-145)

[a]19 mm (0.75 in.) plates.
[b]See Table 3 for rolling schedules.
[c]Avg. values from duplicate tests.

Table 7 Summary of Cooling Data and Transverse Properties of Mo-Nb-V Steels[a] in IAC Study

Steel No.	Climax Heat No.	Rolling Schedule	Cooling from Rolling: Rate, C/s (F/s)	Cooling from Rolling: Stop Temp., C (F)	Yield Strength, MPa (ksi): 0.2%	Yield Strength, MPa (ksi): 1.5%	Tensile Strength, MPa (ksi)	YS/TS Ratio	Total Elong. in 4D, % in 25 mm (1 in.)	Red. of Area, %	Charpy V-Notch Impact Data: Energy @ -20 C (-4 F) J (ft-lb)[c]	Charpy V-Notch Impact Data: 50% Shear FATT, C (F)
8 (0% Mo)	P3004A	C	Air Cooled		504 (73.2)	493 (71.5)	587 (85.2)	0.86	30.8	76	201 (148)	-75 (-105)
	P3004A	C	11.7 (21.0)	510 (950)	577 (83.8)	590 (85.7)	672 (97.6)	0.86	26.8	75	182 (134)	-80 (-115)
9 (0.10% Mo)	P3004B	C	Air Cooled		491 (71.3)	489 (70.9)	590 (85.6)	0.83	31.5	75	226 (167)	-80 (-115)
	P3004B	C	16.8 (30.2)	515 (960)	563 (81.7)	602 (87.4)	693 (100.6)	0.81	25.5	71	170 (125)	-75 (-100)
10 (0.15% Mo)	P3000	C	Air Cooled		462 (67.0)	473 (68.6)	597 (86.7)	0.77	27.8	67	144 (106)	-75 (-105)
	P3000	D	Air Cooled		468 (67.9)	480 (69.8)	604 (87.7)	0.77	28.8	67	121 (89.3)	-80 (-110)
	P3000	C	5.6 (10.1)	495 (920)	545 (79.1)	568 (82.5)	666 (96.6)	0.82	25.8	68	102 (75.0)	-75 (-100)
	P3001	D	7.4 (13.3)	490 (910)	583 (84.6)	609 (88.4)	695 (100.8)	0.84	25.8	71	141 (104)	-75 (-100)
	P3001	C	14.5 (26.2)	505 (940)	592 (85.9)	632 (91.7)	701 (101.7)	0.84	24.0	70	144 (106)	-75 (-100)
	P3001	D	16.3 (29.4)	470 (880)	603 (87.5)	638 (92.6)	705 (102.3)	0.86	23.0	71	152 (112)	-70 (-95)
11 (0.20% Mo)	P2903	C	Air Cooled		441 (64.0)	484 (70.3)	625 (90.7)	0.71	31.3	68	107 (79.0)	-75 (-100)
	P2903	D	Air Cooled		457 (66.4)	500 (72.6)	628 (91.1)	0.73	29.9	65	105 (77.5)	-70 (-90)
	P3003B	C	5.9 (10.6)	500 (930)	555 (80.6)	607 (88.1)	721 (104.7)	0.77	25.8	70	164 (121)	-60 (-80)
	P3003B	D	8.4 (15.2)	505 (940)	553 (80.3)	612 (88.8)	719 (104.3)	0.77	26.0	72	159 (117)	-60 (-80)
	P2903	C	18.4 (33.1)	480 (900)	595 (86.3)	635 (92.2)	714 (103.7)	0.83	24.0	68	108 (79.5)	-75 (-100)
	P2903	D	16.0 (28.8)	495 (920)	591 (85.8)	634 (92.0)	712 (103.3)	0.83	26.8	70	127 (94.0)	-75 (-105)
12 (0.30% Mo)	P2912	C	Air Cooled		448 (65.0)	517 (75.0)	642 (93.2)	0.70	25.4	58	118 (87.0)	-80 (-115)
	P2913	D	Air Cooled		481 (69.8)	542 (78.7)	664 (96.4)	0.72	25.8	63	99.0 (73.0)	-75 (-100)
	P2912	C	6.3 (11.3)	600 (1110)	525 (76.2)	594 (86.2)	711 (103.2)	0.74	25.9	69	125 (92.5)	-75 (-100)
	P2912	C	5.2 (9.3)	490 (910)	577 (83.7)	610 (88.6)	692 (100.5)	0.83	25.5	71	151 (111)	-75 (-100)
	P2913	D	7.1 (12.8)	605 (1120)	531 (77.1)	626 (90.9)	721 (104.7)	0.74	22.9	63	90.9 (67.0)	-60 (-75)
	P2913	D	7.5 (13.6)	515 (960)	548 (79.5)	630 (91.4)	738 (107.1)	0.74	23.4	64	90.6 (66.8)	-75 (-100)
	P2902	C	17.8 (32.0)	615 (1140)	563 (81.7)	662 (96.1)	756 (109.7)	0.74	22.6	65	95.6 (70.5)	-75 (-105)
	P2902	C	18.8 (33.8)	500 (935)	617 (89.6)	664 (96.3)	736 (106.8)	0.84	27.3	69	113 (83.5)	-80 (-110)
	P2902	D	19.1 (34.4)	620 (1145)	565 (82.0)	654 (94.9)	754 (109.5)	0.75	23.9	69	92.9 (68.5)	-55 (-70)
	P2902	D	23.3 (41.9)	470 (875)	575 (83.5)	643 (93.3)	749 (108.7)	0.77	24.2	64	101 (74.5)	-60 (-80)

[a] 19 mm (0.75 in.) plates.

[b] See Table 3 for rolling schedules.

[c] Avg. values from duplicate tests.

strain-enhanced precipitation of carbonitrides in the deformed ferrite. One difference between the X-70 Mo-Nb steels and the X-80 Mo-Nb-V steels is that the former exhibited discontinuous yielding while the latter showed continuous yielding behavior. In the Mo-Nb-V steels, the strength contribution from strain-enhanced precipitation was presumably greater than in the Mo-Nb steels because of the additional element available for precipitation strengthening. An earlier study of steels similar in composition to the present Mo-Nb-V steels support this suggestion, and that study also showed that the magnitude of the substructure effect is 1/2 to 1/3 the size of the strain-enhanced precipitation strengthening effect.[2] In the studies presented here, a detailed analysis was not made of the relative sizes of the substructure and precipitation contributions to strength, but the earlier study suggested that the relative contribution from strain enhanced precipitation increased as ferrite rolling temperature decreased.

The effect of finish rolling temperature on tensile strength is shown in Figure 4* for the Mo-Nb and the Mo-Nb-V steels. Within each band of data, the amount of accumulated reduction at or below the Ar_3 temperature is given for each point. It can be seen that the

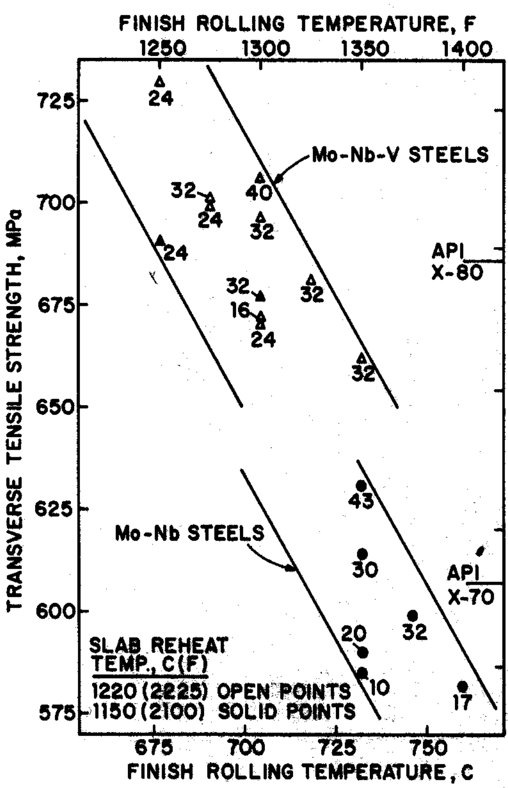


Fig. 4 - Effect of Finish Rolling Temperature on Tensile Strength of Controlled Rolled and Air Cooled 19 mm (0.75 in.) Plates. Numbers by points denote accumulated reduction at or below Ar_3 temperature.

finishing temperature and reduction below Ar_3 both affected the strength. As the finishing temperature was decreased, the tensile strength rose approximately at a rate of 1.6 MPa/C (0.13 ksi/F), based on the slope of the bands. As well as could be determined from the small number of points, this rate was the same for both groups of steels. The effect of total reduction at or below the Ar_3 temperature is most apparent in the lower band of Mo-Nb steels where, at a constant finishing temperature of 730 C (1350 F), the tensile strength rose 46 MPa (6.6 ksi) as the percent reduction increased to 43% from 10%. In the upper band of Mo-Nb-V steels, the points representing 16% and 24% reduction below the Ar_3 are located near the middle or in the lower half of the band, while the points representing 32% and 40% reduction are near the middle or in the upper half of the band. For the Mo-Nb-V steels, the effect of finishing temperature was concluded to be greater than the effect of total reduction below the Ar_3 temperature, within the rather narrow ranges investigated.

The effect of lowering the slab reheat temperature by 70 C (125 F) was determined for the Mo-Nb-V steels with two rolling schedules: finishing at 705 C (1300 F) with 32% reduction below Ar_3 and finishing at 675 C (1250 F) with 24% reduction below Ar_3. The lower reheat temperature reduced the tensile strength by 40 MPa (5.6 ksi) for the plates finish rolled at 675 C (1250 F) by 20 MPa (2.7 ksi) for the plates finish rolled at 705 C (1300 F). This was interpreted to mean that the reduction in precipitation strengthening due to reduced dissolution of carbonitrides was greater than any gain in strength from ferrite grain refinement derived from reduced austenite grain growth at the lower reheat temperature.

The strength-toughness balance of the steels in the CR-AC study is shown in Figure 5 where tensile strength is plotted against Charpy V-notch energy absorbed at -20 C (-4 F). For the Soviet Grade 70 [70 kg/mm² (99.6 ksi) tensile strength] line pipe, a minimum CVN energy of 94 J (69 ft-lb) at -20 C (-4 F) is a frequently used target. Four of the Mo-Nb-V steel plates met that target.

Regarding the influence of accumulated reduction at or below the Ar_3 temperature, the

*The plate tensile strengths indicated on the charts for X-70 and X-80 pipes are based on regression analyses of commercial pipe yield strength (flattened strap) versus plate tensile strength data (Ref. 6), and are minimum values to guarantee the respective pipe yield strengths.

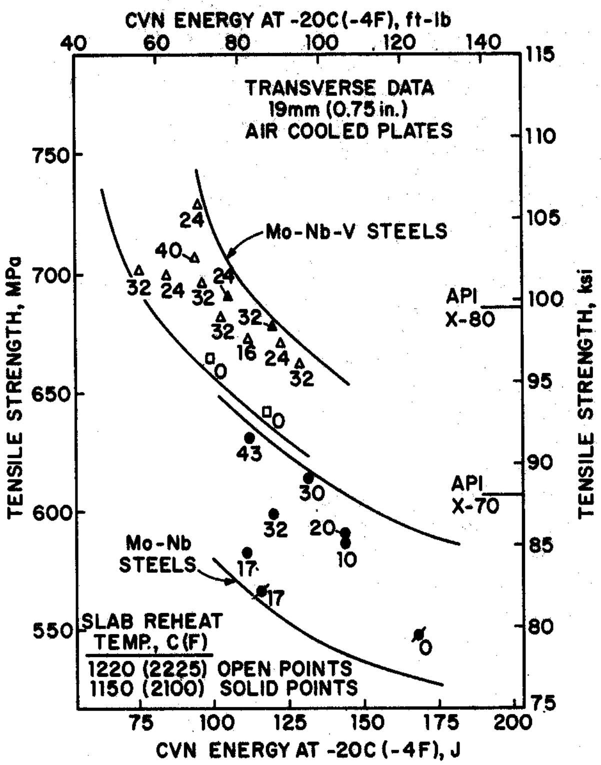


Fig. 5 - Strength-Toughness Diagram for Mo-Nb and Mo-Nb-V Steels in CR-AC Study. Numbers by points denote total reduction (%) at or below Ar_3. Squares and solid circles with slashes are from IAC study.

strength-toughness balance* was essentially unaffected by the amount of reduction below Ar_3, within the ranges studied. With excessive degrees of reduction above the 40% used as an upper limit in the present studies, the strength-toughness balance would be expected to deteriorate.

An excellent strength-toughness balance was produced in the Mo-Nb-V steels when a low slab reheat temperature [1150 C (2100 F)] was employed. This type of behavior has been observed many times in other studies, and it is usually explained in terms of ferrite grain refinement derived from the reduced austenite grain growth at the reheat temperature and the resultant finer austenite grain size at the time of the transformation to ferrite.

*By definition, points in Figure 5 near the upper-right side of a band indicate a high strength-toughness balance, and those near the lower-left side indicate a low strength toughness balance.

IAC Study - The strength properties of the interrupted accelerated cooled plates were governed mainly by the degree to which polygonal ferrite and pearlite are replaced by bainite or acicular ferrite plus M-A constituent as a result of alloying with molybdenum or accelerated cooling from rolling or both. Representative plots of tensile strength versus cooling rate are presented in Figure 6. They include all of the data for the 0.15% Mo-0.04% Nb steel (Steel No. 5) and the 0.30% Mo-0.055% Nb-0.08% V steel (Steel No. 12). As can be seen, the strength rose rapidly at first, followed by a decreasing rate of increase and finally reached an apparent plateau. The initial rate of strengthening, up to a cooling rate of 6 C/s (10 F/s), was greater in the more highly alloyed Steel No. 12. This was to be expected from the more efficient suppression of polygonal ferrite effected by the higher manganese, molybdenum and niobium contents. The total increase in strength from the air cooled to the fastest cooled plates was the same for the two steels, approximately 94 MPa (14 ksi). This is rather surprising in view of the fact that suppression of polygonal ferrite formation in Steel No. 5 was less complete than in Steel No. 12 (Table 4). It must be assumed that there was a compensating difference in the two steels regarding the relative magnitude of the precipitation strengthening contributions in each.

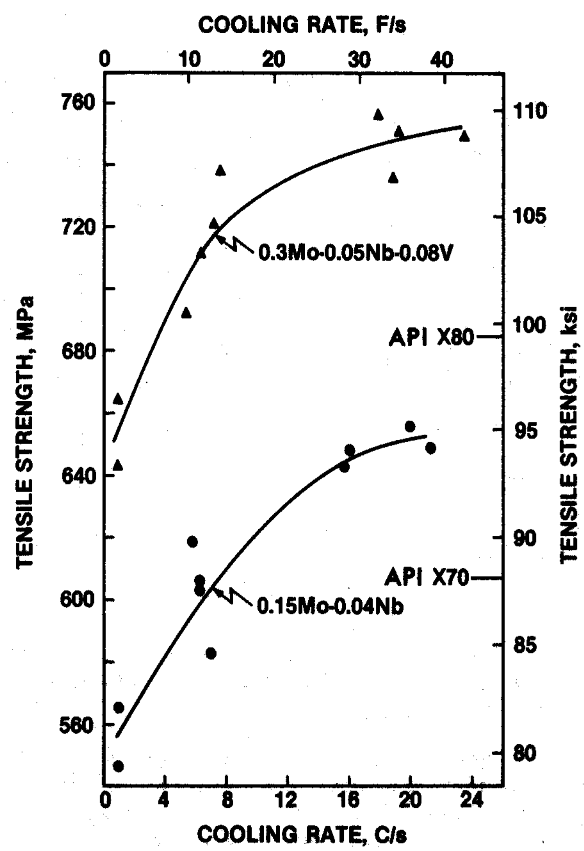


Fig. 6 - Tensile Strength vs. Cooling Rate in IAC Processed 19 mm (0.75 in.) Plates.

The influence of molybdenum content on tensile strength is shown in Figure 7 for the air cooled and the fastest cooled plates of the Mo-Nb steels and the Mo-Nb-V steels. The air cooled plates in this IAC study are not to be confused with the air cooled plates in the CR-AC study where significant strengthening was achieved by deformation of ferrite below the Ar_3 temperature. The air cooled plates in the IAC study are significantly weaker because they were finish rolled at or a little above the Ar_3 temperature. They were intended to provide a baseline for direct comparison with higher cooling rates to show the effect of interrupted accelerated cooling.

In general, the addition of molybdenum was very effective in raising the strength of IAC processed plates. The most visible reason is

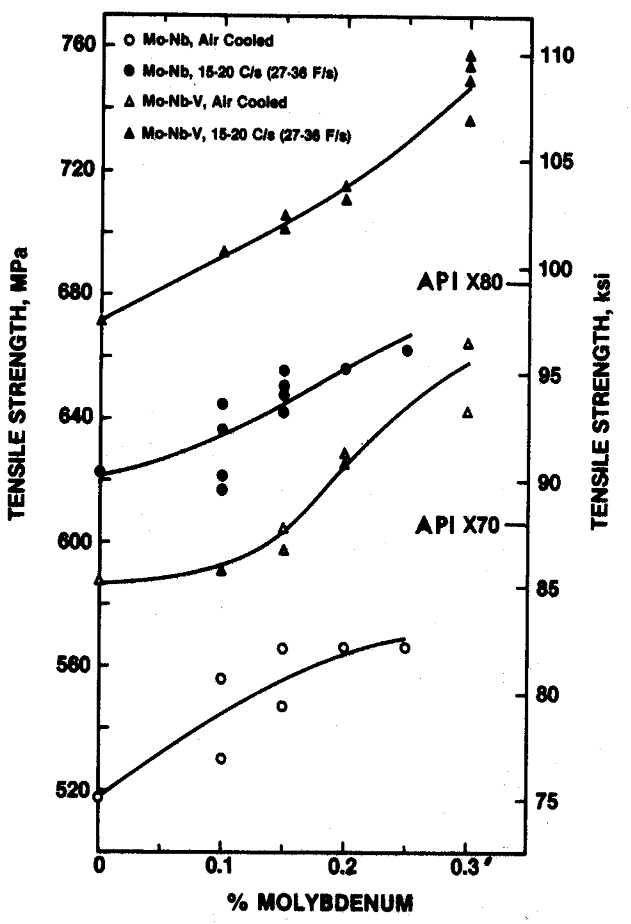


Fig. 7 - Tensile Strength vs. Molybdenum Content for 19 mm (0.75 in.) Plates Finish Rolled Near the Ar_3 Temperature.

that molybdenum helped suppress the polygonal ferrite transformation, and promoted the formation of acicular ferrite and M-A. However, there is no doubt that molybdenum's established role as an inhibitor of carbonitride precipitation in austenite[7,8] was also helping by allowing more precipitation to occur in the acicular ferrite. Regarding the specific features of the curves in Figure 7, the rate of strength increase between 0% and 0.1% Mo in the fast cooled plates was greater for the Nb-V steels than for the Nb steels, but from 0.1% to 0.25% Mo, the strengthening rates in the two steels were equal. Above 0.25% Mo, the strenthening effect of molybdenum appeared to accelerate moderately.

It appears possible to obtain X-80 strength properties in a 0.10%/0.15% Mo-0.055% Nb-0.08% V steel by accelerated cooling at 15 C/s (27 F/s) to 500 C (930 F) and air cooling. If the same processing were applied to a 0.30% Mo-0.055% Nb-0.08% V steel, properties approaching X-90 could be produced.

While the upgrading of strength properties by IAC processing is useful and important, an even more significant benefit of rapid cooling is the improvement in strength-toughness balance. That means that the increase in strength produced by IAC processing does not result in a loss of toughness. This can be seen in Figures 8 and 9. In Figure 8, the tensile strength is plotted against the CVN 50% shear FATT. The open points representing air cooled plates generally lie directly below the points from the IAC processed plates. The latter exhibit as much as 138 MPa (20 ksi) higher tensile strength than the air cooled plates, but with essentially equivalent impact transition temperatures.

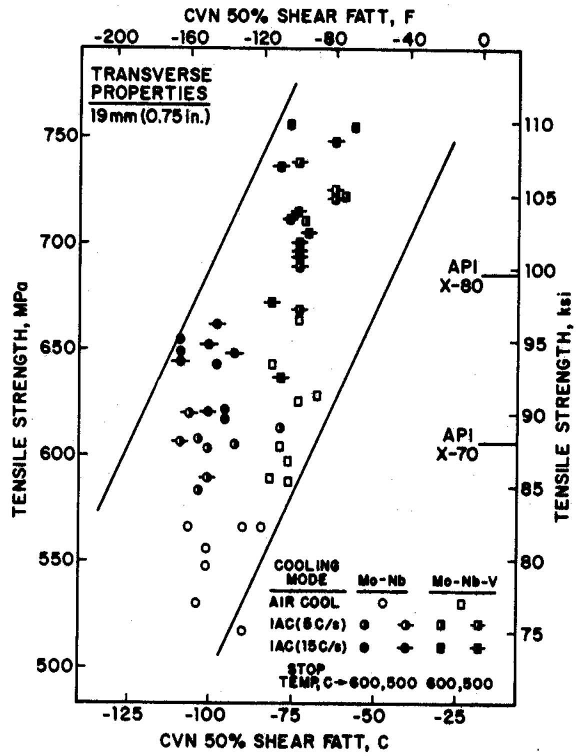


Fig. 8 - Summary of Tensile Strength vs. FATT for Mo-Nb and Mo-Nb-V Steel Plates in IAC Study.

In Figure 9, tensile strength is plotted against CVN energy absorbed at -20 C (-4 F). To show the effect of IAC processing, data points from the 0.15% Mo-Nb steel and the 0.30% Mo-Nb-V steel have been grouped by nominal cooling rate and the groups connected by arrows indicating progression toward the faster cooling rates. Again, it is seen that accelerated cooling leads to marked strength improvements with little or no loss in toughness.

An examination of the data in Figure 9 for the purpose of sorting out the effects of stop cooling temperature and the effects of the small changes in finish rolling temperature (i.e., rolling schedules A vs B and C vs D, although not coded in Figure 9) indicated that there were no significant effects of these parameters within the ranges investigated. Also, a tendency was observed for the better combinations of strength and toughness to be associated with mixed structures of fine polygonal ferrite plus bainite or acicular ferrite + M-A constituent. This was the case, for example, for the two points (half-filled squares) from the 0.20% Mo-Nb-V steel in the upper-right part of Figure 9. These plates exhibited the best overall

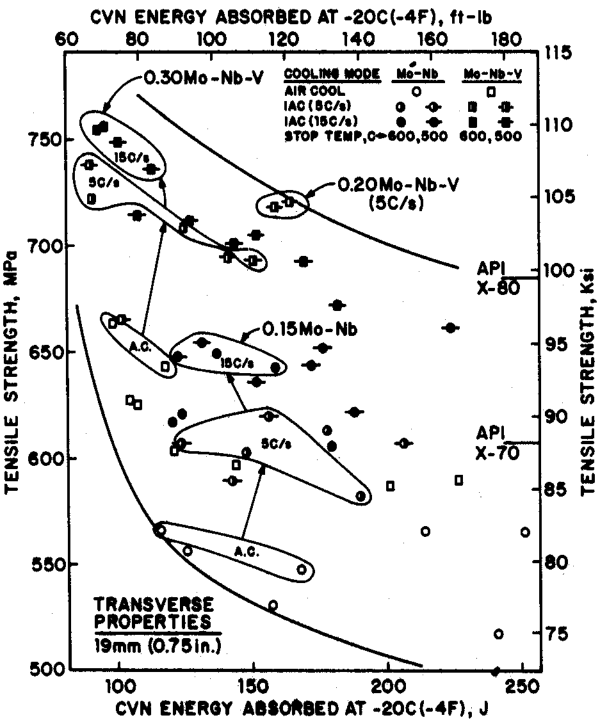


Fig. 9 - Summary of Tensile Strength vs. CVN Energy Absorbed at -20 C (-4 F) for Mo-Nb and Mo-Nb-V Steel Plates in IAC Study.

strength-toughness balance, and their microstructures comprised 15% to 40% polygonal ferrite plus bainite plus acicular ferrite + M-A constituent.

GENERAL DISCUSSION - The results presented here are relevant to all X70/X80 line pipe steel producers--those who have facilities for accelerated cooling after plate rolling and those who do not. For the latter, who can only air cool after rolling, composition and processing information indicate that X-70 as well as X-80 skelp can be produced, utilizing optimum combinations of ferrite substructure strengthening (from intercritical rolling) and strain enhanced precipitation strengthening from microalloy carbonitrides. The more advanced mills equipped with on-line accelerated cooling units can take advantage of the significant upgrading in strength-toughness balance that rapid cooling imparts.

Clear evidence of the effectiveness of IAC processing for upgrading the strength and toughness properties simultaneously can be seen in the number of plates meeting the often-cited property targets for Soviet Grade 70 line pipe. In the CR-AC study, four of the air cooled plates met these requirements, while 14 rapidly cooled plates from the IAC study qualified.

CONCLUSIONS

CR-AC Study

1. X-70 properties can be produced in steels containing nominally 0.08% C, 1.55% Mn, 0.20% Si, 0.15% Mo, 0.04% Nb, 0.015% Ti, 0.05% Al, 0.005% N, 0.01% P and 0.005% S by using a slab reheat temperature of 1150 C (2100 F), a 60-70% reduction below 900 C (1650 F), a 30-40% reduction below the Ar_3 temperature [770 C (1420 F)], and a finish rolling temperature of 730 C (1350 F).

2. After the above processing, Steel No. 1 exhibited discontinuous yielding with a 0.2% yield strength of 550 MPa (79.8 ksi), a tensile strength of 631 MPa (91.6 ksi), a CVN energy at -20 C (-4 F) of 112 J (82.5 ft-lb), and a CVN 50% shear FATT of -85 C (-120 F).

3. Steels containing nominally 0.08% C, 1.65% Mn, 0.10% Si, 0.30% Mo, 0.055% Nb, 0.080% V, 0.015% Ti, 0.04% Al, 0.005% N, 0.01% P and 0.006% S will yield X-80 properties when processed with a slab reheat temperature of 1220 C (2225 F), 60-65% reduction below 900 C (1650 F), 30-40% reduction below the Ar_3 temperature [760 C (1400 F)], and a finish rolling temperature of 705 C (1300 F).

4. Steel No. 2, when rolled as described above, exhibited continuous yielding with a 0.2% yield strength of 577 MPa (83.8 ksi), a 1.5% yield strength of 617 MPa (89.6 ksi), a tensile strength of 696 MPa (101.0 ksi), and a CVN energy at -20 C (-4 F) of 97 J (71.5 ft-lb).

5. Strength properties increase strongly with decreasing finish rolling temperature below the Ar_3 for X-70 Mo-Nb steels as well as X-80 Mo-Nb-V steels. The effect of total reduction below the Ar_3 temperature with a constant finish rolling temperature is also significant, especially for the Mo-Nb steels which exhibit a very strong increase in tensile strength with increasing reduction, up to 43%, below the Ar_3.

IAC Study

6. Interrupted accelerated cooling is very effective for raising the strength without decreasing the toughness of X-70 Mo-Nb and X-80 Mo-Nb-V line pipe steels.

7. The effect of IAC processing on microstructure is to suppress the formation of polygonal ferrite and pearlite and promote the formation of acicular ferrite or bainite. The presence of molybdenum promotes this change, especially in the vanadium-containing steels where complete elimination of polygonal ferrite can be achieved by finish rolling above the Ar_3 and cooling at 15 C/s (27 F/s) to 500 or 600 C (930 or 1110 F).

8. In X-70 Mo-Nb type steels containing nominally 0.08% C, 1.55% Mn, 0.30% Si, 0.10% to 0.15% Mo, 0.04% Nb, 0.015% Ti, 0.07% Al, 0.0044% N, 0.01% P and 0.005% S, the use of IAC processing results in tensile strength increases of 70 to 100 MPa (10 to 15 ksi) with no decrease in CVN toughness. The best properties from these steels were obtained in a 0.10% Mo plate which exhibited a 0.2% yield strength of 541 MPa (78.5 ksi), a tensile strength of 644 MPa (93.4 ksi), a CVN 50% shear FATT of -110 C (-165 F), and a CVN energy at -20 C (-4 F) of 172 J (127 ft-lb).

9. In X-80 Mo-Nb-V type steels containing nominally 0.08% C, 1.65% Mn, 0.30% Si, 0.20% to 0.30% Mo, 0.055% Nb, 0.080% V, 0.013% Ti, 0.05% Al, 0.005% N, 0.01% P and 0.006% S, IAC processing produces similar increases in tensile strength as in the X-70 type steels above. Again, there is little or no loss in toughness accompanying the strength increase.

10. Of the three processing variables investigated, cooling rate is the most influential, with strength rising strongly with increasing cooling rate. The finish rolling temperature and the stop cooling temperature have little or no effect on the strength-toughness balance in the ranges studied.

11. For a given cooling rate, the tensile strength of IAC processed plates increases with increasing molybdenum content because of suppression of polygonal ferrite and pearlite and promotion of bainite, acicular ferrite and M-A constituent, and presumably also because of enhancement of precipitation strengthening.

12. The best combination of strength and toughness is produced with a mixed structure of fine polygonal ferrite plus acicular ferrite or bainite. An example is a 0.20% Mo plate cooled at 5.9 C/s (10.6 F/s) to a stop temperature of 500 C (930 F), having a 0.2% yield strength of 555 MPa (80.6 ksi), a 1.5% yield strength of 607 MPa (88.1 ksi), a tensile strength of 721 MPa (104.7 ksi), and a CVN energy at -20 C (-4 F) of 164 J (121 ft-lb).

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