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CONTINUOUSLY ANNEALED COLD-ROLLED MICROALLOYED STEELS WITH DIFFERENT MICROSTRUCTURES

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THE VERSATILITY of a modern continuous annealing line(1,2) in generating different thermal profiles can be used to vary the nature of the second phase (carbides, pearlite, martensite) in a ferrite matrix that is either recovered or fully recrystallized. These different microstructures, in conjunction with alloying additions, can be used to generate different strength levels in cold-rolled steels, primarily for automotive applications.

Several investigations(3,4) have studied the effects of processing parameters and microalloying additions (Nb, V, Ti) on the tensile properties in recrystallized ferrite/pearlite steels. Ultra-high strength levels have been produced in recovered ferrite/martensite steels alloyed with Ti(5). Ti- and Nb-stabilized steels (interstitial-free steels) have received considerable attention for applications requiring excellent formability and strain-aging resistance(6). A recent investigation studied (a) the effect of Mn on the recrystallization behavior and tensile properties of recrystallized ferrite/pearlite Nb and Nb-V steels and (b) the effects of alloying additions (Mn, Nb, V) and processing parameters on the tensile properties of recovered ferrite/carbides and recrystallized ferrite/martensite steels. The findings of that investigation are discussed in this paper. In addition, the role of microalloying additions in continuously annealed cold-rolled sheet steels having different microstructures is reviewed.

EXPERIMENTAL DETAILS

To study the effects of alloying additions and processing parameters on tensile properties of steels exhibiting different microstructures,

viz., recovered ferrite/carbides, recrystallized ferrite/pearlite and recrystallized ferrite/martensite, samples from a number of alloys were subjected to laboratory simulations of hot rolling and continuous annealing.

MATERIALS

To evaluate the effects of Nb and V, a .06 P/.50 Si steel (Alloy 2) was selected as the base alloy. Alloys 3 to 5 and 6 to 8 featured increasing levels of Nb and V, respectively. Mn additions ranging from about 0.4 to 1.6% were made to a .06 P/.04 Nb steel (Alloys 9 to 12) and a .06 P/.04 Nb/.085 V steel (Alloys 13 to 15) in order to investigate the effect of Mn. The detailed chemical analyses are given in Table I.

PROCESSING

Hot rolling of slabs to 2.5 mm hot band was conducted in the laboratory(7). Slabs were soaked at 1260°C for 1 h and reductions of about 50, 60, and 30% were taken at, respectively, 1095°C, 1010°C, and a finishing temperature of 895°C. Coiling temperature was varied between 565 and 730°C. The hot-rolled material was cold reduced about 70%. Continuous annealing was simulated by heating tensile specimens in a neutral salt bath and annealing for 1 min at various temperatures between 565 and 845°C. Following the anneal, different cooling paths and post-annealing treatments (Fig. 1) were employed to generate the different microstructures.

TABLE I. CHEMICAL COMPOSITIONS OF THE STEELS

Alloy Number	Chemical Composition, wt %				
	Si	Mn	Nb	V	N
1	-	.37	-	-	.007
2	.51	.48	-	-	.005
3	.49	.40	.010	-	.007
4	.53	.40	.035	-	.004
5	.57	.39	.065	-	.004
6	.43	.44	-	.027	.010
7	.51	.43	-	.048	.010
8	.52	.43	-	.078	.011
9	-	.42	.040	-	.004
10	-	.89	.039	-	.004
11	-	1.30	.040	-	.005
12	-	1.60	.045	-	.004
13	-	.46	.042	.087	.018
14	-	.85	.038	.089	.016
15	-	1.35	.043	.085	.016

All steels were Al-killed with C: 0.05/0.06, P: 0.05/0.07.

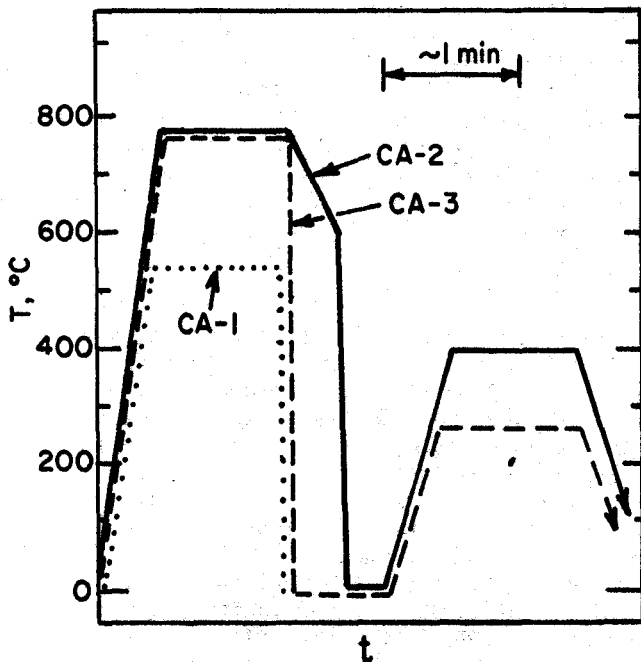


FIG. 1 DIFFERENT CONTINUOUS-ANNEALING THERMAL PROFILES.

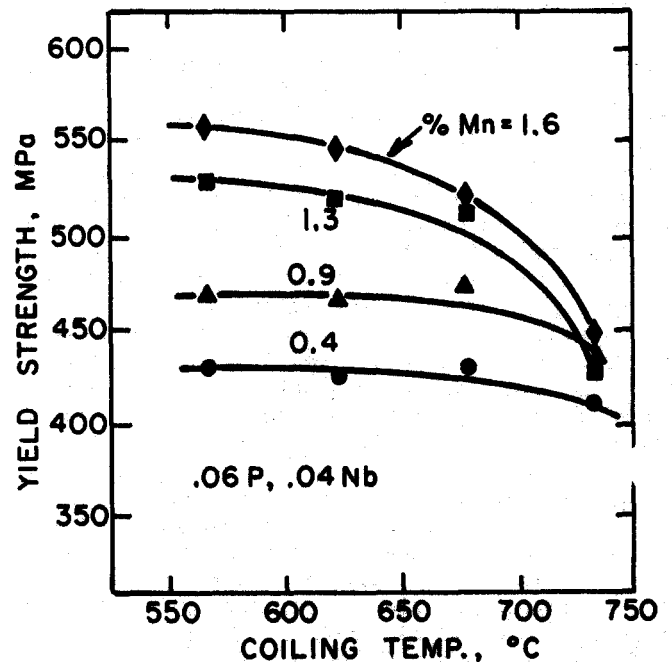


FIG. 2 EFFECT OF HOT-MILL COILING TEMPERATURE ON HOT BAND YIELD STRENGTH FOR VARIOUS Mn LEVELS IN THE Nb STEEL.

RESULTS AND DISCUSSION

HOT ROLLED

Effect of Coiling Temperature: It has previously been shown(3) that for the Nb steels (Alloys 3 to 5), the yield strength decreased only slightly with increasing coiling temperature above 620°C due to decreasing precipitation strengthening as a result of some coarsening of Nb carbonitride precipitates at the higher temperatures. For the V steels (Alloys 6 to 8), this decrease in yield strength was more rapid due to the fact that V nitride precipitates exhibit a greater tendency to coalesce than Nb carbonitride precipitates.

Figure 2 illustrates the effect of coiling temperature for various Mn levels in a Nb steel (Alloys 9 to 12). At the lower Mn levels, the slight decrease in yield strength evidenced on increasing the coiling temperature above 620°C was primarily a result of a decrease in precipitation strengthening as mentioned earlier. At the higher Mn levels, the drop in yield strength was more pronounced and is attributed to (a) a decrease in precipitation strengthening, as well as (b) coarsening of the ferrite grains -- for example, at the 1.6 Mn level (Alloy 12), ferrite grain size increased from 2.2 to 3.6 microns on increasing the coiling temperature from 620 to 730°C. This trend of increasing sensitivity to coiling temperature with increasing Mn content was evidenced in the Nb-V steel (Alloys 13 to 15) as well.

All subsequent studies were limited to material coiled at about 620°C, a temperature at which precipitation strengthening in the hot band was maximized.

Effect of Alloying Additions on Tensile Properties: Earlier studies(3) have shown that both P and Si increase the yield strength of the hot band in a linear fashion via solid solution strengthening -- 8.3 MPa per 0.1% Si addition and 63 MPa per 0.1% P addition. The addition of Nb or V resulted in the presence of carbide/nitride precipitates which led to (a) a refinement of the ferrite grains due to the ability of the precipitate particles to retard austenite recrystallization and (b) precipitation strengthening which increases with increasing precipitate volume fraction (i.e., increasing Nb and V additions). These factors resulted in an increase in yield strength with increasing Nb and V additions as seen in Fig. 3.

Increasing the Mn content in either the Nb or Nb-V steels resulted in a linear increase in yield strength of about 10.5 MPa per 0.1% Mn addition (Fig. 4) indicating that the effect of Mn was more than just solid solution

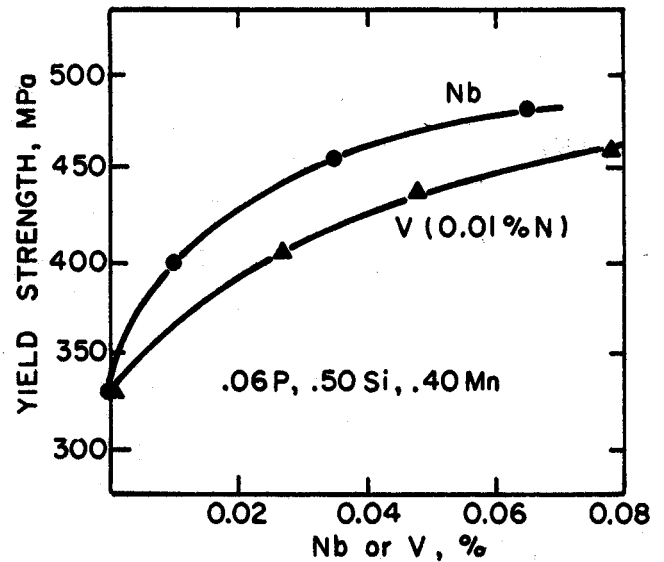


FIG. 3 EFFECT OF Nb AND V ADDITIONS ON HOT BAND YIELD STRENGTH (COILING TEMP. = 620°C).

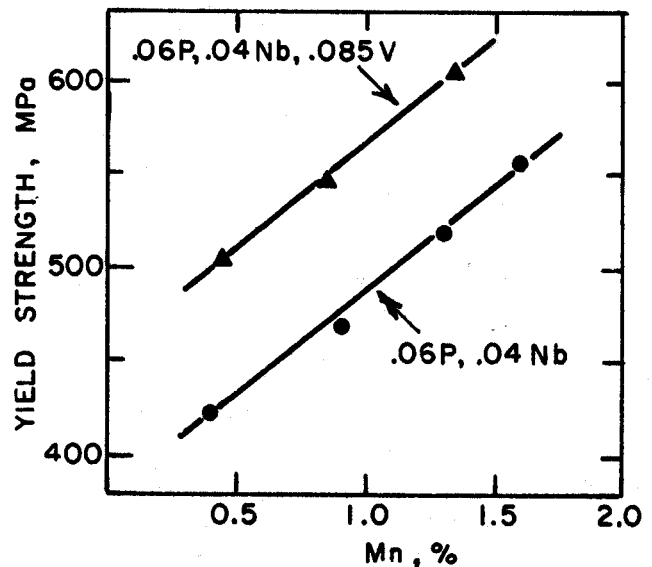


FIG. 4 EFFECT OF Mn ADDITION ON HOT BAND YIELD STRENGTH IN THE Nb AND Nb-V STEELS (COILING TEMP. = 620°C).

strengthening (2.8 MPa per 0.1% Mn). As seen in Table II, the Mn addition refined the ferrite grain size.

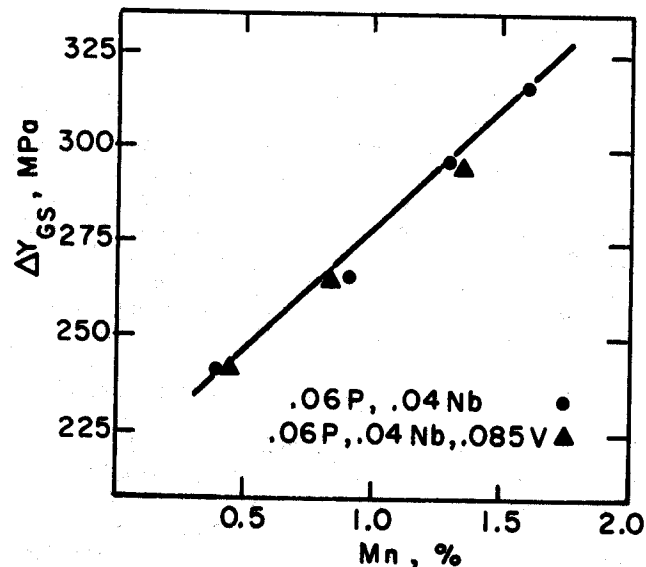
Table II. Ferrite Grain Size as a Function of Mn Content in Nb and Nb-V Steels

Alloy Number	Mn, %	Ferrite Grain Size, Microns
9	0.40	3.9
10 Nb	0.90	3.3
11 Steels	1.30	2.6
12	1.60	2.2
13	0.45	4.0
14 Nb-V	0.85	3.4
15 Steels	1.35	3.0

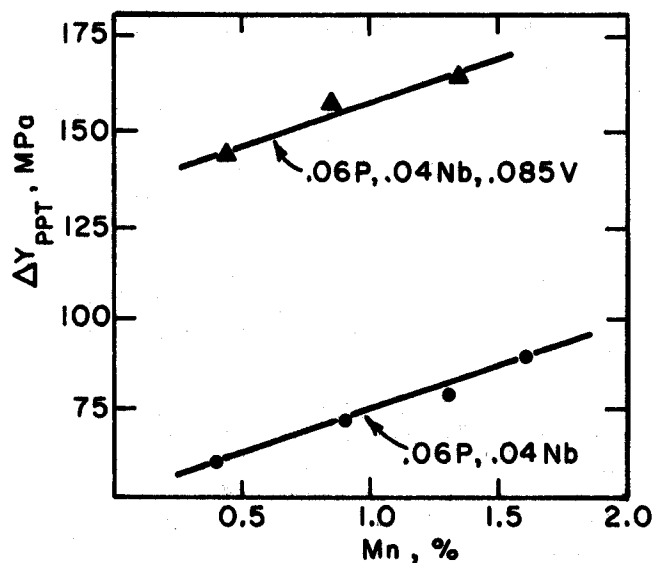
The total yield strength can be divided into the various strengthening components (7) -- solid solution, grain refinement (ΔY_{gs}) and precipitation (ΔY_{pnt}). Fig. 5a illustrates that for both the Nb and Nb-V steels, grain refinement (Table II) resulted in an increase in ΔY_{gs} with increasing Mn content. The ferrite grain refinement is attributed to the ability of Mn to lower the ferrite transformation temperature (8). Fig. 5b shows that increasing Mn also enhanced precipitation strengthening and is probably a result of an influence of Mn on precipitation kinetics (9). At a given Mn level, addition of 0.085 V resulted in a 80 MPa increase in yield strength (Fig. 4) due to an increase in precipitation strengthening (Fig. 5b).

COLD-ROLLED CONTINUOUSLY ANNEALED

In a plain-carbon steel, recrystallization initiated at about 600°C and was completed at 635°C, for an annealing time of 1 min. Addition of Si produced a small retarding effect on the recrystallization kinetics, while Nb and V additions had a very potent retarding effect (3). As seen in Figs. 6a and b, Mn also retarded the recrystallization kinetics in both the Nb and Nb-V steels possibly due to both solute drag and an increase in the precipitate volume fraction. It is seen from the recrystallization curves that annealing at a temperature of about 560°C would produce a recovered (non-recrystallized) microstructure even in the plain-carbon steel. On the other hand, annealing temperature has to be in excess of the R_f (recrystallization-finish) temperature to generate a fully-recrystallized ferritic structure. The R_f temperature increased with increasing Nb, V and Mn contents as seen in Figs. 7 and 8.

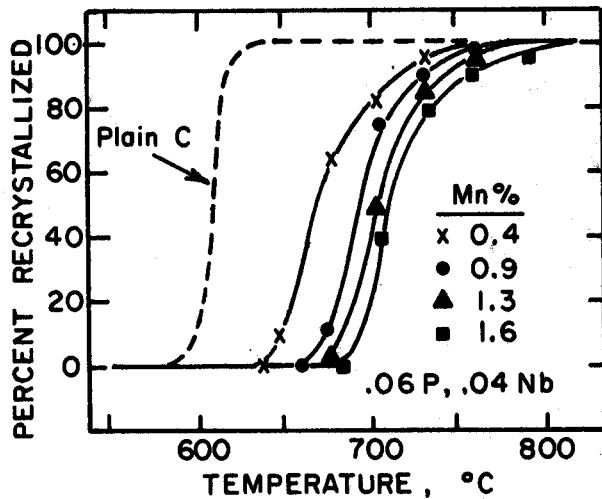


(a)

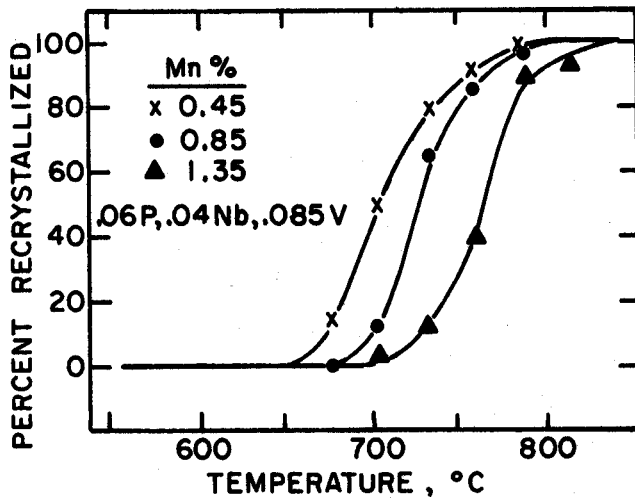


(b)

FIG. 5 EFFECT OF Mn ADDITION ON (a) GRAIN REFINEMENT STRENGTHENING AND (b) PRECIPITATION STRENGTHENING IN THE Nb AND Nb-V STEELS (COILING TEMP. = 620°C).



(a)



(b)

FIG. 6 EFFECT OF Mn ADDITION ON RECRYSTALLIZATION KINETICS ($t = 1$ min) IN COLD-ROLLED (a) Nb AND (b) Nb-V STEELS.

Recovered Ferrite/Carbides: The recovered structure(10) that results on annealing at 560°C provided a large increase in yield strength via substructure strengthening; in a plain-carbon steel this increment was about 360 MPa. Yield strength could be increased further by addition of Nb, V or Mn (Figs. 9 and 10) in a manner similar to that in the hot band (Figs. 3 and 4). The strengthening increments (solid solution, grain refinement, and precipitation) imparted by these elements are nearly identical in both the hot-rolled and recovery-annealed conditions as can be seen in Fig. 11.

For these steels, the continuous annealing cycle involved annealing at 560°C for about 1 min. followed by quenching to the ambient temperature (CA-1 in Fig. 1). These steels are characterized by very high yield strengths (600 - 1,000 MPa) at low alloy contents, with only very limited ductility.

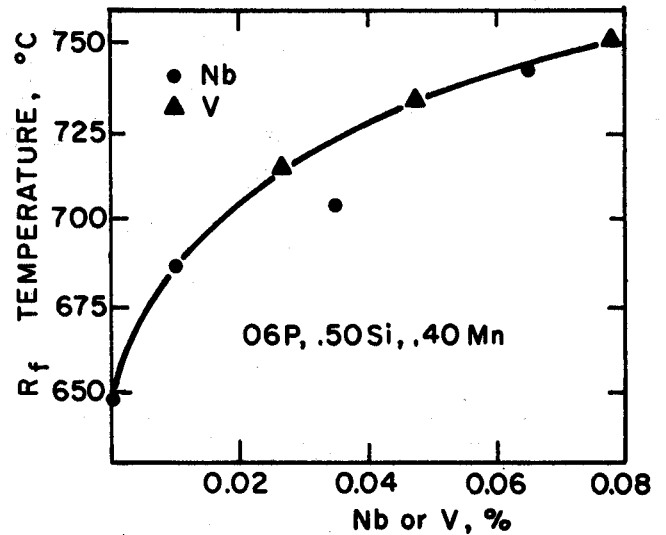


FIG. 7 EFFECT OF Nb AND V ADDITION ON RECRYSTALLIZATION-FINISH TEMPERATURE ($t = 1$ min).

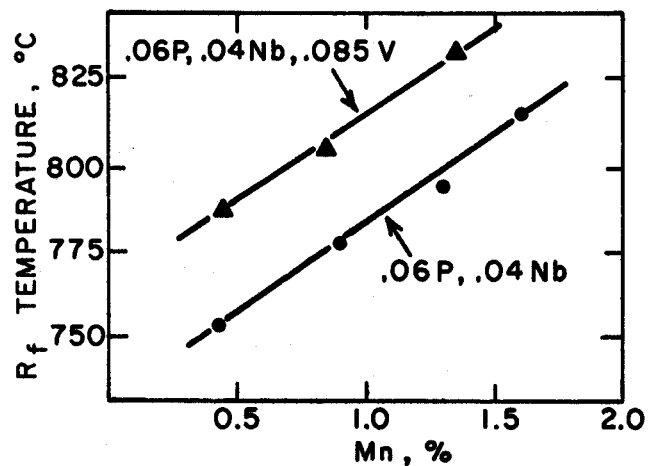


FIG. 8 EFFECT OF Mn ADDITION ON RECRYSTALLIZATION-FINISH TEMPERATURE ($t = 1$ min) IN THE Nb AND Nb-V STEELS.

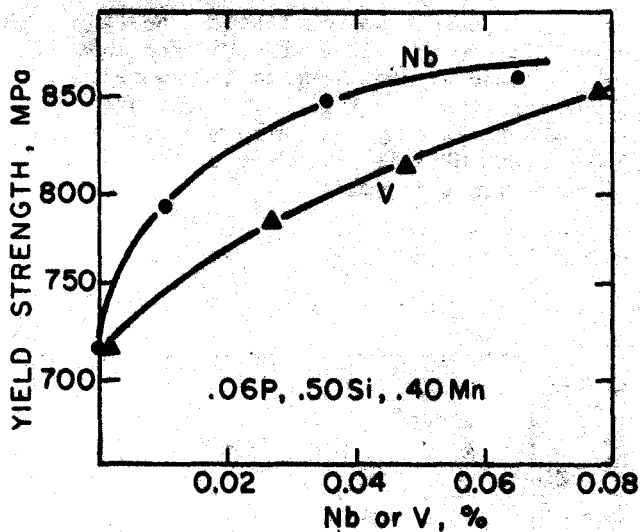


FIG. 9 EFFECT OF Nb AND V ADDITION ON YIELD STRENGTH IN RECOVERED FERRITE/CARBIDES STEELS.

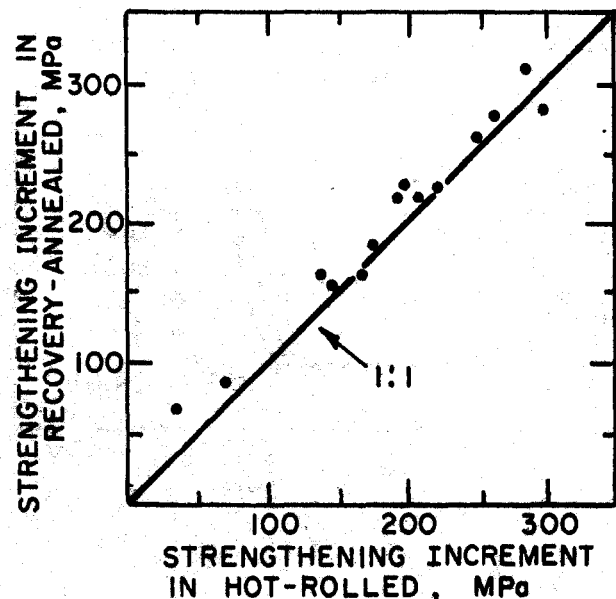


FIG. 11 COMPARISON OF THE STRENGTHENING INCREMENTS IN THE RECOVERED FERRITE/CARBIDES STEEL AND THE PARENT HOT BANDS.

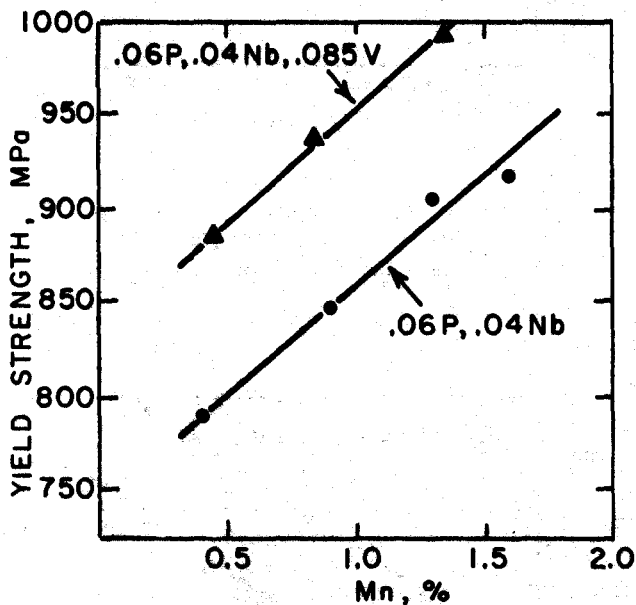


FIG. 10 EFFECT OF Mn ADDITION ON YIELD STRENGTH IN RECOVERED FERRITE/CARBIDES STEELS ALLOYED WITH Nb AND Nb-V.

Recrystallized Ferrite/Pearlite: The cold reduction of 70% followed by the very short annealing time (about 1 min) resulted in a fine recrystallized ferrite grain size (about 4 microns), the magnitude of which was independent of alloy content. Increasing the annealing temperature did not appreciably change the

ferrite grain size. However, increasing the annealing temperature did coarsen the precipitate size distribution(3) leading to a decrease in precipitation strengthening. The decrease in precipitation strengthening was greater for the steels with larger precipitate volume fractions (i.e., higher Nb, V and Mn contents). Also, the decrease in precipitation strengthening was greater in case of vanadium nitride precipitates compared to the niobium carbonitrides.

At a given annealing temperature in the fully-recrystallized regime:

- P and Si increased yield strength solely via solid solution strengthening -- 63 and 8.3 MPa per 0.1% addition, respectively(3).
- Increasing Nb or V content increased the yield strength (Fig. 12) by increasing the precipitation strengthening component(3). For a given alloy content, however, the precipitation strengthening was less than in the parent hot band, especially in the case of the V steels. The behavior of Ti(4) was similar to that of Nb.
- Because the ferrite grain size was essentially independent of alloy content, the effect of Mn (3.4 MPa increase in yield strength for every 0.1% addition) was primarily that of solid solution strengthening (Fig. 13). At a given Mn content, addition of 0.085 V increased the yield strength by about 35 MPa. This was much less than the increase evidenced in the

hot-rolled condition (80 MPa in Fig. 4) due to coarsening of the vanadium nitride precipitates during annealing.

For these steels high yield strengths (300-500 MPa) with good ductility can best be achieved through solid solution strengthening with P and Si, and precipitation strengthening via addition of Nb. The Nb addition is limited by the fact that it increases the R_f temperature (Fig. 7), thus requiring a higher annealing temperature; this results in a greater loss in precipitation strengthening(4).

For these recrystallized ferrite/pearlite steels, following an annealing treatment above the R_f temperature, the material was gas-jet cooled (15°C/ sec) to about 600°C prior to the quench (Cycle CA-2 in Fig. 1). The slow-cooling segment generally assured a non-martensitic structure. (For the steels containing >1.3% Mn, i.e., Alloys 11, 12, and 15, less than 2 volume percent martensite was detected.) Carbon retained in interstitial solid solution because of the rapid quench was precipitated by "tempering" at 400°C for 90 sec -- this treatment increased the aging resistance(11).

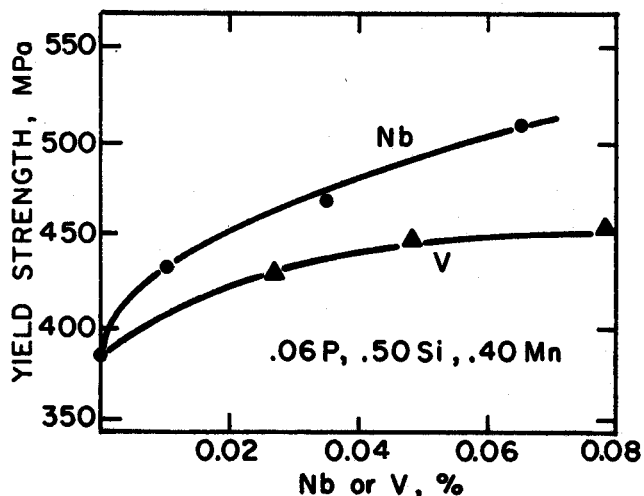


Fig. 12 EFFECT OF Nb AND V ADDITIONS ON YIELD STRENGTH IN RECRYSTALLIZED FERRITE/PEARLITE STEELS.

Recrystallized Ferrite/Martensite: Annealing in the intercritical (ferrite/austenite) region, followed by a direct quench (Cycle CA-3 in Fig. 1), results in a ferrite-martensite or dual-phase microstructure; a subsequent tempering treatment (12,13) at 260°C for 1-1/2 min is needed to improve room temperature stability and optimize the strength-ductility

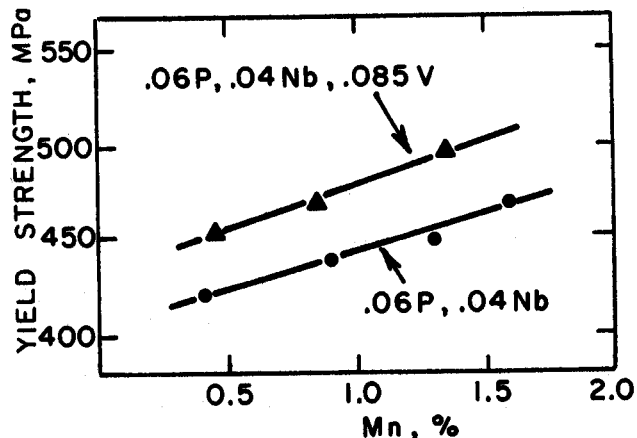


FIG. 13 EFFECT OF Mn ADDITION ON YIELD STRENGTH IN RECRYSTALLIZED FERRITE/PEARLITE STEELS ALLOYED WITH Nb AND Nb-V.

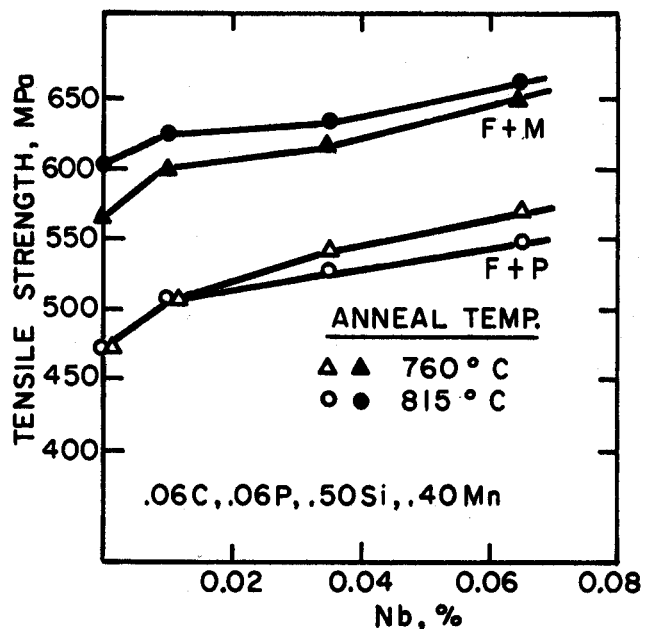


Fig. 14 EFFECT OF Nb ADDITION ON TENSILE STRENGTH IN RECRYSTALLIZED FERRITE/MARTENSITE AND RECRYSTALLIZED FERRITE/PEARLITE STEELS.

combination. The data for Alloys 2 to 5 is shown in Fig. 14 for two annealing temperatures, viz. 760 and 815°C, -- F+M indicates a ferrite-martensite microstructure obtained by quenching directly from the annealing temperature, while F+P indicates a ferrite-pearlite microstructure generated by gas-jet cooling to about 600°C

prior to the quench. At the annealing temperature of 760°C, the Nb addition raised the tensile strength in similar fashion in both the F+M and F+P steels via precipitation strengthening, as mentioned previously. At a given Nb level, the presence of martensite raised the tensile strength by about 7 MPa for every 1 percent martensite(12). The amount of martensite is primarily a function of the C content of the steel; specifically for Alloys 2 to 5, the C content was approximately 0.06% resulting in about 12% martensite. Increasing the annealing temperature to 815°C resulted in a decrease in tensile strength in the F+P steels solely due to some precipitate coarsening(3). On the other hand, in the F+M steels, an increase in the amount of martensite from 12 to 19% resulted in an overall increase in tensile strength as seen in Fig. 14.

Presence of martensite alters the initial yielding behavior due to the presence of mobile dislocations introduced by the austenite-to-martensite transformation(14). For the F+P steels, the yield point elongation was 5-6% while in the F+M steels it was only 1.5-2.5%. As such, elimination of the yield point elongation by means of a temper-rolling reduction is easier in the F+M steels. While the effect on tensile strength is essentially straight-forward as seen in Fig. 14, the effect on yield strength was complicated by the effect of martensite on the yielding behavior. In the temper-rolled condition -- about 1.75% temper-rolling reduction for the F+P steels and about 0.75% reduction for the F+M steels -- the overall effect of the introduction of martensite was to increase the yield strength only slightly. As such, direct quenching of these HSLA steels from the intercritical annealing temperature(1) lowered the yield ratio (yield strength/tensile strength) primarily due to an increase in tensile strength and (2) facilitated elimination of the yield point elongation.

Up to this point, results of the investigation dealing with the effect of alloying additions and processing parameters on the tensile properties of recovered ferrite/carbides, recrystallized ferrite/pearlite and recrystallized ferrite/martensite steels have been discussed. What follows is a summary of the application of microalloying elements in other cold-rolled continuously annealed steel grades.

Recovered Ferrite/Martensite(5): Titanium carbide precipitates delay the onset of recrystallization, and for a 0.11% Ti addition, recrystallization does not commence until about 750°C (4,5). As such, an intercritical annealing treatment can be carried out with ferrite remaining in the recovered condition; subsequent quenching from this temperature (as in CA-3 in Fig. 1) results in a recovered ferrite/martensite structure. Ultra-high strengths

(tensile strengths from 1,000 to 1,400 MPa) can thus be obtained and, although it is a recovery-annealed structure, it shows work-hardening characteristics due to the presence of martensite. At an equivalent strength level, these steels exhibit superior ductility compared to the recovered ferrite/carbide steels discussed previously. Carbon level and annealing temperature are critical because they determine the volume percent martensite.

Interstitial-Free Ferrite(6): Deep-drawing applications require low yield strengths (<200 MPa), high \bar{r} values and resistance to strain aging. Large recrystallized ferrite grains, which lead to both the low yield strength and superior \bar{r} (15), can be realized within the short annealing time (CA-2 in Fig. 1) by getting interstitial atoms (C, N) with either Ti or Nb. Chemistry requirements include a Nb/C of about 1 and a Ti*/C of 1 to 5, where

$$Ti^* = Ti - \frac{48}{32} S - \frac{48}{14} N.$$

For excellent strain aging resistance, Ti*/C has to be about 5. In addition, very low C levels (.01% max) are necessary.

Addition of P results in a higher yield strength at the expense of some deterioration in \bar{r} and the possibility of cold-work embrittlement. Resistance to cold-work embrittlement can be increased by annealing at high temperatures (870-900°C) which probably lead to some dissolution of the titanium or niobium carbides(6). The resultant product is described as a deep-drawable and bake-hardenable high-strength sheet steel.

SUMMARY

Rephosphorized Mn-steels alloyed with Nb, V or Nb-V were subjected to laboratory simulations of hot-rolling and subsequent continuous annealing of the cold-rolled material. Different microstructures were generated by altering the continuous annealing thermal profile.

In the hot-rolled condition, increasing Mn, Nb or V contents increased the yield strength via grain refinement and enhancement of precipitation strengthening.

For the cold-rolled continuously annealed condition, the key findings were:

- For the recovered ferrite/carbides microstructure, substructure strengthening provided a large increase in yield strength; additionally, the Mn, Nb and V additions increased the yield strength in a manner similar to that in the parent hot band.

- For the recrystallized ferrite/pearlite microstructure, increase in yield strength was due to solid solution strengthening in case of Mn and precipitation strengthening in case of the Nb and V additions.
- For recrystallized ferrite/martensite microstructure, introduction of martensite increased the tensile strength and decreased both the yield ratio and yield point elongation.
- Recovered ferrite/martensite microstructure provided ultra-high yield strengths with ductility superior to the recovered ferrite/carbide steels.

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