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EFFECTS OF PHOSPHORUS ON THE ANNEALING TEXTURE, PLASTIC ANISOTROPY, AND MECHANICAL PROPERTIES OF LOW-CARBON STEELS

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Abstract: The effects of phosphorus on the annealing texture, plastic anisotropy, and mechanical properties of low-carbon steels containing 0.11 percent manganese have been studied. Both vacuum-melted and air-melted heats, with phsophorus additions up to 0.12 percent, were used. Results show that with a cold reduction of 80 percent, followed by annealing at temperatures in the range 710 to 820°C, the plastic strain ratios, r_m and Δr, as well as the strength of the steels were substantially improved by phosphorus. Annealing at the intercritical temperatures 780 and 820°C further improved the strain ratios. The strong tendency for phosphorus to segregate at the subgrain and grain boundaries is believed to have played an important role in controlling the formation of annealing textures in these steels.

INTRODUCTION

During the past decade, the additions of minor alloying elements for improving the drawability of low-carbon steel sheets have been studied by many researchers.[1-5] Teshima and Shimizu[1] showed that the plastic strain ratio, or r value* was significantly increased by

*The definitions of these parameters are as follows: $r = \varepsilon_w/\varepsilon_t$, the ratio of true strain in the width dimension to that in the thickness dimension in tensile deformation.

adding phosphorus and copper to the steel and by annealing the cold-rolled sheet in a decarburizing atmosphere at a high temperature. Such decarburized P-Cu steels, according to Teshima and Shimizu, had a tendency to split in a brittle manner at severely deformed regions during the cup-drawing operation.[1] This may have been the reason that further investigations on phosphorus-containing steels for deep-drawing applications have not been conducted to a great extent. In view of recent need for developing high-strength deep drawing sheet for automobile applications, and of the fact that phosphorus is a potent solution-strengthener in iron and steel,[6] the effect of phosphorus on the drawability and strength of low-carbon steels would be both commercially and scientifically of great interest.

Following the findings that the r_m (or $\bar{r}$) value* of low-carbon steel can be substantially increased by lowering its manganese content,[7] an exploratory investigation of the effect of phosphorus on the drawability of a vacuum-melted low-carbon low-manganese (∿0.04% C and 0.10% Mn) steel, as a function of cold-rolling reduction and annealing temperature, was conducted in our laboratory. The results showed that the r_m value was increased markedly by the addition of phosphorus when processed by cold rolling greater than 80 percent and subsequent annealing in the intercritical temperature range 780 to 870°C (1435 to 1600°F). Within the composition range studied (0.015 to 0.12% P), the r_m value increased and the Δr value* decreased, almost linearly with the phosphorus content. It was also shown that such dependence of r_m and Δr on phosphorus was further amplified by increasing the prior cold-rolling reduction.[8] For example, when the steels were cold-rolled 82 percent and annealed 20 hours at 820°C (∿1500°F), the r_m values increased from 2.36 to 3.28, whereas the absolute values of Δr decreased from 0.5 to 0.2. By increasing the cold reduction to 88 percent, the same annealing treatment produced r_m values ranging from 2.73 to 3.82, whereas Δr decreased from 0.8 to 0.3. Since high r_m values indicate strong resistances to thinning, and low Δr values, weak tendencies for earing, in drawing deformations, these anisotropy parameters of phosphorus-containing steels are much superior to those of deep-drawing aluminum-killed steels for which the approximate average of r_m is 1.6 and of Δr is 0.5.

These preliminary observations were made on relatively thin strips, a consequence of the relatively heavy

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*$r_m = (r_0 + 2r_{45} + r_{90})/4$, and $\Delta r = (r_0 + r_{90} - 2r_{45})/2$ where the subscripts are angles from the rolling direction of the strip.

cold-rolling reductions employed for the hot-rolled bands. Consequently, the anisotropy parameters were all determined by the dynamic modulus measurements,[9] and the mechanical properties of the steels were not obtained.

To investigate the characteristics of phosphorus-containing steels more thoroughly and to explore the feasibility of commercial application of these steels, a series of vacuum-melted phosphorus-containing steels was produced in the laboratory. In addition, a few air-melted heats with comparable phosphorus contents were also prepared for investigation. Results of these studies are presented in this paper.

MATERIALS AND EXPERIMENTAL WORK

Vacuum-Melted and Air-Melted Steels

Six 50-pound (22.7 kg) ingots of low-carbon, low-manganese steels with various phosphorus contents were cast from a 300-pound (136 kg) vacuum heat made in the laboratory. Chemical compositions of hot-rolled plates of these steels are shown in Table I. Three 100-pound (45.5 kg) ingots from an air-melted heat, containing phosphorus up to the same maximum level as the vacuum-melted steels, were also made in the laboratory; small amounts of aluminum were used to control the rimming action during solidification. The compositions of these steels are shown in Table II(A). To ascertain the results for the air-melted steels, additional three 100-pound ingots were made later by the same techniques, the phosphorus contents being intermediate between those of the earlier series. The chemical compositions of the second series of air-melted steels are shown in Table II(B)

Hot-Processing Procedures

Since the ingot size of the vacuum-melted steels is relatively small, to assure homogeneity in composition and in structure, the ingots (3 by 5-1/2 by 10 inches or 7.5 by 14 by 25 cm) were first hot-forged at 1230°C (∿2250°F) around all sides to a cross section of approximately 2-3/4 by 4-1/2 inches (∿7 by 11 cm). The forged pieces were then reheated to 1230°C, hot-rolled from 2-3/4 to 0.5 inch (∿70 to 12.5 mm) with finish rolling at 900°C (∿1652°F), and air-cooled.

For the air-melted steels, no forging was employed. The ingots (3 by 8 by 14 inches or ∿7.5 by 20 by 36 cm) were heated to 1230°C and hot-rolled from 3 to 1 inch (∿75 to 25 mm), finish rolling being at 900°C. After

Table I

Chemical Compositions of the Vacuum-Melted Steels, wt %

Heat No. and Steel	C	Mn	P	S	Si	Cu	Ni	Cr	N	Al Sol	Al Insol	Al Total	O, ppm
7261-8001													
A Top	0.017	0.11	0.12	0.017	0.034	0.007	0.022	0.016	0.004	<0.001	<0.001	<0.002	39
A Bottom	0.016	0.11	0.12	0.010	0.034	0.007	0.022	0.018	0.004	<0.001	0.001	<0.002	34
B Top	0.018	0.11	0.093	0.017	0.034	0.007	0.022	0.018	0.004	0.001	<0.001	<0.002	43
B Bottom	0.018	0.11	0.091	0.016	0.034	0.007	0.022	0.016	0.004	0.001	0.004	0.005	37
C Top	0.019	0.11	0.063	0.016	0.034	0.007	0.022	0.016	0.004	<0.001	<0.001	<0.002	47
C Bottom	0.018	0.11	0.062	0.016	0.034	0.007	0.022	0.016	0.004	0.001	<0.001	<0.002	45
D Top	0.020	0.11	0.031	0.016	0.032	0.007	0.020	0.014	0.004	<0.001	<0.001	<0.002	45
D Bottom	0.019	0.11	0.030	0.016	0.030	0.007	0.020	0.014	0.003	0.001	<0.001	<0.002	46
E Top	0.020	0.11	0.015	0.016	0.032	0.007	0.020	0.014	0.004	0.001	0.001	<0.002	39
E Bottom	0.019	0.10	0.015	0.016	0.032	0.007	0.020	0.016	0.004	0.001	<0.001	<0.002	47
F Top	0.020	0.10	0.004	0.017	0.032	0.007	0.020	0.014	0.003	0.001	<0.001	<0.002	63
F Bottom	0.020	0.10	0.004	0.016	0.024	0.007	0.020	0.014	0.003	0.001	<0.001	<0.002	59

Table II

Chemical Compositions of the Air-Melted Steels, wt %

Steel	C	Mn	P	S	Si	Cu	Ni	Cr	N	O, ppm	Al Sol	Al Insol	Al Total
A. Series I (Heat No. 7261-8003)													
A Bottom	0.027	0.097	0.022	0.020	0.027	0.010	0.11	0.018	0.007	619	0.013	0.009	0.022
B Bottom	0.028	0.11	0.056	0.020	0.021	0.010	0.10	0.018	0.007	665	0.008	0.014	0.022
C Bottom	0.028	0.11	0.12	0.020	0.016	0.010	0.11	0.020	0.007	594	0.007	0.032	0.039
B. Series II (Heat No. 7261-8003-2)													
A Top	0.021	0.092	0.043	0.018	0.007	0.015	0.015	0.020	0.008	541	0.005	0.047	0.052
A Bottom	0.020	0.10	0.041	0.018	0.016	0.014	0.015	0.025	0.006	658	0.007	0.054	0.061
B Top	0.017	0.10	0.087	0.020	0.005	0.015	0.016	0.023	0.008	489	0.001	0.010	0.011
B Bottom	0.018	0.11	0.072	0.016	0.008	0.012	0.015	0.026	0.005	625	0.003	0.019	0.022
C Top	0.025	0.12	0.10	0.020	0.004	0.012	0.015	0.023	0.008	794	0.011	0.040	0.051
C Bottom	0.016	0.14	0.09	0.016	0.011	0.012	0.015	0.024	0.006	780	0.001	0.017	0.018

cooling in air, the plates were cut into ∿10-inch-long (∿25 cm) plates and machined to 0.75 inch (19 mm) to remove the surface irregularities.

Final hot processing consisted of reheating the 0.5-inch-thick (vacuum-melted steel) or the 0.75-inch-thick (air-melted steel) plates to 1230°C and hot rolling to a thickness of 0.150 inch (3.8 mm), the temperature for the finishing pass being about 975°C (∿1780°F). The hot-rolled bands were immediately dipped into iced water for 1.5 to 2 seconds to simulate the water-spray cooling, and were subsequently furnace-cooled from 620°C (1150°F) to room temperature at a rate of approximately 40°C (∿75°F) per hour. This furnace-cooling treatment was to simulate the thermal conditions in coiled strips.

Cold Rolling and Final Anneals

Prior to cold rolling, the hot-rolled bands were sandblasted and pickled to remove surface scales. They were then cold-rolled ∿80 percent to 0.030 inch (0.76 mm). Tension specimens were machined from blanks cut from the cold-rolled strips at 0, 45, and 90 degrees to the rolling direction. To obtain quick results on r_m and Δr values, corresponding sets of narrow strip specimens (0.250 by 4.1195 inches or 6.35 by 104.6 mm) were also prepared for dynamic modulus measurements; the anisotropy parameters, r_m and Δr, were then calculated.

These specimens were finally annealed in loose packs in 15 percent $H_2 + N_2$ at a heating rate of 20 to 25°C (40 to 50°F) per hour to 710°C (1310°F), 780°C (1436°F), or 820°C (1508°F), held at temperature for 20 hours, and furnace-cooled (simulated box anneal).

Exploration of the Hot-Rolling Finishing Temperature

Before the hot-processing procedures (as described in an earlier section) were adopted, experiments were conducted to establish the hot-finishing temperature for best anisotropy properties. These consisted of reheating the 0.150-inch hot-rolled band, originally finished at 900°C, to various temperatures ranging from 900 to 1000°C (1652 to 1832°F) for a final reduction to 0.100 inch (2.5 mm) at that temperature. To investigate also whether the manner of cooling has any significant effect on the final properties, the 0.100-inch hot-rolled band was either cooled in air or dipped immediately into iced water for 1.5 seconds, and then furnace-cooled from 620°C to ambient at a rate of 40°C per hour to simulate coiling.

After cleaning, these hot-rolled bands were cold-rolled 82 percent to 0.018 inch (0.46 mm). Specimens for modulus measurements were annealed in 15 percent $H_2 + N_2$ at a heating rate of 20 to 25°C (40 to 50°F) per hour to 820°C, held at temperature for 20 hours, and furnace-cooled.

The modul-r_m [9] and Δr values of duplicate specimens tested are shown in Table III. These results indicate that if fast cooling from the finishing temperature to 620°C is employed, followed by slow cooling to the ambient temperature, a finishing temperature in the range 900 to 1000°C appears to be satisfactory in the final anisotropy properties. On the other hand, if the hot-rolled strip is to be cooled in air, a finishing temperature of 900°C would be too low for high r_m and low Δr values to be developed in the annealed strips.

In the present investigation, we adopted 975°C (1790°F) as our finishing temperature in hot rolling. Since a drop in temperature inevitably occurred during the transfer of the steel from the reheating furnace to the rolling mill, the actual finishing temperature should be lower than that specified.

RESULTS AND DISCUSSION

Microstructure and Texture of the Hot-Rolled Bands

The 0.150-inch-thick hot-rolled bands of all the steels were fully recrystallized with fairly equiaxed grains. In the air-melted steels there were considerable amounts of inclusions and stringers, presumably oxides. Some variations in grain size from the surface to the midthickness positions were evident. The grains were in general finer in the air-melted steels than in the vacuum-melted steels. Figure 1 shows the microstructures typical of the series of steels. The photomicrographs were taken from the transverse cross section of the hot-rolled band, and were centered at a position on the specimen corresponding approximately to 1/4 thickness down from the surface, which is above the top edge of the photograph. Thus, the fine-grained region at a short distance below the surface is shown.

The texture of the hot-rolled band was examined at three sections parallel to its surface: (1) just below the surface, (2) at 1/4 thickness down from the surface, and (3) at 1/2 thickness or the midplane. As shown by the integrated X-ray peak intensities of the various reflections, Table IV, the texture of the hot-rolled band is not random, particularly at its midthickness section. The average grain sizes at corresponding locations in the hot-rolled band are also included in this tabulation.

These results show some common features among the steels. For example, the (222) and (211) orientations

Table III

Effect of Finishing Temperature and Cooling Rate on Modul-$\bar{r}_m$ and Δr of the Steels

Heat No.	Steel	P, wt %	Finishing Temp	Cooling* Method	r_m	Δr
7261-8001 (Vac-Melts)	A	0.120	900°C (1652°F)	Air-Cool	1.89	0.48
				Simulate Coiling	2.58	0.18
	B	0.092	"	Air-Cool	1.86	0.49
				Simulate Coiling	2.55	0.19
	C	0.062	"	Air-Cool	1.75	0.47
				Simulate Coiling	2.45	-0.03
	D	0.030	"	Air-Cool	1.58	0.68
				Simulate Coiling	2.12	0.22
	E	0.015	"	Air-Cool	1.49	0.68
				Simulate Coiling	1.92	0.17
	F	0.004	"	Air-Cool	1.57	0.45
				Simulate Coiling	1.85	-0.12
	A	0.120	950°C (1742°F)	Air-Cool	2.32	0.40
				Simulate Coiling	2.42	0.04
	B	0.092	"	Air-Cool	2.46	0.28
				Simulate Coiling	2.44	-0.02
	C	0.062	"	Air-Cool	2.28	0.08
				Simulate Coiling	2.31	-0.07
	D	0.030	"	Air-Cool	2.21	0.05
				Simulate Coiling	2.27	-0.22
	E	0.015	"	Air-Cool	2.11	0.04
				Simulate Coiling	2.00	-0.25
	F	0.004	"	Air-Cool	1.95	-0.01
				Simulate Coiling	1.93	-0.33

(Continued)

Table III (Continued)

Heat No.	Steel	P, wt %	Finishing Temp	Cooling* Method	r_m	Δr
	A	0.120	975°C (1787°F)	Simulate Coiling	2.80	-0.01
	B	0.092	"	"	2.52	-0.04
	C	0.062	"	"	2.31	-0.05
	D	0.030	"	"	2.07	-0.07
	E	0.015	"	"	1.98	-0.16
	F	0.004	"	"	1.93	-0.22
	A	0.120	1000°C (1832°F)	Simulate Coiling	2.58	-0.13
	B	0.092	"	"	2.58	-0.12
	C	0.062	"	"	2.35	-0.13
	D	0.030	"	"	2.30	-0.16
	E	0.015	"	"	2.10	-0.17
	F	0.004	"	"	1.93	-0.05
7261-8003 (Air-Melts Series I)	A	0.022	900°C (1652°F)	Air-Cool	1.63	-0.12
				Simulate Coiling	1.75	-0.21
	B	0.056	"	Air-Cool	1.82	0.27
				Simulate Coiling	2.07	0.09
	C	0.120	"	Air-Cool	1.67	0.21
				Simulate Coiling	2.14	-0.01
	A	0.022	950°C (1742°F)	Air-Cool	1.80	-0.20
				Simulate Coiling	1.66	-0.52
	B	0.056	"	Air-Cool	2.27	-0.03
				Simulate Coiling	2.14	-0.35
	C	0.120	"	Air-Cool	2.19	0.08
				Simulate Coiling	2.21	-0.15
	A	0.022	975°C (1787°F)	Simulate Coiling	1.68	-0.47
	B	0.056	"	"	2.17	-0.24
	C	0.120	"	"	2.33	-0.24
	A	0.022	1000°C (1832°F)	Simulate Coiling	1.71	-0.46
	B	0.056	"	"	2.21	-0.19
	C	0.120	"	"	2.34	-0.23

* "Simulate Coiling" refers to fast cooling from the finishing temperature to 620°C (~1150°F) by immediately dipping the hot-rolled band into iced water for 1.5 sec, followed by furnace cooling from 620°C to room temperature at a rate of 40°C/hr.

Table IV

Texture and Grain Size of the Hot-Rolled Bands

				X-ray Intensity, random units					Grain Size	
Heat No.	Steel	P, wt%	Section	(110)	(200)	(211)	(310)	(222)	μm	ASTM
7261-8001 (Vac-Melts)	A	0.120	s	1.17	1.55	1.31	1.37	1.22	20	8.0
			1/4 t	0.81	1.86	1.49	1.39	1.93	11	9.7
			1/2 t	0.61	2.02	1.70	1.30	2.10	14	9.0
	B	0.092	s	0.90	2.15	1.46	1.31	1.64	18	8.3
			1/4 t	0.80	1.74	1.46	1.37	1.89	12	9.5
			1/2 t	0.66	1.92	1.79	1.23	1.87	15	8.8
	C	0.062	s	0.89	1.91	1.50	1.33	1.50	17	8.5
			1/4 t	0.85	1.76	1.42	1.34	1.79	12	9.5
			1/2 t	0.70	1.89	1.72	1.29	1.98	15	8.8
	D	0.030	s	0.97	1.82	1.35	1.30	1.44	18	8.3
			1/4 t	0.69	1.65	1.58	1.25	1.98	16	8.6
			1/2 t	0.59	1.76	1.70	1.29	2.17	15	8.8
	E	0.015	s	1.05	1.40	1.38	1.32	1.27	18	8.3
			1/4 t	0.84	1.79	1.47	1.27	1.85	13	9.2
			1/2 t	0.71	1.96	1.62	1.23	2.26	14	9.0
	F	0.004	s	1.13	1.46	1.34	1.32	1.46	19	8.1
			1/4 t	0.76	1.80	1.49	1.26	1.81	17	8.5
			1/2 t	0.68	2.11	1.71	1.25	2.53	17	8.5

7261-8003 (Air-Melts Series I)	A	0.022	s	0.87	1.63	1.60	1.32	1.45	7	11.0
			1/4 t	0.83	2.43	1.49	1.25	1.78	10	10.0
			1/2 t	0.78	2.51	1.70	1.26	1.93	11	9.7
	B	0.056	s	0.95	1.56	1.50	1.28	1.41	9	10.3
			1/4 t	0.85	2.40	1.41	1.27	1.70	12	9.5
			1/2 t	0.62	2.40	1.96	1.15	2.14	11	9.7
	C	0.120	s	0.92	1.49	1.29	1.14	1.54	17	8.5
			1/4 t	0.59	2.17	1.63	1.23	2.13	11	9.7
			1/2 t	0.42	2.76	2.30	0.93	3.05	11	9.7
7261-8003(2) (Air-Melts Series II)	A	0.042	s	0.97	2.12	1.60	1.08	1.29	27	7.1
			1/4 t	0.62	1.85	1.79	1.21	1.90	12	9.5
			1/2 t	0.55	1.99	2.16	1.17	2.35	12	9.5
	B	0.080	s	0.90	1.85	1.40	1.38	1.33	18	8.3
			1/4 t	0.65	1.82	1.53	1.19	2.02	10	10.0
			1/2 t	0.41	3.09	2.19	0.90	2.91	11	9.7
	C	0.120	s	1.01	1.32	1.36	1.34	1.48	15	8.8
			1/4 t	0.54	2.37	1.71	1.15	2.43	11	9.7
			1/2 t	0.30	4.41	2.56	0.63	3.35	11	9.7

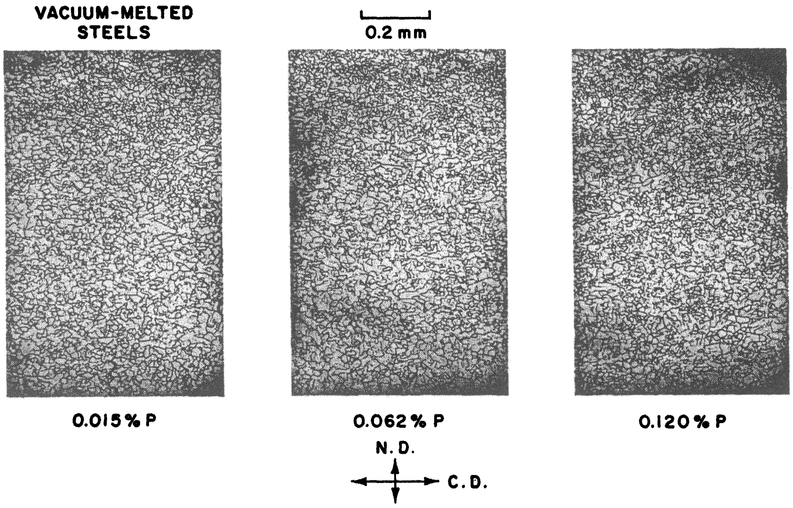

Figure 1A. Microstructures of the hot-rolled bands of vacuum-melted phosphorus-containing low-carbon (0.11% Mn) steels.

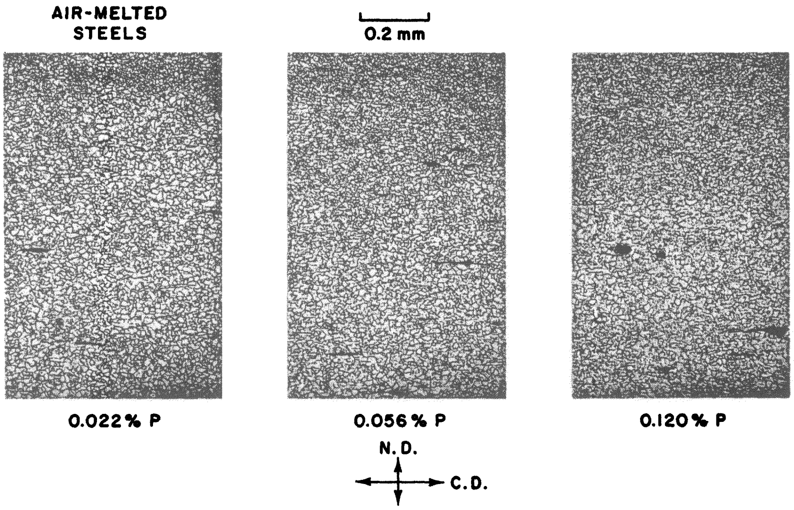

Figure 1B. Microstructures of the hot-rolled bands of air-melted phosphorus-containing low-carbon (0.11% Mn) steels.

are stronger at the midthickness section of the hot-rolled band than at its surface, whereas the opposite is true for the (110) and (310) orientations. With only a few exceptions, the (200) orientation also tends to be stronger at the midthickness section than at the surface. For most of the steels, the grain size is larger in the surface layer than in the interior sections; this is due presumably to decarburization. In consideration of the compositional variations among the steels, the overall consistency in this hot-rolling behavior under the specified conditions appears satisfactory.

Cold-Rolling Texture

After a reduction in thickness from 0.150 to 0.030 inch (3.8 to 0.76 mm) by cold rolling, the textures at the surface and at the midthickness section of the strip were examined. Table V lists the integrated X-ray

Table V

Texture of Cold-Rolled Strips

Heat No.	Steel	P, wt %	Section	X-ray Intensity, random units (110)	(200)	(211)	(310)	(222)
7261-8001 (Vac-Melts)	A	0.120	s	0.10	5.09	3.10	0.23	7.48
			1/2 t	0.17	3.81	2.39	0.24	6.59
	C	0.062	s	0.08	6.44	3.29	0.22	6.95
			1/2 t	0.15	3.83	2.51	0.23	6.90
	E	0.015	s	0.08	6.72	3.48	0.24	7.48
			1/2 t	0.14	4.10	2.61	0.19	7.22
7261-8003(2) (Air-Melts)	A	0.042	s	0.07	6.50	3.52	0.20	7.84
			1/2 t	0.14	3.76	2.62	0.20	6.79
	B	0.080	s	0.08	5.62	3.24	0.23	7.86
			1/2 t	0.14	3.97	2.45	0.22	6.59
7261-8003 (Air-Melts)	C	0.120	s	0.10	5.46	2.98	0.31	6.63
			1/2 t	0.15	4.03	2.37	0.26	6.24

peak intensities of the various reflections. As can be noted, the cold-rolling textures of the steels with various phosphorus contents are largely the same; small variations may have resulted from the texture variations that existed in the hot-rolled bands. The present results are largely consistent with an earlier observation of the nearly identical cold-rolling textures in low-carbon steels containing various levels of manganese.[7] It is expected that minor variations of the alloying elements should not significantly affect the basic deformation mechanisms of the steels, hence their deformation textures.

Effect of Annealing Temperature on Plastic Anisotropy

In essential agreement with the results obtained earlier[8] the r_m value of the phosphorus-containing low-carbon, low-manganese steels increases with the phosphorus content. For a given phosphorus concentration in the steel, the r_m value increases with the annealing temperature. The anisotropy parameters, r_m and Δr, of the vacuum-melted steels annealed 20 hours at 710, 780, and 820°C are shown in Figure 2 as a function of the phosphorus

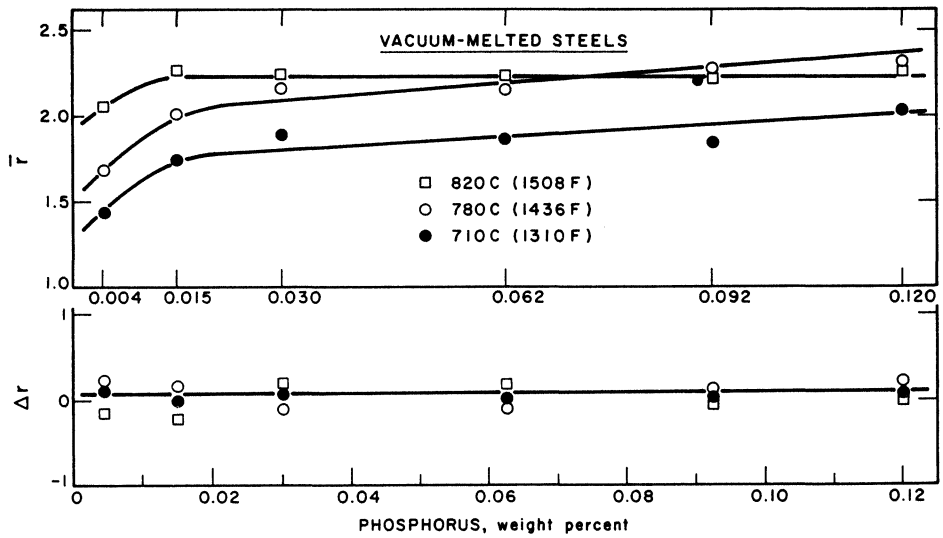

Figure 2. Effect of phosphorus on anisotropy parameters of vacuum-melted low-carbon steels. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at temperatures indicated.

content. These r_m and Δr values were determined from tension tests at a uniform elongation of 15 percent. The present results show that the r_m values for steels containing at least 0.015 percent phosphorus are about 2.20, and that Δr values are nearly equal to zero. These values are considerably superior to those of deep-drawing aluminum-killed or straight low-manganese, low-oxygen steels.[7]

For the air-melted steels, similar plots of the r_m and Δr values are shown in Figures 3 and 4. These results indicate that the beneficial effect of phosphorus on r_m goes through a maximum at the intermediate range of concentrations (approximately 0.04 to 0.08% P). At still higher phosphorus concentrations, the r_m values

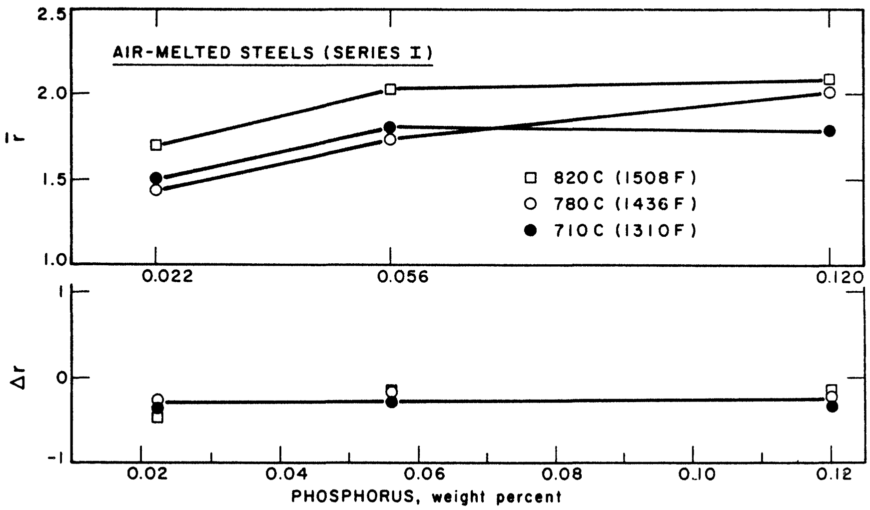

Figure 3. Effect of phosphorus on anisotropy parameters of air-melted low-carbon steels. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at temperatures indicated.

decline. However, the effect of phosphorus does not appear to be detrimental to the r_m values even at the highest concentration (0.12% P) as compared with the r_m values of low-carbon, low-manganese steels containing very little (<0.005% P) or no phosphorus. Within the favorable range of phosphorus concentrations (from ∿0.04 to 0.08%), the r_m values range from 2.00 to 2.20, and the Δr values from -0.2 to -0.3, if the steels are annealed at the intercritical temperatures. These values are also superior to those for aluminum-killed deep-drawing or straight low-manganese, low-oxygen steels.[7]

Texture of the Annealed Strips

In agreement with the excellent anisotropy parameters observed in the phosphorus-containing steels, their annealing textures consisted of predominantly (111), a little (112), and practically no other grain orientations which are undesirable for deep-drawing applications. These are shown in Figures 5A and 5B by the integrated X-ray peak intensities of various reflections measured from the plane of the sheet. These measurements were taken from the surface of the sheet. Textures at the mid-thickness section of the sheet are shown in Figures 6A and 6B by the (200) pole figures. The texture consisted predominantly of two complementary components of the (111)[112] orientations, and the continuous spreads between them effectively make the overall texture a [111] fiber

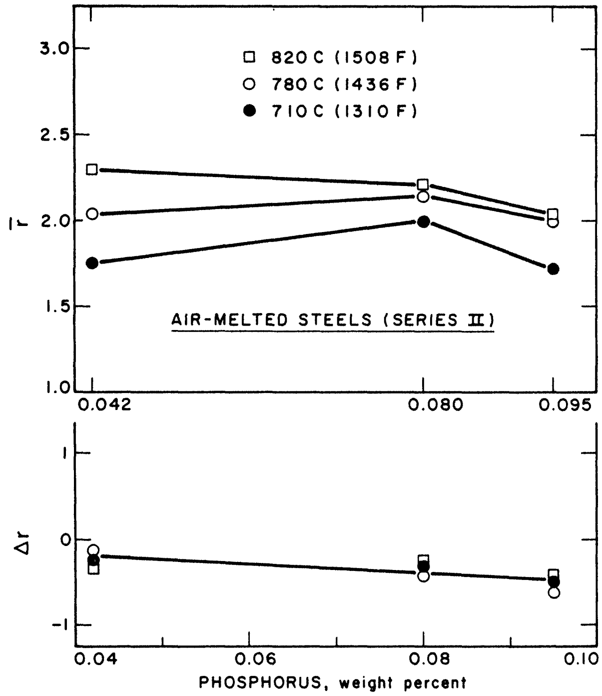

Figure 4. Effect of phosphorus on anisotropy parameters of air-melted low-carbon steels. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at temperatures indicated.

texture with the sheet-plane normal being the fiber axis. There are only very minor differences, mainly in intensity and sharpness, between the textures of the vacuum-melted steel (0.12% P) and the air-melted steel (0.042% P), both having an r_m value of nearly 2.30 (see Figures 2 and 4). These pole figures are significantly different from those of straight low-manganese steels[7] or aluminum-killed steels.[10]

It was mentioned earlier that in making the air-melted steels, aluminum was used to control rimming in solidification. The excellent r_m values observed in these steels could not have resulted from AℓN precipitates, as in aluminum-killed steels. Evidence in support of this statement is obvious: (1) the residual soluble-aluminum contents in these steels are twoo low (see Table II) to be effective in controlling the annealing textures; (2) the textures of the phosphorus-containing steels, as shown by the pole figures in Figures 6A and 6B are different from those of the aluminum-killed steels;[10] (3) the grains in the phosphorus-containing steels are equiaxed, whereas those in aluminum-killed steels are pancake-

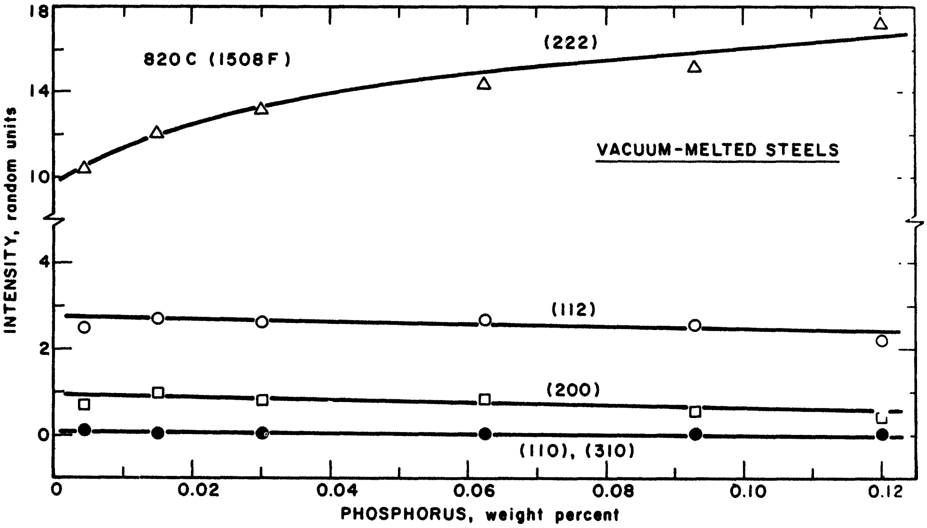

Figure 5A. Effect of phosphorus on annealing texture of vacuum-melted low-carbon steels. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at 820°C (1508°F).

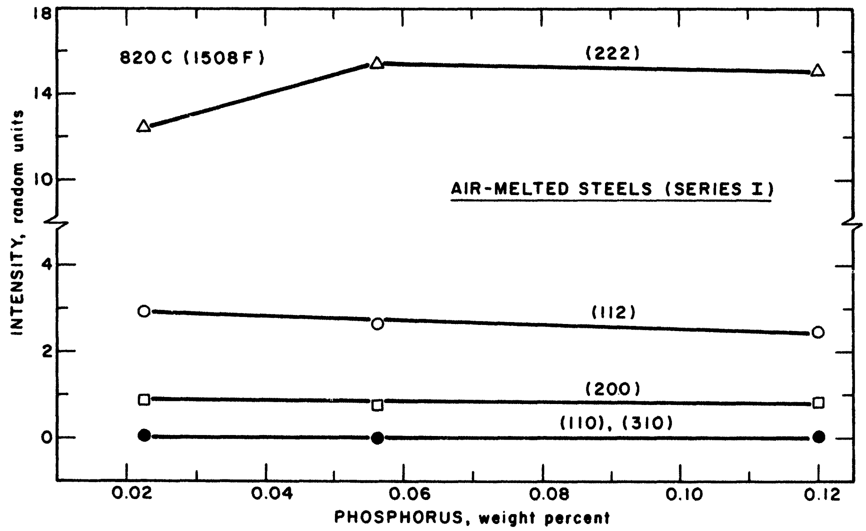

Figure 5B. Effect of phosphorus on annealing texture of air-melted low-carbon steels (Series I). Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at 820°C (1508°F).

shaped; (4) the r_m value of the air-melted steel containing the lease soluble aluminum aluminum [Steel B, Table II(B)] is considerably higher than that of the steel

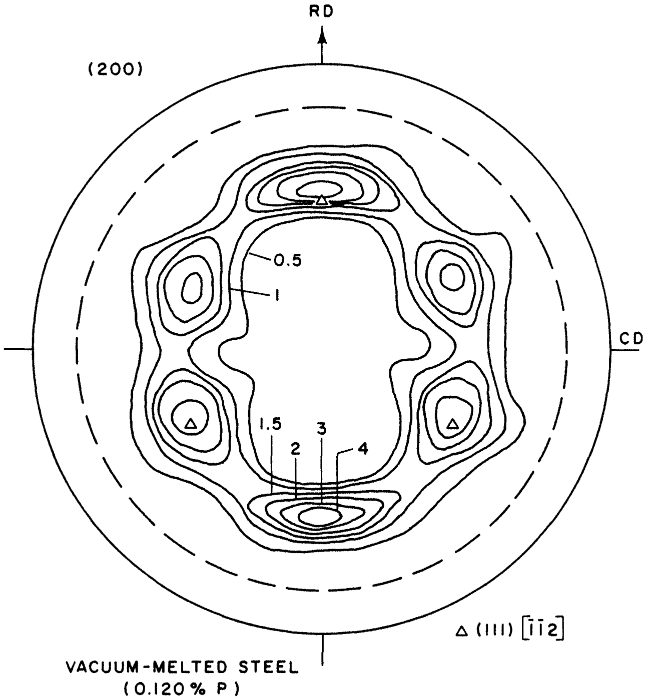

Figure 6A. Pole figure of vacuum-melted low-carbon steel containing 0.12% P. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at 820°C (1508°F)

containing the highest soluble aluminum [Steel A, Table II(A)]; and (5) the strain-aging characteristics of the present steels, as will be discussed in a later section, are typical of rimmed steels, whereas aluminum-killed steels are known to be nonaging.

Mayer and Wise[11] reported that the r_m value of unkilled steels (∿0.10% C, ∿0.40% Mn) was improved by the addition of phosphorus (0.03 to 0.09%), if the steels were processed by cold rolling 52 to 62 percent and by open-coil annealing to 698°C (1290°F) in a wet 18 percent $H_2 + N_2$ atmosphere to decarburize the steel to 0.004% C. The highest r_m value obtained by these authors was 1.36. Results of the present investigation showed that with a phosphorus concentration of 0.015 to 0.120 percent, r_m values much higher than those reported by Mayer and Wise[11] were obtained in low-carbon, low-manganese steels properly processed without decarburization during the final anneal. As shown by the chemical compositions of the steels before and after the final annealing of 20 hours at 820°C in 15 percent $H_2 + N_2$, there is no significant change in the carbon, phosphorus, sulfur, and nitrogen contents, Table VI.

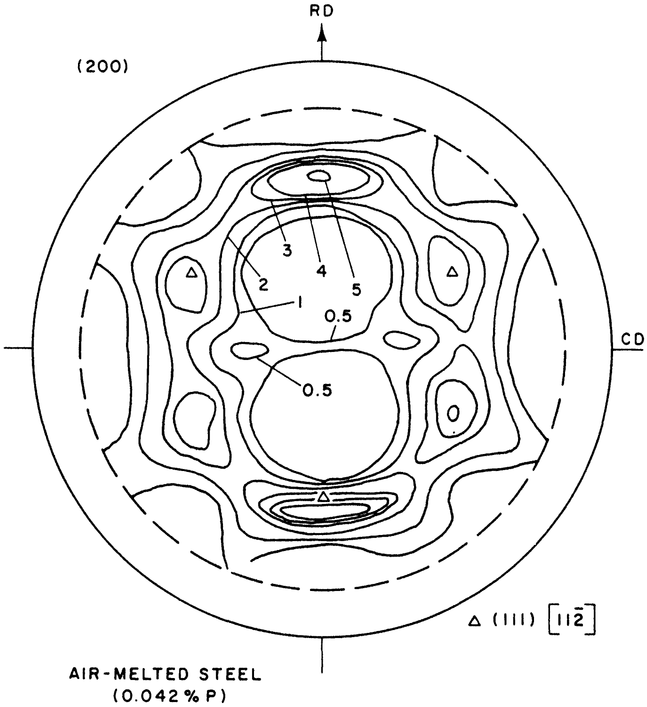

Figure 6B. Pole figure of air-melted low-carbon steel containing 0.042% P. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at 820°C (1508°F).

Table VI

Concentrations of Carbon, Phosphorus, Sulfur, and Nitrogen before and after Annealing

		Composition, wt %			
Steel	Condition	C	P	S	N
(vac-melt)					
A	Before anneal	0.017	0.120	0.017	0.004
	After anneal	0.014	0.120	0.016	0.004
C	Before anneal	0.019	0.063	0.016	0.004
	After anneal	0.017	0.063	0.015	0.003
E	Before anneal	0.020	0.015	0.016	0.004
	After anneal	0.019	0.016	0.016	0.004

Teshima and Shimizu[1] studied the effects of phosphorus in the range >0.01 to <0.06 percent and of phosphorus plus copper (∿0.2% Cu) on the r_m values of low-carbon steels, cold-rolled 70 to 75 percent and annealed in wet 18 percent H_2 + N_2 atmosphere for decarburization. They found that the r_m values were improved by such decarburization anneals.

The exact mechanism of how phosphorus influences the annealing textures of low-carbon, low-manganese steels is not yet clear. However, it is known[12,13] that phosphorus tends strongly to segregate at the grain boundaries in iron and mild steels. It was also shown by Leslie *et al.*[14] that a small amount of phosphorus markedly retards the recrystallization of high-purity iron, presumably because phosphorus segregation at the subgrain boundaries and grain boundaries inhibits recrystallization. Since the degree of solute segregation at the boundary would depend on the atomistic structure of the boundary, which is determined by the grain orientations across the boundary, the solute pinning effect would be different for different types of boundaries. On this basis, it is reasonable to expect that the annealing texture would be affected by a solute such as phosphorus.

The significance of intercritical annealing is believed to be largely an effect of the higher temperatures, which promote grain growth following complete recrystallization with less difficulty. Microscopic examinations of water-quenched thin specimens indicate that at 820°C the amount of austenite (shown as martensite in quenched specimens) in steels containing 0.015 to 0.120 percent phosphorus is only about 10 percent. During furnace cooling in the simulated box anneals, these austenite grains would be absorbed by the adjacent ferrite grains by boundary migration. That phosphorus has inhibited grain growth is indicated by the smaller grain size in the present steels as compared with the grain size in low-carbon, low-manganese steels without phosphorus. For example, the grain size of the vacuum-melted 0.10 percent manganese steel after the 710°C anneal is about ASTM 8.5,[7] whereas that of the present vacuum-melted steels containing phosphorus is ASTM 9.0 to 10.5, although the amount of cold-rolling reduction is higher.

Yield Strength and Grain Size of the Annealed Strips

The conventional lower yield stresses (applied load at the lower yield point divided by the original cross-section area) of the annealed strips are shown in Figures 7A to 7C. There is a gentle rise in strength with phosphorus as a consequence of solution hardening. For the vacuum-melted steels, Figure 7A, the yield stresses of the steel containing 0.004 percent phosphorus are even slightly higher than those of the steel having the next higher phosphorus content. This irregularity is believed to be due to its appreciably higher oxygen content (Steel

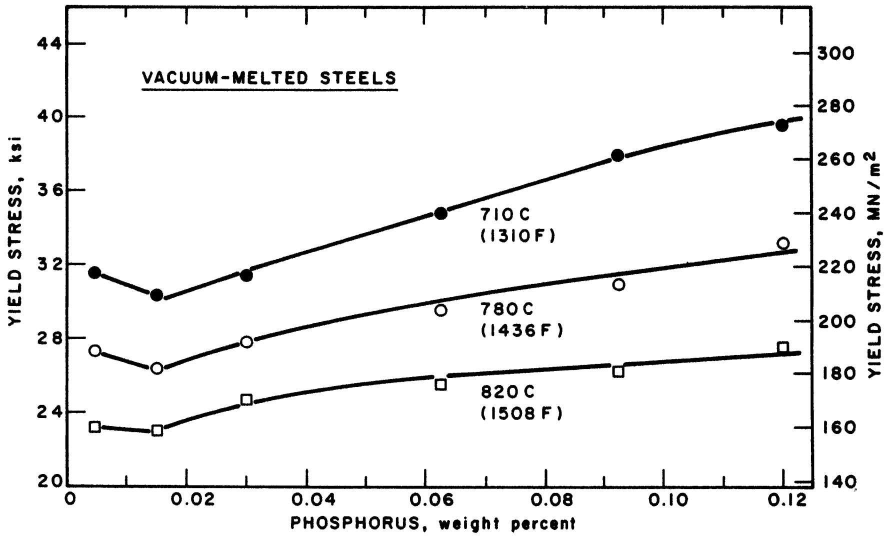

Figure 7A. Effect of phosphorus on the lower yield stress of vacuum-melted low-carbon steels. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at temperatures indicated.

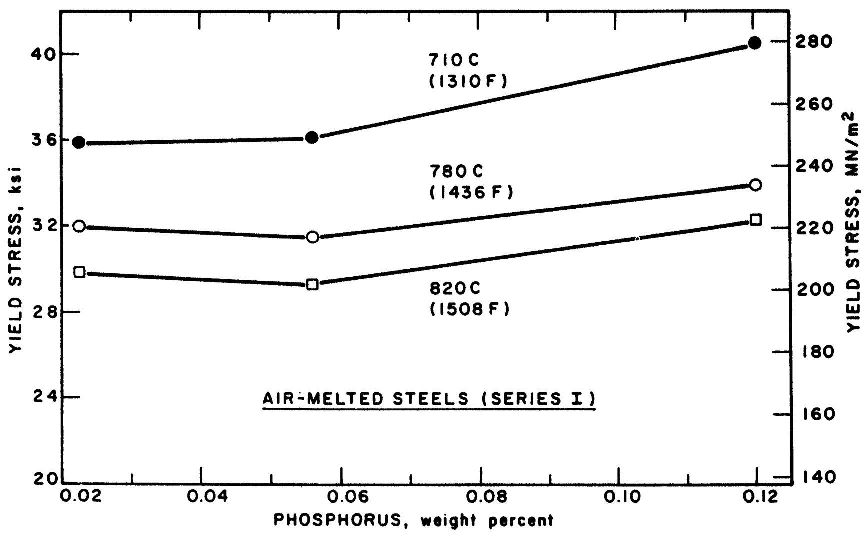

Figure 7B. Effect of phosphorus on the lower yield stress of air-melted low-carbon steels (Series I). Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at temperatures indicated.

F, Table I) than all the other steels in the series. As a function of the annealing temperature, corresponding steels are stronger after annealing at a lower temperature

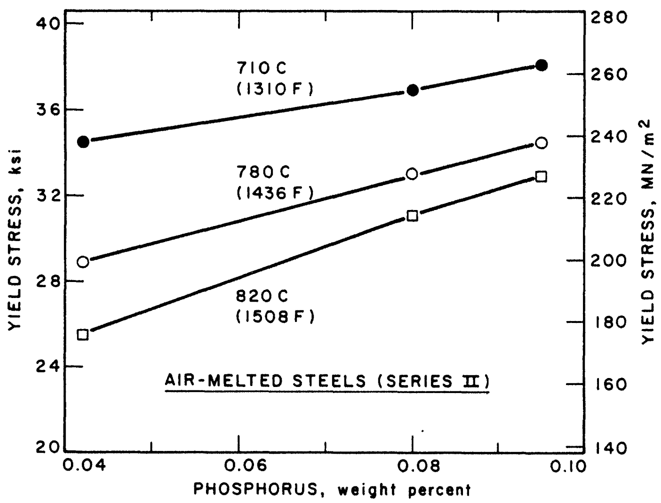

Figure 7C. Effect of phosphorus on the lower yield stress of air-melted low-carbon steels (Series II). Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at temperatures indicated.

than at a higher temperature, because the grain size is smaller. The same general features are shown by the air-melted series, Figures 7B and 7C. For the same annealing temperature, the grain sizes of the air-melted steels are finer than those of the vacuum-melted steels. As a consequence, the yield stresses of the air-melted steels are higher than those of the corresponding vacuum-melted steels. For the same annealing temperature, the grain size varies only slightly with the phosphorus content. The characteristics are indicated by the results in Table VII.

Table VII

Grain Size of Steels after Annealing at Various Temperatures

Steels	Grain Size, ASTM No. (After 20 hr at temperature) 710°C (1310°F)	780°C (1436°F)	820°C (1508°F)
Vacuum-melted	9.0 - 10.5 (14 - 10 μm)	7.0 - 8.0 (28 - 20 μm)	6.5 - 7.5 (34 - 24 μm)
Air-melted	10.0 - 11.0 (10 - 7 μm)	9.0 - 10.0 (14 - 10 μm)	7.5 - 9.0 (24 - 14 μm)

Since the grain-size data for a particular steel had only three points with the present annealing treatments, meaningful analyses of the yield-stress - grain-size relations could not be obtained for the steels individually. However, if the conventional yield stresses of all the steels are plotted as a function of $d^{-1/2}$, where d is the average grain diameter, all data points fall within a narrow band, as shown in Figure 8. The width of the scatter

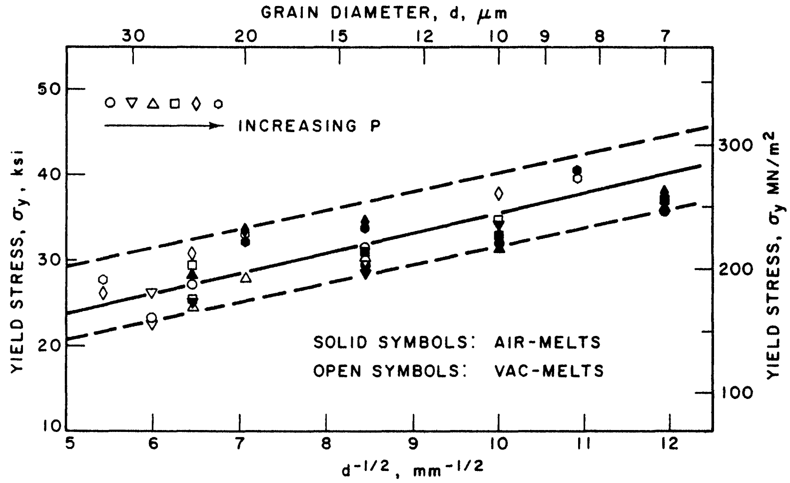

Figure 8. Relation between lower yield stress and grain size of phosphorus-containing low-carbon steels.

is less than 9 ksi. Consistent with the results shown in Figures 7A to 7C, the data points close to the upper bound are mostly from steels having the relatively high phosphorus concentrations. The full line represents a least-squares fit to the data, and corresponds to a Hall-Petch relation[15,16] of

$$\sigma_y = \sigma_o + k_y d^{-1/2} \quad (1)$$

where σ_o = 12.2 ksi, the intercept

k_y = 2.4 ksi/mm$^{-1/2}$, the slope, of the straight line

These results are in good agreement with the observations of Morrison[17] on low-carbon steels having various carbon concentrations. The plot in Figure 8 also shows that the air-melted steels have somewhat smaller grains than do the vacuum-melted steels.

Tensile Strength and Uniform Elongation

The ultimate tensile strength and uniform elongation of the steels were determined for the strips annealed at 820°C. Results for duplicate specimens taken at both 0 and 90 degrees to the rolling direction and averaged are shown in Figures 9A and 9B. As can be seen,

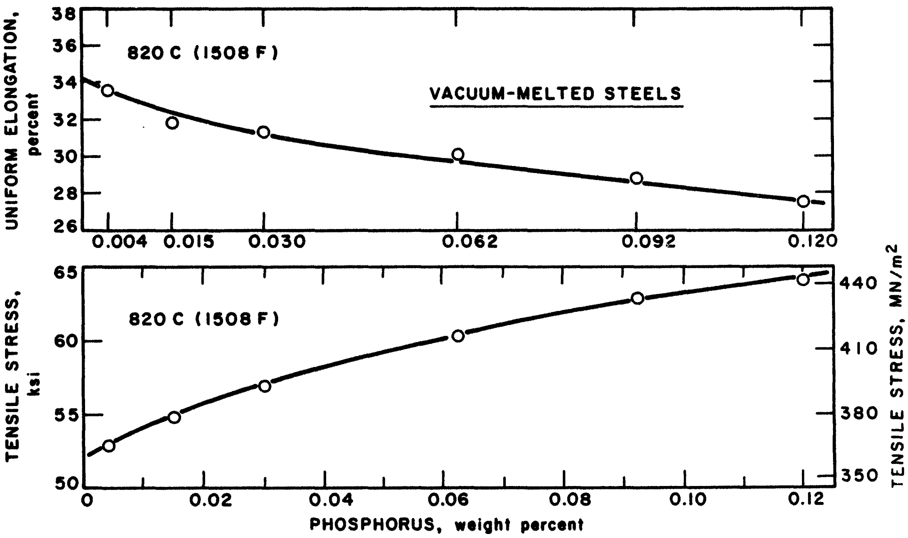

Figure 9A. Effect of phosphorus on uniform elongation and the ultimate tensile stress of vacuum-melted low-carbon steels. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at 820°C (1508°F).

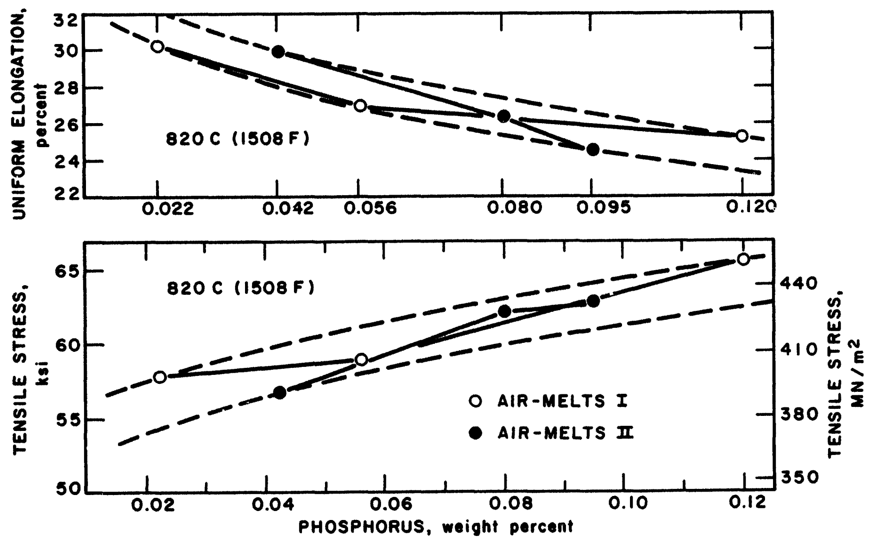

Figure 9B. Effect of phosphorus on uniform elongation and the ultimate tensile stress of air-melted low-carbon steels (Series I and II). Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at 820°C (1508°F).

the tensile stress increases, whereas the uniform elongation decreases, with increasing phosphorus. For the air-melted steels, the data are somewhat scattered, presumably because of the inconsistency in base composition and the variable distribution of the inclusions. However, the general trend of the narrow band of scatter is clearly indicated. The magnitude of elongation is notably lower for the air-melted steels than for the vacuum-melted steels (∿30%). The ultimate tensile stresses of the air-melted steels are slightly higher than those of the vacuum-melted steels, a consequence arising likely from the small difference in grain size.

Strain-Hardening and Strain-Aging Characteristics

The strain-hardening characteristics of the steels were examined by determining the true stress - true strain relations of the specimens pulled to necking. Duplicate specimens cut at both 0 and 90 degrees to the rolling direction of the strip and annealed at 820°C for 20 hours were tested. Results indicate that they all closely obey the empirical equation first proposed by Ludwik[18]

$$\sigma = K\varepsilon^n \tag{2}$$

where σ and ε = true stress and true strain, respectively

K and n = parameters depending on material.

In most cases, the log-log plot of true stress versus true strain within the range of homogeneous deformation (from the end of Lüder's strain, which is about 4% elongation, to necking strain or the end of uniform elongation) deviates from a single straight line at high strains. Similar observations were described by Morrison[17] as composed of two straight lines in the plot, or the "double n" behavior associated with the formation of cells. In other cases, a single straight line can be drawn through all the points. These are shown in Figure 10. For the double-n cases, the n value at low strains is usually higher than that at high strains, and the average of the two n values was taken as the strain-hardening exponent. There is very little difference in the n values of specimens from strips cut at 0 and 90 degrees to the rolling direction.

The upper curve of Figure 11 shows the average n values for all the steels annealed 20 hours at 820°C, as a function of the phosphorus content. There is a slight tendency for a decrease in the n value with increasing phosphorus. On the whole, the strain-hardening exponent of all these steels is approximately 0.30.

The strain-aging index, as defined by the percentage increase in the flow stress of the steels at 8 percent strain after aging 4 hours at 100°C (212°F), is shown in

H

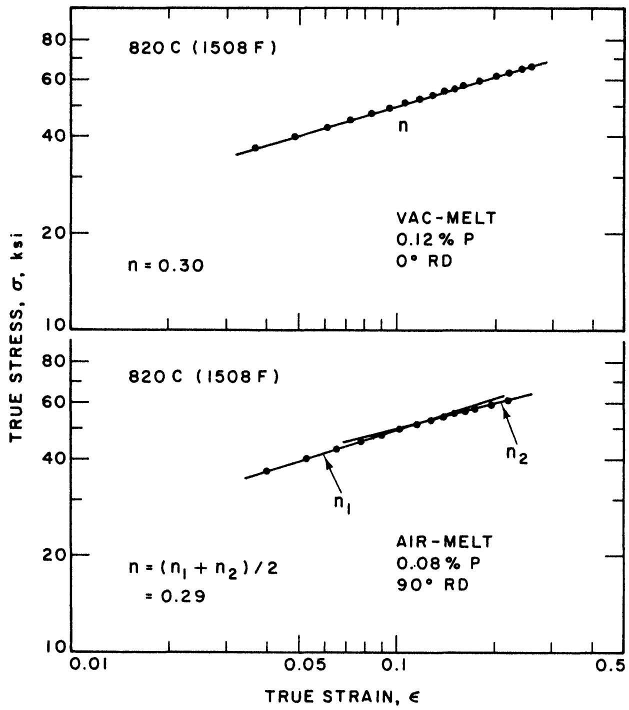

Figure 10. Strain-hardening characteristics of phosphorus-containing low-carbon steels. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at 820°C (1508°F).

the lower curve. The data points represent the average values for duplicate specimens taken at 0 and 90 degrees to the rolling direction after the simulated box anneal of 20 hours at 820°C. There appears to be a slight decrease in the strain-aging index with increasing phosphorus, from about 25 percent at 0.004 percent phosphorus to about 20 percent at 0.12 percent phosphorus. These values are typical of unkilled low-carbon steels.

Effect of Reheating Temperature for Hot Rolling on Anisotropy Parameters

All the results presented above were for 0.5-0.75-inch plates hot-rolled from a reheating temperature of 1230°C (∿2250°F) and finished at 975°C (1780°F) to 0.150 inch. To investigate whether the reheating temperature for hot rolling has any effect on the final properties, several additional experiments were conducted, and the properties of fully processed strips were tested. These were as follows:

1. The plates were reheated to 1150°C (∿2100°F) and hot-rolled with a finishing temperature of 975°C (1780°F).

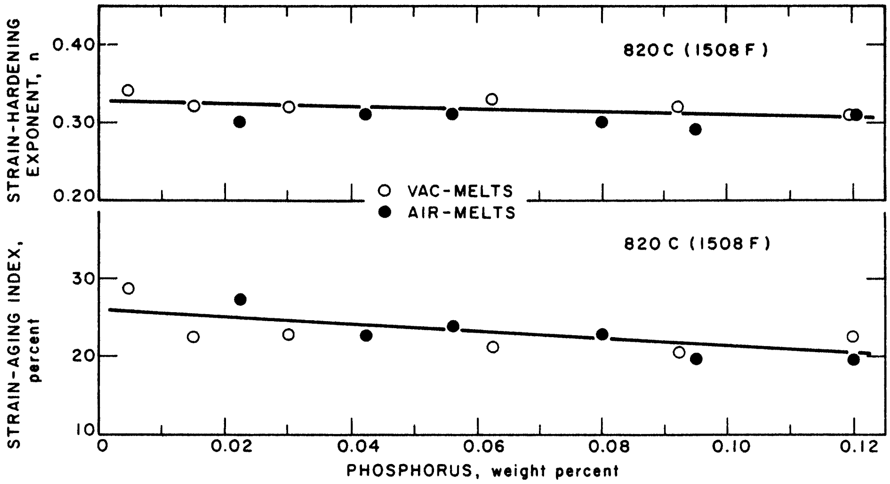

Figure 11. Effect of phosphorus on strain-hardening exponent and strain-aging index of low-carbon steels. Cold-rolled 80% to 0.030 inch (0.76 mm). Annealed 20 hours at 820°C (1508°F).

2. The plates were reheated to 1050°C (∿1920°F) and hot-rolled with a finishing temperature of 975°C.

3. The plates were reheated to 975°C and isothermally hot-rolled to finish by reheating the piece to temperature after each pass.

The properties of fully processed strips from all these experiments showed very little difference from the results presented heretofore. This indicates that with an appropriate finishing temperature, the temperature of reheating the plate for hot rolling is insignificant.

SUMMARY AND CONCLUSIONS

1. The effects of phosphorus on the annealing texture, plastic anisotropy, and mechanical properties of low-carbon (0.02%) low-manganese (0.11%) steels have been investigated. The steels, containing up to 0.12 percent phosphorus, were vacuum- and air-melted heats produced in the laboratory. These steels were hot-rolled to 0.150 inch, cold-rolled 80%, and annealed at temperatures ranging from 710°C (1310°F) to 820°C (1508°F) for 20 hours. Results show that phosphorus had substantially improved the anisotropy parameters, r_m and Δr, as well as increased the strengths of the steels. Annealing at the intercritical temperatures of 780 and 820°C (1436 and 1508°F) further improved the r_m and Δr values.

2. For the vacuum-melted steels, the increase in r_m was almost linear with the concentration of phosphorus

from 0.015 to 0.12 percent phosphorus. Annealing at a subcritical temperature of 710°C produced similar effects, although the r_m values were at appreciably lower levels. At high phosphorus concentrations, the r_m values were nearly the same upon annealing within the intercritical temperature range 780 to 820°C. The planar anisotropy parameter, Δr, was for all the vacuum-melted steels very small, being close to zero.

3. For the air-melted steels, the increase in r_m with increasing phosphorus appeared to go through a maximum at intermediate phosphorus concentrations (~0.04 to 0.08% P). Within this range of phosphorus, the r_m values were as high as 2.20 for steels annealed at 820°C. These r_m values are comparable in magnitude to those of the vacuum-melted steels. The absolute values of Δr of the air-melted steels (around 0.2 and 0.3) were somewhat higher than those of the vacuum-melted steels. These anisotropy parameters are considerably superior to those of deep-drawing aluminum-killed steels.

4. Responsible for the excellent anisotropy parameters of the phosphorus-containing steels are their annealing textures, which were predominantly $(111)[\bar{1}\bar{1}2]$ and $(111)[11\bar{2}]$. These orientations plus their spreads effectively made the texture nearly equivalent to a [111] fiber texture with the sheet-plane normal as the fiber axis. These annealing textures differed in detail from those of straight low-carbon, low-manganese steels or the aluminum-killed steels, and suggested that the mechanism of annealing-texture formation in phosphorus-containing steels is different from that in low-manganese or aluminum-killed steels.

5. On the basis of a strong tendency for phosphorus to segregate at the grain boundaries and subgrain boundaries in iron and steel, the annealing textures would be expected to be influenced by the consequences of such boundary segregations. It is known that solute segregation at the boundary retards the mobility of the boundary, and that the degree of segregation, or inhibition, for a given solute concentration depends on the atomistic structure, or the type, of the boundary. Hence, the nucleation of recrystallized grains and their subsequent growth would be influenced preferentially, leading to an annealing texture characteristic of the segregating solute and the processing treatments.

6. The grain size and mechanical properties such as yield stress, uniform elongation, strain-hardening exponent, and strain-aging index of the phosphorus-containing steels were comparable with, or better than, those of low-carbon rimmed steels. Results of the present investigation also indicated that phosphorus not only raised the manganese limit for high r_m values, but also increased the tolerance of the steels to relatively high oxygen levels.

ACKNOWLEDGMENTS

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