EFFECT OF CARBON CONTENT ON ANNEALING TEXTURE, PLASTIC ANISOTROPY, AND MECHANICAL PROPERTIES OF 0.07% PHOSPHORUS SHEET STEELS

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Abstract: The effects of carbon content on the crystallographic texture, plastic anisotropy, and mechanical properties of cold-rolled and annealed sheets of 0.07 percent phosphorus steels have been studied. Both vacuum- and air-melted laboratory heats were used. Results show that although the strength of the sheet increased with increasing carbon content, the r_m value decreased. The detrimental effect of carbon on r_m value was more pronounced after annealing at an intercritical temperature of 780°C (1435°F) than at a subcritical temperature of 710°C (1310°F). These and other observations, including variations in texture, anisotropy, strength, work hardening, and grain size, are discussed.

INTRODUCTION

It was reported earlier^{1*} that excellent deep-drawing properties, as indicated by the high r_m and low Δr values of the sheet, could be produced in vacuum-melted or air-melted low-carbon low-manganese steels containing phosphorus, when hot-rolled bands 3.8 mm (0.150 in.) in thickness were cold-rolled 80 percent, with simulated box annealing at an intercritical or a subcritical temperature. It was also shown² that with a concentration of 0.067 percent phosphorus in the low-carbon (0.03%) steel, a higher manganese level could be tolerated without adversely affecting the high r_m values of the steel.

For example, the r_m values of the vacuum-melted phosphorus-containing (0.067% P) steels having a manganese concentration of 0.21 percent were approximately 1.65 and 1.86 when the steels were annealed at a subcritical temperature of 710°C (1310°F) and an intercritical temperature of 780°C (1435°F), respectively. For a similar steel containing 0.20 percent manganese but without a phosphorus addition³ the r_m value was only about 1.35 after annealing at 710°C (1310°F). In the

*See References.

air-melted phosphorus-containing (0.067% P) steel having a manganese content of 0.25 percent, the r_m values were even higher than those of the vacuum-melted counterpart, being approximately 1.90 and 2.20, respectively, after the 710°C and 780°C anneals.

These results indicated that the addition of phosphorus to low-carbon steels not only improved the plastic anisotropy parameters (r_m and Δr values), but also reduced the generally observed detrimental effects of oxygen and manganese on these anisotropic properties. The possibility of complex interactions of manganese with other solute elements, and the potent effect of phosphorus as a grain-boundary segregant in steel on recrystallization texture formation have been discussed previously.¹⁻³ As would be expected, the strength of the steels was also improved by the addition of phosphorus because phosphorus is a strong solution-strengthener in iron and steel.

As an extension of this earlier work, the effect of carbon content on the annealing texture, plastic anisotropy, and mechanical properties of such steels containing 0.07 percent phosphorus and 0.20 percent manganese has been studied. Results of these studies are presented in this paper.

MATERIALS AND EXPERIMENTAL WORK

Vacuum-Melted and Air-Melted Steels

Four or five levels of carbon, ranging from 0.02 to 0.11 percent, were selected in making the vacuum-melted and air-melted heats having an aim base composition of about 0.20 percent Mn, 0.07 percent P, and 0.03 percent Si, with residual levels of other elements. A 90.8-kg (200 lb) split heat was melted in vacuum and was cast into four 22.7-kg (50 lb) ingots, 7.5 by 14 by 25 cm (3 by 5½ by 10 in.), each with a different concentration of carbon. The air-melted steels were produced from individual 45.5-kg (100 lb) heats with the same aim compositions as the vacuum-melted steels, and were cast into ingots 7.5 by 20 by 36 cm (3 by 8 by 14 in.). To control the rimming action during solidification, small amounts of aluminum were added to the air-melted steels. The amount of aluminum added was so small that it had no detectable effect on the annealing behavior or the texture development of these steels.

As shown in Table I, the vacuum-melted steels had a consistent and satisfactory base composition except for the higher oxygen in Steel A. The air-melted steels, however, showed appreciable variations in the concentrations of silicon, aluminum, and nickel (in higher than normal levels), Table II. The silicon content was substantially higher in the air-melted than in the vacuum-melted steels. For most of the elements, the variations in concentration between the top and bottom of the ingots were rather small.

TABLE I
Chemical Compositions of the Vacuum-Melted, Phosphorus-Containing Steels, Weight Percent

Steel	C	Mn	P	S	Si	Cu	Ni	Cr	Alsol	Alttotal	N	O* ppm
7364-8010												
A T	0.019	0.24	0.071	0.020	0.032	0.005	0.020	0.022	0.001	<0.002	0.004	158
B	0.019	0.24	0.074	0.021	0.032	0.005	0.022	0.022	0.001	<0.002	0.004	177
B T	0.046	0.23	0.071	0.021	0.030	0.005	0.020	0.022	<0.001	<0.002	0.004	95
B	0.044	0.23	0.070	0.020	0.024	0.005	0.018	0.020	<0.001	<0.002	0.004	81
C T	0.070	0.24	0.073	0.022	0.034	0.005	0.022	0.022	<0.001	<0.002	0.005	77
B	0.068	0.24	0.068	0.020	0.030	0.005	0.022	0.022	<0.001	0.002	0.004	74
D T	0.092	0.23	0.069	0.021	0.030	0.005	0.022	0.022	<0.001	<0.002	0.006	64
B	0.092	0.24	0.066	0.019	0.030	0.005	0.022	0.022	<0.001	<0.002	0.005	49

T and B denote top and bottom of ingot.

*These oxygen contents are appreciably higher than generally expected for vacuum-melt heats (~50 ppm).

TABLE II
Chemical Compositions of the Air-Melted, Phosphorus-Containing Steels, Weight Percent

Steel	C	Mn	P	S	Si	Cu	Ni	Cr	Alsol	Altotal	N	Oppm
7364-8011												
2A T	0.025	0.21	0.075	0.025	0.076	0.015	0.10	0.024	0.007	0.010	0.003	425
B	0.025	0.21	0.076	0.026	0.078	0.012	0.10	0.024	0.007	0.012	0.003	488
B T	0.029	0.21	0.070	0.025	0.062	0.005	0.046	0.020	0.008	0.017	0.003	566
B	0.028	0.19	0.069	0.025	0.033	0.010	0.050	0.020	0.009	0.020	0.003	430
2B T	0.051	0.21	0.078	0.024	0.067	0.012	0.10	0.024	0.005	0.015	0.003	337
B	0.048	0.21	0.075	0.025	0.073	0.012	0.10	0.024	0.005	0.014	0.003	343
D T	0.089	0.20	0.070	0.025	0.044	0.010	0.050	0.022	0.006	0.014	0.004	482
B	0.091	0.21	0.071	0.024	0.041	0.010	0.054	0.024	0.011	0.026	0.004	458
2C T	0.11	0.21	0.078	0.024	0.063	0.012	0.10	0.024	0.002	0.009	0.003	276
B	0.11	0.21	0.075	0.025	0.065	0.012	0.10	0.024	0.002	0.009	0.003	211

T and B denote top and bottom of ingot.

Hot-Processing Procedures

The hot-processing procedures for the present steels were essentially the same as those employed in previous investigations.^{1,2} For the vacuum-melted steels, the ingots were heated to 1230°C (2250°F) and hot-forged on all four sides to approximately 70 by 110 mm (2-3/4 by 4-1/2 in.) in cross section. The forged pieces were then reheated to 1230°C, hot-rolled from 70 to 12.5 mm (2-3/4 to 0.5 in.) in thickness, and air-cooled. Samples for chemical analysis were cut from the 12.5-mm plate at locations corresponding to the top and bottom of the ingot. Final hot rolling was accomplished by reheating the 12.5-mm plate to 1230°C and hot rolling to 3.8 mm (0.150 in.) with a finishing temperature of 925°C (1700°F). The hot-rolled band was cooled by water spray at the exit of the finishing pass to a temperature of approximately 620°C (1150°F), then furnace-cooled at about 40°C (75°F) per hour to simulate the coil-cooling conditions.

For the air-melted steels, no hot forging was applied to the ingots. After reheating to 1230°C, the ingots were hot-rolled from 76 to 25 mm (3 to 1 in.) in thickness and air-cooled. Samples were cut from the 25-mm plate at locations corresponding to the top and bottom of the ingot for chemical analysis. The final hot rolling from 25 to 3.8 mm was conducted in a manner similar to that described for the vacuum-melted steels.

Cold Rolling and Annealing

After the hot-rolled bands were cleaned by sandblasting and pickling, they were cold-reduced approximately 80 percent to 0.76 mm (0.030 in.). Tension specimens were machined from blanks cut from the cold-rolled strips at 0, 45, and 90 degrees to the rolling direction. These specimens were then annealed in loose packs in 15 percent H₂ + N₂ by heating at a rate of 20 to 25°C (36 to 45°F) per hour to 710 or 780°C, held at temperature for 20 hours, and furnace-cooled. These heating and cooling conditions have been employed in the laboratory to simulate commercial box-annealing practice. The lower temperature anneal (710°C) is a subcritical anneal, whereas the higher temperature anneal (780°C) is an intercritical anneal.

The anisotropy parameters, $r_m = (r_0 + 2r_{45} + r_{90})/4$ and $\Delta r = (r_0 + r_{90} - 2r_{45})/2$, where the subscripts denote the angles from the rolling direction of the strip, were determined along with other mechanical properties from uniaxial tension tests.

RESULTS AND DISCUSSION

Microstructure and Crystallographic Texture of Hot-Rolled Bands

The microstructure of the hot-rolled bands indicated that all these steels were completely recrystallized with equiaxed grains. For both the vacuum-melted and the air-melted steels,

some variations in grain size from the surface to the midthickness positions were evident, Table III. In general, the grain size of the subsurface layer was appreciably finer than that of either the surface or the interior of the hot-rolled bands. With increasing carbon content in the steel, the average grain size decreased, and the amount of carbide and pearlite colonies increased. For the air-melted steels with low carbon contents, many oxide inclusions and some stringer-type inclusions were present. These microstructural features were what might be expected.

The crystallographic textures of the hot-rolled bands were examined by X-ray peak intensity measurements at the surface, at the quarterthickness, and at the midthickness. The results are shown in Table III. It can be seen that the textures of the hot-rolled bands were not random and that there were definite variations of the texture from the surface to the interior of the hot-rolled band. In general, the (110) intensity was stronger at the surface and quarterthickness than at the midthickness, whereas the (200) intensity was strongest at the midthickness. There was some tendency for the (222) intensity to be weaker at the quarterthickness, where the grains were finer, than at either the surface or the midthickness locations. The (211) intensity varied very little through the thickness of the specimen, and the (310) intensity showed a tendency to increase from the surface to the interior. These features were largely consistent with previous observations on phosphorus-containing steels.^{1,2}

Texture of Cold-Rolled Strips

The crystallographic textures of the cold-rolled strips, after a reduction in thickness of 80 percent from 3.8 to 0.76 mm (0.150 to 0.030 in.), were examined at the surface and the midthickness. The textures were typical of low-carbon steels and similar to those reported previously,^{1,2} being most strong in (222), fairly strong in (200) and (211), but very weak in (110) and (310) orientations in the plane of the sheet. There were only minor differences between the textures at the surface and the midthickness sections.

Texture of the Annealed Strips

The textures of the annealed strips were examined by X-ray peak intensity measurements as well as by pole figures determined from the {200} reflection. The nature of the texture was largely similar for both the vacuum-melted and the air-melted steels, and for the subcritically and intercritically (710 and 780°C) annealed materials, the main difference being in the degree or sharpness of the (111)[112] texture. As shown in Figures 1A and 1B, which were determined from the specimens of the vacuum-melted steels containing 0.019 and 0.068 percent carbon, respectively, after a simulated box anneal at 710°C for 20 hours, the texture is mainly (111)[112]. The steel having the lower carbon content developed a stronger texture (Figure 1A) than the higher carbon steel (Figure 1B). The same effect can be noted for the air-melted steels, as

TABLE III

Texture and Grain Size of the Hot-Rolled Bands

Steel	Section*	X-Ray Intensity, random units					Grain Size	
		(110)	(200)	(211)	(310)	(222)	μm	ASTM
Vacuum-Melted 7364-8010								
A	S	1.36	0.43	1.41	0.58	1.13	17.0	8.5
	1/4 t	1.63	0.78	0.98	1.01	0.60	10.0	10.0
	1/2 t	0.87	1.39	1.18	1.13	1.27	10.5	9.0
B	S	1.32	0.73	1.30	0.75	1.16	10.5	9.0
	1/4 t	1.45	0.86	0.96	1.04	0.60	7.0	11.0
	1/2 t	0.62	1.64	1.33	1.07	1.79	10.5	9.0
C	S	1.39	0.73	1.16	0.94	1.02	17.0	8.5
	1/4 t	1.42	0.90	1.03	1.04	0.75	7.0	11.0
	1/2 t	0.72	1.88	1.24	1.02	1.76	10.0	10.0
D	S	1.37	0.78	1.14	0.95	1.01	10.5	9.0
	1/4 t	1.17	1.12	1.05	1.08	0.90	5.0	12.0
	1/2 t	0.63	1.76	1.32	1.00	1.78	8.5	10.5
Air-Melted 7364-8011								
2A	S	1.34	0.75	1.13	0.85	0.94	10.5	9.0
	1/4 t	1.58	0.69	0.97	0.96	0.52	12.0	9.5
	1/2 t	0.97	1.19	1.13	1.02	0.93	10.5	9.0
B	S	1.54	0.84	0.96	0.95	0.72	10.5	9.0
	1/4 t	1.11	1.12	1.08	1.13	1.01	10.0	10.0
	1/2 t	0.98	2.03	1.03	1.05	1.12	17.0	8.5
2B	S	1.59	0.43	0.99	0.69	0.71	10.5	9.0
	1/4 t	1.38	0.89	1.05	1.05	0.74	12.0	9.5
	1/2 t	1.08	2.00	0.99	1.02	1.26	10.5	9.0
D	S	1.45	0.84	1.19	0.91	0.90	12.0	9.5
	1/4 t	1.47	0.84	1.05	1.10	0.83	7.0	11.0
	1/2 t	1.11	1.93	1.06	1.03	1.23	10.0	10.0
2C	S	2.21	0.66	1.14	1.12	0.45	10.0	10.0
	1/4 t	1.23	1.03	1.09	1.03	0.88	8.5	10.5
	1/2 t	1.12	2.08	0.98	1.04	1.45	10.0	10.0

*S = surface, 1/4 t = quarterthickness below surface, and 1/2 t = midthickness.

Figure 1A. Pole figure of vacuum-melted phosphorus steel containing 0.019% C, annealed at 710°C (1310°F).

Figure 1B. Pole figure of vacuum-melted phosphorus steel containing 0.069% C, annealed at 710°C (1310°F).

shown by Figures 2A and 2B, which represent the textures of the steels containing 0.025 and 0.110 percent carbon respectively.

Figure 2A. Pole figure of air-melted phosphorus steel containing 0.025% C, annealed at 710°C (1310°F).

Figure 2B. Pole figure of air-melted phosphorus steel containing 0.11% C, annealed at 710°C (1310°F).

Similar effects were also observed for specimens annealed at 780°C. These results indicate that increasing the carbon content tends to deteriorate the (111)[112] texture of the annealed sheet.

Plastic-Anisotropy Parameters

The plastic-anisotropy parameters, r_m and Δr , of the annealed strips are shown in Figure 3 as a function of the carbon content. The r_m value decreased with increasing carbon,

Figure 3. Effect of carbon content on anisotropy parameters of phosphorus steel.

which is consistent with the texture data shown by the pole figures (Figures 1 and 2). The deteriorating effect of carbon on r_m was more pronounced for specimens annealed at the higher than at the lower temperature. This is understandable on the basis that the amount of austenite at an intercritical annealing temperature (780°C) will be larger for higher carbon contents, and that the austenite grains, when present in relatively large volume fractions, will not transform completely upon furnace cooling by the migration of interphase boundaries. The transformation of austenite to ferrite (plus carbide) within the austenite grains will result in orientations differing widely from those of existing ferrite grains. Thus, an inferior texture will be obtained. The present observation is, therefore, consistent with the interpretation advanced earlier¹ that the significance of intercritical

annealing is largely an effect of the higher temperature, which promotes grain growth of the ferrite when the austenite phase is present only in small amounts.

For specimens annealed at the subcritical temperature 710°C, the decrease of r_m value with increasing carbon content can also be explained. As mentioned earlier, the amount of carbide and pearlite colonies in the hot-rolled band increased with the carbon content of the steel. Nucleation of recrystallized grains occurs frequently adjacent to second-phase particles, where deformation is severe and highly inhomogeneous.⁴ The orientations of the recrystallized grains formed adjacent to the carbide or cementite particles are more random.⁵ Thus, the recrystallization texture of the steels with higher carbon contents tends to be less strongly developed (Figures 1B and 2B). Consequently, the r_m value decreases.

In addition to the effects of phase transformation (for intercritical annealing) and of nucleation for recrystallization (for both intercritical and subcritical annealing) on the texture and r_m value of the steels as discussed above, the extent of ferrite grain growth will also be affected by the carbide particles. During the long-time box-annealing treatment, some grain growth usually occurs after recrystallization is complete. In the presence of numerous carbide particles, such as in the higher carbon steels, grain growth will be more inhibited than in the presence of only a few carbide particles in the very-low-carbon steels. The grain size data, as shown in Figure 4, appear to be consistent with this

Figure 4. Effect of carbon content on the grain size of phosphorus steel.

interpretation. Figure 4 shows also that the grain size of the vacuum-melted steels was larger than that of the air-melted steels. This agrees with r_m values (Figure 3) in that more extended grain growth leads to stronger texture, hence higher plastic-strain ratios.

The carbon content of the 0.07 percent phosphorus steels had essentially no effect on the planar anisotropy parameter, Δr , as the top curve in Figure 3 shows. This indicates that the nature of the texture is essentially the same for the range of carbon contents studied. It is the degree of the texture that influenced the normal anisotropy parameter, r_m , depending upon the carbon content. This, again, appears to be consistent with the texture data (Figures 1A and 1B, or Figures 2A and 2B). The Δr values of the present steels were small, a feature characteristic of phosphorus-containing low-carbon steels.^{1,2}

The present results indicate that to produce phosphorus-containing steel sheets with high r_m values (1.5 or greater), hence good drawing properties, the carbon content should be no more than about 0.05 percent for air-melted steels to be annealed at 710°C and no more than about 0.07 percent for vacuum-melted steels to be annealed at 780°C.

Yield and Tensile Strengths of the Annealed Strips

The lower yield point and ultimate tensile strength of the specimens annealed at 780°C are shown in Figure 5. As

Figure 5. Effect of carbon content on the strength of phosphorus steel (simulated box-annealed at 780°C or 1435°F).

would be expected, the strengths of the steels increased with carbon content. The yield strength increased from about 207 MPa (30 ksi) at 0.02 percent carbon to about 262 MPa (38 ksi) at 0.11 percent carbon, and the tensile strength, from 344 to 379 MPa (50 to 55 ksi) for the same carbon increments. Figure 5 also shows that the strengths of the air-melted steels were

somewhat higher than those of the vacuum-melted steels. These values are in good agreement with earlier observations,^{1,2} even though the oxygen contents of the present vacuum-melted steels were appreciably higher than those in previously studied vacuum-melted steels (~50 ppm oxygen or less).

For the specimens annealed at 710°C, tension tests were conducted only for the determination of the r_m and Δr values by straining to 15 percent elongation. Limited data on the yield strength as a function of the carbon content showed that annealing at 710°C produced effects similar to those observed for samples annealed at 780°C, but that the strengths were slightly higher.

Yield-Strength and Grain-Size Correlations

The yield strengths of the present steels can generally be correlated with their grain size by a Hall-Petch type relation,^{6,7} as shown in Figure 6. Within a narrow band

Figure 6. Relation between yield strength and grain size of phosphorus steels.

of scatter of about 34.5 MPa (5 ksi), the average yield strength, as represented by the full line, corresponds to the equation

$$\sigma_y = \sigma_0 + K_y d^{-1/2} = 77.2 + 20.7 d^{-1/2}$$

where σ_y is the yield strength in MPa

d is the grain diameter in mm.

The intercept, or the frictional stress, $\sigma_0 = 77.2$ MPa (11.2 ksi), and the slope, $K_y = 20.7$ MPa (3.0 ksi)/mm^{-1/2}, are similar to those of low-carbon low-manganese steels containing various concentrations of phosphorus [$\sigma_0 = 84.1$ MPa (12.2 ksi), and $K_y = 16.5$ MPa (2.4 ksi)/mm^{-1/2}].¹

In comparison with the low-carbon phosphorus steels having various manganese contents,² the intercept, or σ_0 , of the

present steels is considerably greater (77.2 vs 31.0 MPa or 11.2 vs 4.5 ksi), although the slope or K_y value is approximately the same (20.7 vs 22.4 MPa/mm^{-1/2} or 3.0 vs 3.25 ksi/mm^{-1/2}). It should be pointed out, however, that the grain size of the present steels decreased with increasing carbon content, but that of the steels with manganese additions increased with increasing manganese content.² Thus, a meaningful discussion of the K_y values as influenced by the alloying elements would be very difficult. The physical meaning of these Hall-Petch parameters, σ_0 and K_y , has been discussed extensively by Li and Chou⁸; and the wide applicability of the Hall-Petch relation has been reviewed recently by Armstrong.⁹

Ductility, Strain-Hardening, and Strain-Aging Properties of the Annealed Strips

Figure 7 shows the ductility (uniform elongation), the strain-hardening exponent (n in $\sigma = K\epsilon^n$, where σ and ϵ are

Figure 7. Effect of carbon content on the ductility*, strain-hardening exponent and strain-aging index of phosphorus steel.

true strain and true stress), and the strain-aging index** of the strips annealed at 780°C as a function of the carbon

*Premature necking occurred in two of the air-melted specimens due to surface defects.

**The percentage increase in flow stress after aging the prestrained (8% in tension) specimens at 100°C (212°F) for 4 hours.

content of the steels. There was a slight tendency for the n value to decrease with increasing carbon content, which can be explained on the basis that n decreases with decreasing grain size, or with increasing yield or flow stress.¹⁰ The uniform elongation and the strain-aging index were very little affected by the carbon content within the range studied. For each of these properties, the data points of both vacuum- and air-melted steels can be represented by the same single line. That the air-melted steels did not show a somewhat higher strain-aging index than the vacuum-melted steels is apparently due to the relatively small differences in their nitrogen contents. Moreover, the aluminum and silicon contents of the air-melted steels were appreciably higher (Tables I and II).

SUMMARY AND CONCLUSIONS

As part of a systematic study of the crystallographic texture, plastic anisotropy, and mechanical properties of phosphorus-containing sheet steels, the effects of carbon content (0.02 to 0.11%) on the properties of vacuum- or air-melted steels containing 0.07 percent phosphorus and 0.20 percent manganese have been investigated. The ingots were hot-rolled to 3.8 mm (0.150-in.) in thickness, cold-rolled 80 percent to 0.76 mm (0.030 in.) and simulated box-annealed at 710 and 780°C (1310 and 1435°F). The microstructures and crystallographic textures were examined at various stages of the processing treatments. The anisotropy parameters and other mechanical properties were determined for the annealed strips by tension tests. The results of the study can be summarized as follows:

1. For both the vacuum- and air-melted steels, the r_m value decreased with increasing carbon content. The detrimental effect of carbon on r_m was more marked after annealing at 780°C (intercritical) than at 710°C (subcritical). The Δr values of all these steels are fairly small, and were essentially unaffected by increasing the carbon content. Possible reasons for these and related observations have been discussed.

2. With increasing carbon, the yield and tensile strengths of the 0.07 percent phosphorus sheet steels increased. Moreover, the grain size became finer with higher carbon contents. These effects were shown by both vacuum- and air-melted steels, and were more pronounced, after annealing at the higher temperature (780°C). Within a narrow band of scatter, the yield-strength and grain-size data for all these steels can be expressed by a Hall-Petch relation. The ductility, as shown by the extent of uniform elongation, appears to be little affected by the carbon contents of the steels within the range studied.

3. The strain-hardening exponent, or n value, of the steels decreased slightly with increasing carbon content. This is consistent with the general observation that the n value decreases with increasing yield or flow stress, or with decreasing grain size. The strain-aging index of all these steels was similar in magnitude to that of ordinary low-carbon steels and was nearly unaffected by the carbon variations studied.

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