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EFFECT OF DYNAMIC STRAIN AGING ON THE PLASTIC ANISOTROPY AND MECHANICAL PROPERTIES OF LOW-CARBON PHOSPHORUS STEELS

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Abstract: The effects of a dynamic-strain-aging treatment, as compared with a static-strain-aging treatment, on plastic anisotropy and mechanical properties has been determined for vacuum-melted low-carbon phosphorus steels containing various amounts of silicon. It was found that prestraining at 185°C, as compared with straining at 22°C followed by aging for four hours at 100°C, resulted in about twice the increase in yield strength (90 versus 48 MPa) on subsequent tension testing at 22°C and an improvement in r_m values from about 1.8 to 2.0.

Analyses of the textures and dislocation structures of the steels after the two strain-aging treatments and after subsequent deformation at 22°C showed that a greater dislocation density gives rise to the greater strengthening of dynamic-strain-aged specimens, and a finer polyhedral network of dislocation tangles is believed to be the reason for their higher r_m values.

INTRODUCTION

Previous studies[1-3] have shown that the addition of up to about 0.1 percent phosphorus to low-carbon, low-manganese, steels greatly improves their deep-drawing properties (that is, r_m values). Additions of phosphorus up to 0.05 percent increase the strength of iron and steel with no significant effect on toughness.[4,5] To gain additional strengthening, static-strain-aging treatments were applied to low-carbon, low-manganese, silicon steels containing about 0.05 percent phosphorus,[2] and increases in strength of about 15 percent were obtained with no appreciable changes in r_m values. Reasonably good ductility (∿13% uniform elongation) remained

after the strain-aging treatment. Because dynamic-strain-aging treatments on iron-phosphorus alloys[6] and 0.1C-1.0Mn-0 to 0.2P steels[7] have been shown to produce greater increases in strength (with no appreciable decreases in subsequent uniform elongation) than static-strain-aging treatments, the effect of a dynamic-strain-aging treatment on the plastic anisotropy and mechanical properties of some of the steels used in a previous study[2] was investigated.

MATERIALS AND PROCEDURES

In a previous study[2] a 136-kg (300 lb) vacuum-melted laboratory heat with a base composition of 0.025C-0.2Mn-0.05P-0.02S was split to give 23-kg (50 lb) ingots of steels with silicon contents ranging from 0.02 to 0.7 percent. Four of these steels were used in this study; the chemical compositions are given in Table I. To assure homogeneity in composition and structure, the ingots of these steels (75 by 140 by 250 mm or 3 by 5.5 by 10 inches) were first hot-forged at 1230°C (2250°F) on all sides to a cross section of about 70 by 110 mm (2.75 by 4.5 inches). The forged pieces were then reheated to 1230°C, hot-rolled from 70 to 12.5 mm (2.75 to 0.5 inches) with finish rolling at 900°C (1652°F), and air-cooled. Final hot processing consisted of reheating the 12.5-mm-thick plates to 1230°C and hot rolling to a thickness of 3.8 mm (0.150 inch), the temperature for the finishing pass being about 925°C (1697°F). These hot-rolled bands were immediately dipped into iced water for 1.5 to 2 seconds to simulate water-spray cooling, and were subsequently furnace-cooled from 620°C (1150°F) to room temperature at a rate of about 40°C (72°F) per hour. This furnace-cooling treatment was to simulate the thermal conditions in coiled strips.

Prior to cold rolling, the hot-rolled bands were sandblasted and pickled to remove surface scale. They were then cold-rolled about 80 percent to 0.8 mm (0.03 inch). Tension specimens with a gage section of 6.35 by 25.4 mm (0.25 by 1.0 inch) were machined from blanks cut from the cold-rolled strips at 0, 45, and 90 degrees to the rolling direction. These specimens were annealed in loose packs in 15 percent $H_2 + N_2$ at a heating rate of 20 to 25°C (36 to 45°F) per hour to 650°C (1202°F), held at temperature for 20 hours, and furnace-cooled (simulated box anneal). Larger specimens (19.1 by 25.4 mm or 0.75 by 1.0 inch) were made for texture determinations and dislocation-structure analyses after the different aging treatments.

Tension tests were performed at a cross-head speed of 0.5 mm/min (0.02 inch/min). Specimens given the static-strain-aging treatment were aged for four hours at 100°C (212°F) after 6 percent strain at 22°C (72°F), whereas those given the dynamic-strain-aging treatment were prestrained 6 percent at 185°C (365°F) because this was the temperature at which serrated flow was most pronounced in the steels used in this study.

The anisotropy parameters $r_m = (r_0 + 2r_{45} + r_{90})/4$ and $\Delta r = (r_0 - 2r_{45} + r_{90})/2$ were determined from tension tests

TABLE I. Chemical Composition of the Steels Investigated, Weight Percent

Steel	Sample Location*	C	Mn	P	S	Si	Cu	Ni	Cr	Al_{sol}	Al_{total}	N	O_{ppm}
A	T	0.027	0.19	0.037	0.022	0.021	<0.005	0.020	0.018	<0.001	0.002	0.004	219
	B	0.020	0.20	0.043	0.021	0.021	0.005	0.020	0.020	<0.001	<0.002	0.004	93
B	T	0.025	0.20	0.047	0.020	0.032	<0.005	0.020	0.018	0.001	0.005	0.004	127
	B	0.028	0.20	0.048	0.021	0.042	0.005	0.020	0.020	<0.001	<0.002	0.003	92
C	T	0.025	0.20	0.047	0.021	0.079	<0.005	0.022	0.018	0.001	0.003	0.004	70
	B	0.024	0.19	0.046	0.022	0.078	0.005	0.022	0.020	<0.001	<0.002	0.003	78
D	T	0.026	0.20	0.047	0.022	0.194	<0.005	0.020	0.020	<0.001	<0.002	0.003	55
	B	0.014	0.20	0.043	0.019	0.183	0.005	0.022	0.020	0.001	<0.002	0.006	52

*T = top; B = bottom.

in the usual manner. In these equations, $r = \varepsilon_w/\varepsilon_t$, the ratio of true strain in the width dimension to that in the thickness dimension, and the subscripts denote the angles of the specimens from the rolling direction of the strip.

Thin foils for transmission electron microscopy were prepared from the gage lengths of the tension specimens. These were examined at 1000 kV, and stereographic techniques were used to interpret the three-dimensional dislocation arrangements in sections up to 2 μm thick.

To conserve material, Steels B and D (Table I) were used for the mechanical-property and plastic-anisotropy analyses (Table II) and Steels A and C were used for characterization of the textures and dislocation structures after the strain-aging treatments and after subsequent straining at 22°C (Table III). The difference in silicon content of the steels has been found to have little effect on texture or plastic-anisotropy values.[2-4]

RESULTS AND DISCUSSION

Microstructure and Texture of Steels

The microstructure of the hot-rolled bands and the texture of the steels after hot rolling, cold rolling, and annealing have been reported previously[2] and will only be summarized here. The microstructures of the steels after hot rolling were similar and exhibited complete recrystallization and fairly equiaxed grains. The average grain size was ASTM 9 to 10. The texture of the steels after hot rolling was very weak. After cold rolling 80 percent, the steels had a texture characterized by strong (222), (200), and (211) intensities, which is typical of the cold-rolled texture of iron and low-carbon steels (Table III). Annealing resulted in stronger (222) and weaker (200) intensities, and the annealed texture was similar in all the steels (Table III).

Mechanical Properties and Plastic Anisotropy

Typical stress-strain curves for Steels B and D showing the prestraining and subsequent straining deformation are presented in Figures 1 and 2 for the specimens oriented parallel to the rolling direction. The specimens oriented at 45 and 90 degrees to the rolling direction showed behavior similar to that shown in Figures 1 and 2. The dynamically-strain-aged specimens showed serrated yielding and a high work-hardening rate during prestraining at 185°C (365°F). After prestraining at 185°C, these specimens were re-strained at 22°C to maximum load. The static-strain-aged specimens were prestrained at 22°C, aged for 4 hours at 100°C (212°F), then re-strained at 22°C to the same strain the dynamic-strain-aged specimens received at maximum load. This allowed comparison of the anisotropy parameters at the same equivalent total strain, which is more meaningful in steels with strong textures because the plastic-strain ratio (or r value) is strain-dependent.[8] The static-strain-aged specimens showed slightly greater uniform elongation on subsequent straining at 22°C,

TABLE II. Mechanical Properties of Steels

Steel	Flow Stress at End of Prestrain, MPa (ksi)	Yield Strength, MPa (ksi)	Tensile Strength, MPa (ksi)	Uniform Elongation, %	TS/YS	r_m	Δr	Aging Index* %
Values at 22°C After Simulated Box Anneal at 650°C for 20 Hours								
B		252.3 (36.6)	341.9 (49.6)	28.8	1.36	1.38**	-0.16	
D		267.4 (38.8)	360.2 (52.2)	28.4	1.35	1.50**	-0.12	
Values at 22°C After Prestraining 6 Percent at 22°C Followed by Aging at 100°C for 4 Hours (Static-Strain-Aged)								
B	301.9 (43.8)	350.0 (50.7)	376.6 (54.6)	15.0***	1.08	1.78****	0.02	15.9
D	319.8 (46.3)	375.0 (54.4)	409.0 (59.3)	11.9***	1.09	1.74****	0.46	17.3
Values at 22°C After Prestraining 6 Percent at 185°C (Dynamic-Strain-Aged)								
B	361.9 (52.4)	393.3 (57.0)	393.3 (57.0)	15.0***	1.0	1.97**	0.66	30.3
D	371.8 (53.9)	408.5 (59.2)	424.2 (61.5)	12.0***	1.04	2.11**	0.16	27.7

* Ratio of increased flow stress increment after strain-aging-treatment to flow stress at 6 percent strain at 22°C.

** Determined after straining to maximum load.

*** Includes prestrain.

**** Determined at same total strain (10% elongation) as that for dynamic-strain-aging treatment.

TABLE III. Texture of Steels

Steel	X-Ray Intensity, Random Units (110)	(200)	(211)	(310)	(222)
Cold Rolled-Strip					
A	0.12	3.10	2.18	0.23	6.81
B	0.13	3.20	2.19	0.24	6.93
C	0.12	3.08	2.14	0.21	6.84
D	0.10	3.28	2.17	0.18	7.36
Cold-Rolled and Annealed Strip					
A	0.11	0.87	1.95	0.25	8.19
B	0.13	0.83	1.89	0.36	7.29
C	0.15	0.73	1.84	0.26	7.76
D	0.13	0.85	1.86	0.28	8.43
Static-Strain-Aged Specimens					
Strained 6 Percent at 22°C, Aged 4 Hours at 100°C					
A	0.14	1.11	2.08	0.29	8.66
Static Strain Aged Followed by 13 Percent Strain at 22°C					
C	0.14	0.91	2.18	0.33	8.54
Dynamic-Strain-Aged Specimens					
A	0.14	1.11	2.09	0.28	8.84
Dynamic Strain Aged Followed by 13 Percent Strain at 22°C					
C	0.16	0.94	2.17	0.35	8.24

whereas the dynamic-strain-aged specimens had a less extensive Lüders region during prestraining and re-straining.

The 6 percent prestrain used in this study was a compromise so that both strain-aging treatments would have the same amount of prestrain while ensuring that the specimens receiving the static-strain-aging treatment would have sufficient uniform prestrain for strain aging. In reality, a smaller prestrain during the dynamic-strain-aging treatment would result in a greater uniform elongation on re-straining at 22°C, although the increase in strength would be decreased slightly.[6]

Figures 1 and 2 also show that while the static-strain-aging treatment increased the flow stress at 22°C by about 50 MPa (7 ksi), the dynamic-strain-aging treatment increased it by about 90 MPa (13 ksi). The strengthening from either strain-aging treatment was not significantly affected by the silicon content of the steel. The mechanical properties of Steels B and D resulting from the two strain-aging treatment are

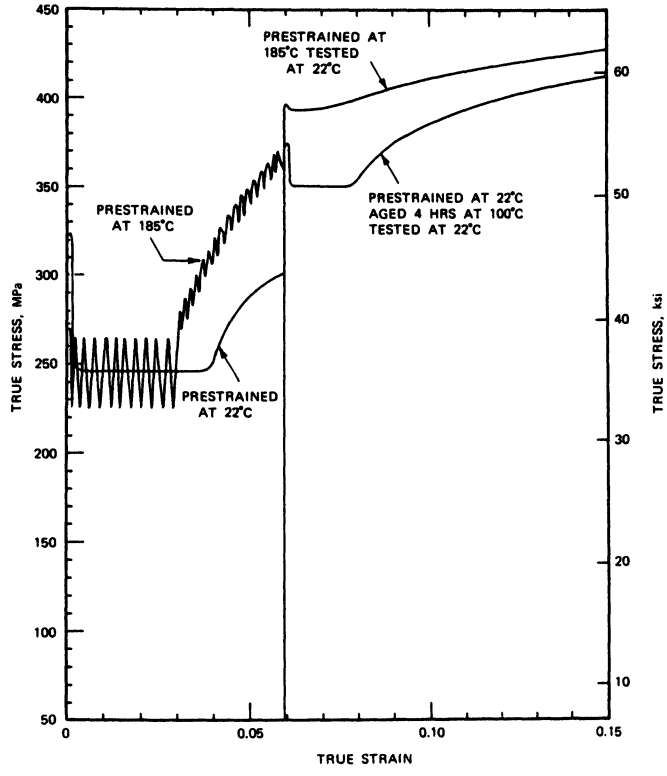


Figure 1. Stress-Strain curves of specimens of Steel B oriented parallel to the rolling direction.

summarized in Table II. The dynamic treatment almost doubled the aging index, defined as the ratio of the increased flow stress increment after the aging treatment to the flow stress at 6 percent strain at 22°C. The tensile strength to yield strength ratio (TS/YS) was reduced by the dynamic treatment solely because of the larger than adequate prestrain used in this study. A prestrain of 5 percent at 185°C results in yield and tensile strengths and uniform elongations on subsequent straining at 22°C that are equivalent to those obtained after the static treatment used in this study. Therefore, a lesser amount of prestrain is required in the dynamic flow region than at 22°C to obtain the same strain-aged mechanical properties.

The plastic aniostropy parameters r_m and Δr are summarized in Table II for Steels B and D after the two strain-aging treatments. For comparison, values of r_m and Δr are also shown for these steels in the simulated box-annealed condition without strain aging. However, these values were determined after straining to maximum load (over 28% elongation). If r_m had been determined at the same level of strain used to determine r_m in the strain-aged specimens (about 15 and 12% rather than about 28%), r_m would be increased to about 1.6 and 1.8 (instead of 1.38 and 1.50) for Steels B and D,

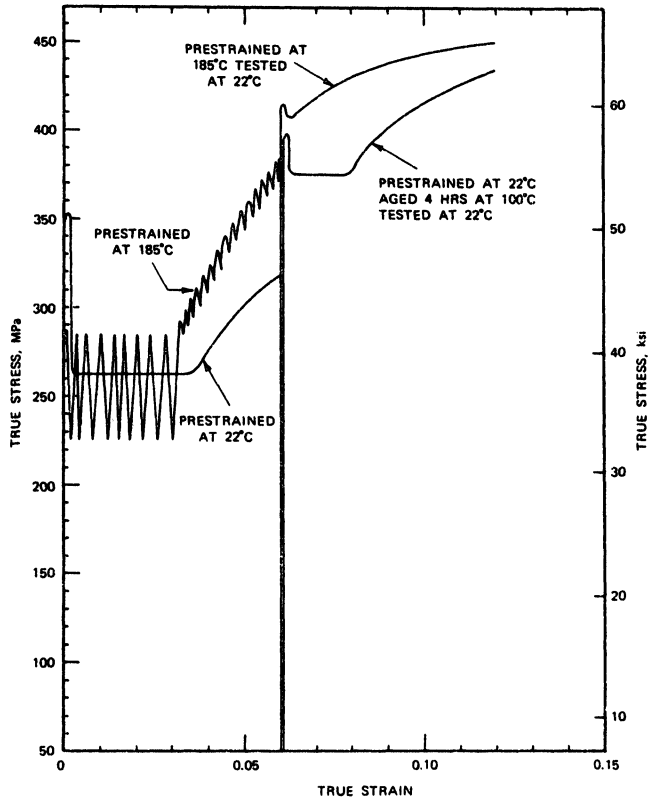


Figure 2. Stress-Strain curves of specimens of Steel D oriented parallel to the rolling direction.

respectively, on the basis of the known strain dependence of r_m in these steels.[8] This shows that the static-strain-aging treatment had no significant effect on the plastic anistropy values if the effect of the strain-aging treatment in reducing the total uniform elongation is taken into account.

Comparison of the r_m values in Table II for Steels B and D after the two strain-aging treatments shows that these values were significantly greater after the dynamic treatment than after the static treatment. Again, the silicon content of the steel had no significant effect on r_m value. The Δr values varied for the two steels after the two strain-aging treatments and exhibited no consistent trend. Directly after the strain-aging treatments (at 6% strain) the r_m values were about 2.2 and 3.0 for the static and dynamic-strain-aged specimens, respectively.

It is worth noting that a 5 percent prestrain at 185°C results in r_m and Δr values essentially the same as those obtained after the 6 percent prestrain at 185°C. Therefore, a prestrain of 5 percent at 185°C results in strength properties on subsequent straining at 22°C that are essentially identical to those observed after the static-strain-aging treatment with

6 percent prestrain and still produces a significant improvement in r_m.

Mechanism of Enhanced Plastic Anisotropy After Dynamic Strain Aging

In an attempt to determine the mechanism responsible for the higher r_m values after dynamic strain aging, larger specimens were fabricated for more accurate x-ray and pole-figure determinations of the textures developed as a result of the two strain-aging treatments. Table III shows the textures of the steels after the strain-aging treatments and after subsequent straining at 22°C. The textures present after the static- and dynamic-strain-aging treatments were practically identical and showed a strong {111} component much the same as that which existed prior to the aging treatment (Table III). Figures 3, 4 and 5 are pole figures of the static- and dynamic-strain-aged specimens that were subsequently strained 13 percent at 22°C, which was equivalent to the strain at maximum load for the dynamic-strain-aged specimen. From a comparison of these pole figures and the data in Table III, it appears that the two strain-aging treatments did not result in any significant differences in the textures developed after the tension testing, as determined by the x-ray techniques employed.

Additional specimens given the static- and dynamic-strain-aging treatments were used for analysis of the dislocation structures formed after strain aging and after subsequent straining at 22°C to the strain corresponding to the maximum load for the dynamic-strain-aged specimen. Figure 6 shows the types of dislocation structures observed after the two strain-aging treatments. As observed by others,[9-11] the dynamic-strain-aging treatment results in a greater dislocation density with more dislocation tangles than are present after equivalent strain at ambient temperature. These tangles appear to be arranged in a polyhedral-type network, with the tangles forming the walls of the polyhedra. The dislocation tangles appear to be incomplete in that numerous dislocations are observed to pervade through adjacent polyhedra.

On further straining at 22°C following the strain-aging treatments, the static-strain-aged specimen shows a change in dislocation structure with a diffuse cellular network of dislocation tangles having formed, Figure 7. The additional deformation at 22°C appears to decrease the size of the polyhedral network of dislocation tangles in the dynamic-strain-aged specimens so that the resulting network is smaller and more uniform than that observed in the static-strain-aged specimen.

The results of the dislocation-structure analysis show that the dynamic-strain-aged specimens have a greater dislocation density and a finer and more uniform polyhedral network of dislocation tangles. This finer and more uniform network of dislocation tangles is expected to make it easier for the crystal lattice to rotate toward the ideal (111)[110]-type end orientation during tensile deformation, and thereby give

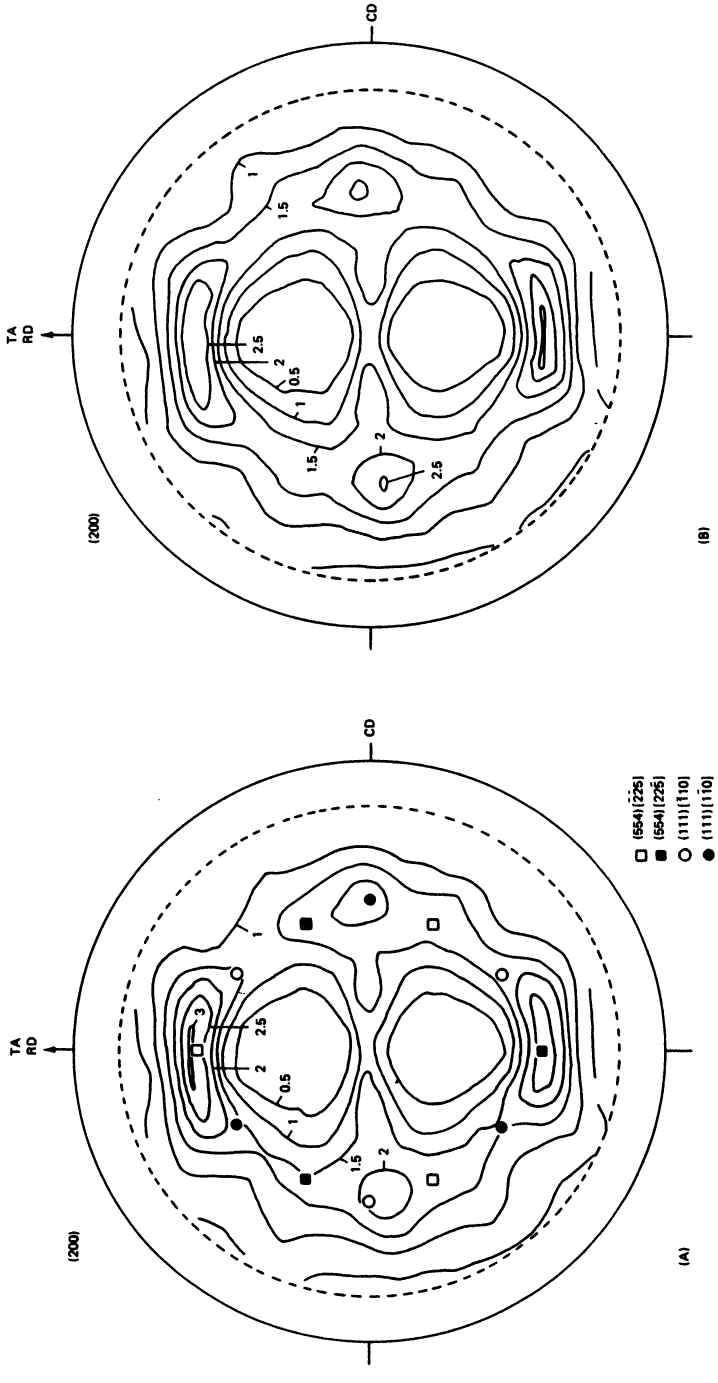


Figure 3. Pole figures for Steel C showing texture of (A) statically strain-aged and (B) dynamically strain-aged specimens after subsequent tensile straining 13% in the rolling direction (0°) at 22°C.

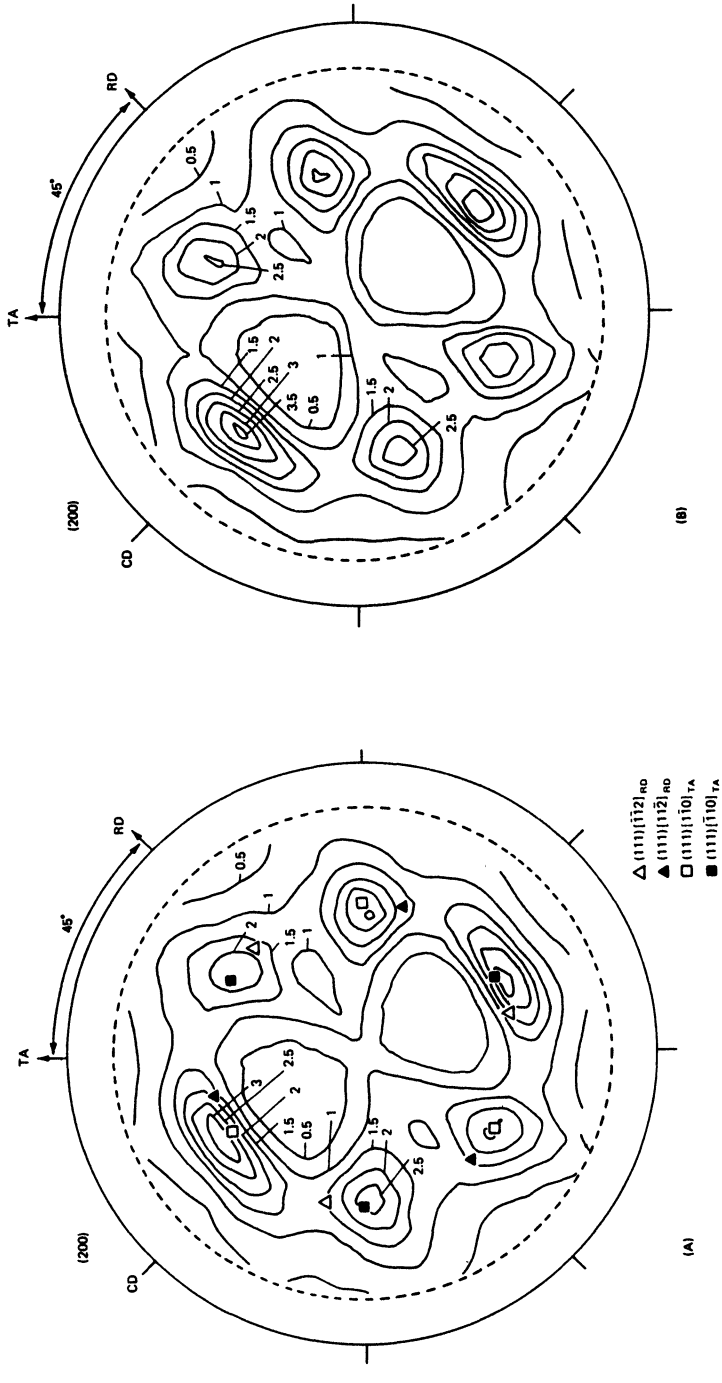


Figure 4. Pole figures for Steel C showing texture of (A) statically strain-aged and (B) dynamically strain-aged specimens after subsequent tensile straining 13% in the diagonal direction (45°) at 22°C.

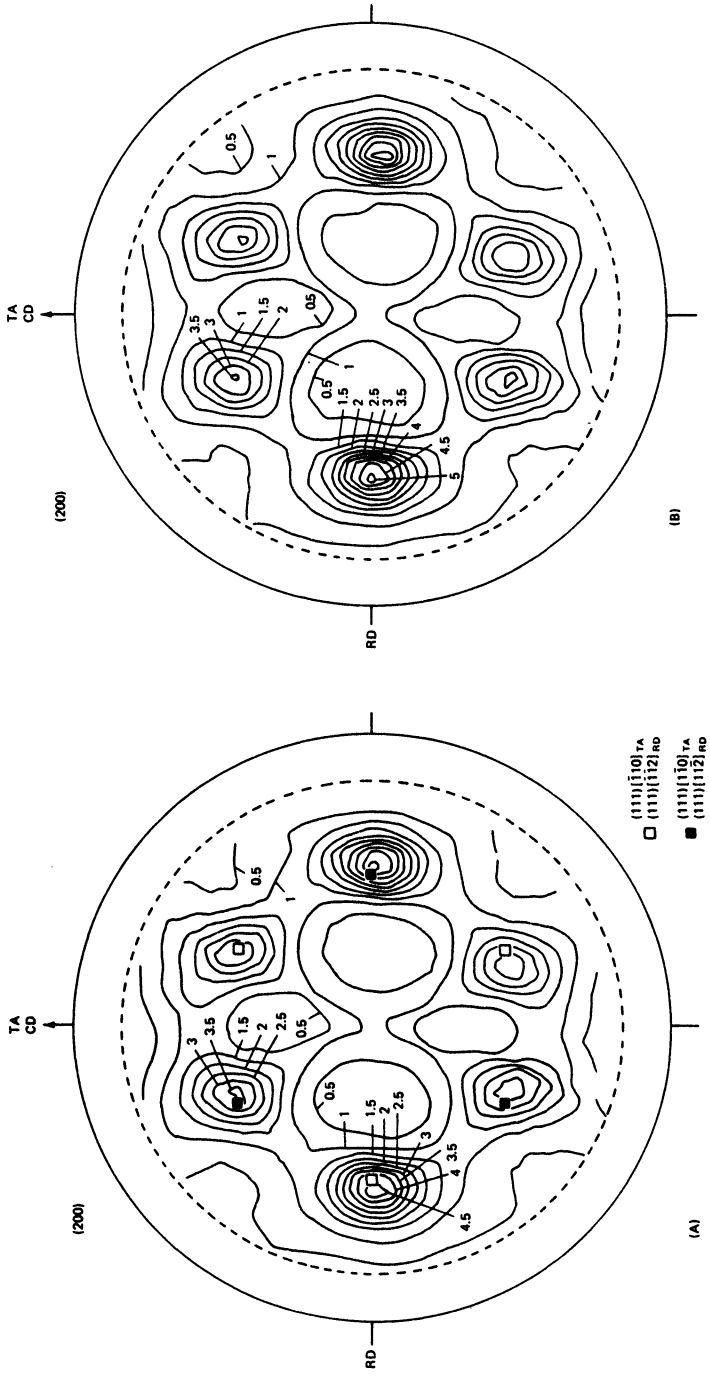
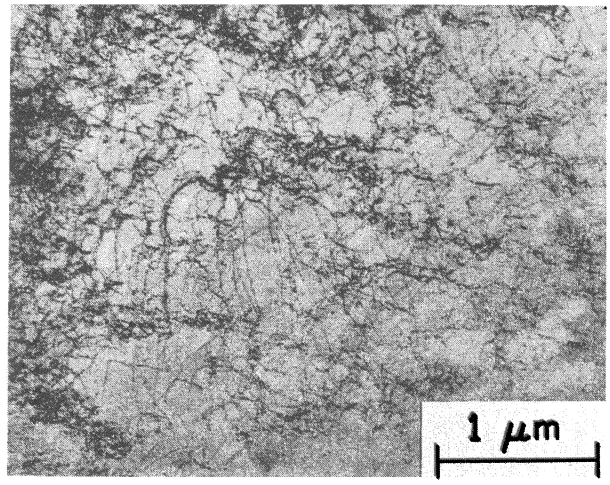
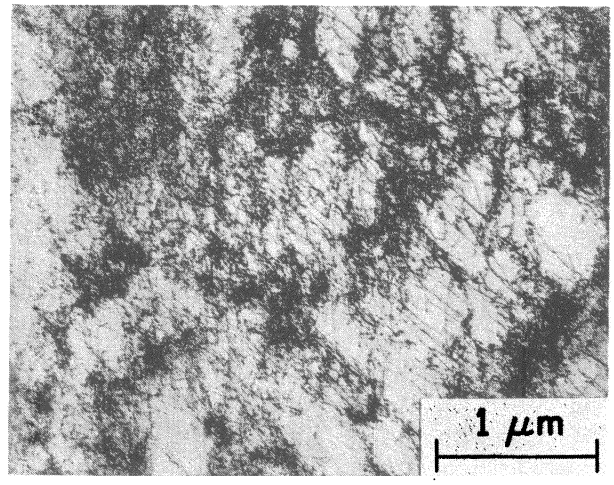


Figure 5. Pole figures for Steel C showing texture of (A) statically strain-aged and (B) dynamically strain-aged specimens after subsequent tensile straining 13% in the cross direction (90°) at 22°C.



A. Static strain aged

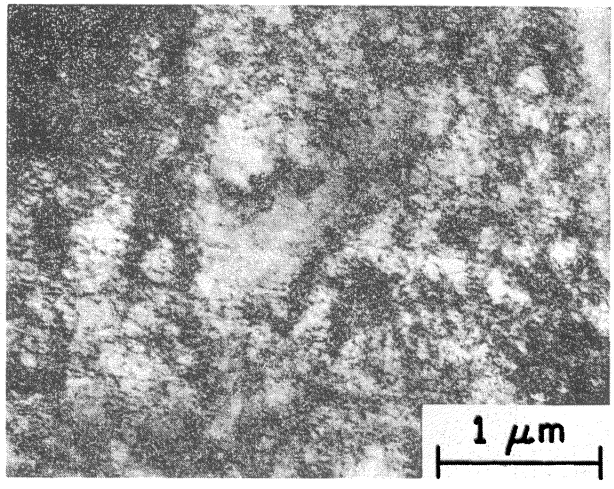


B. Dynamic strain aged

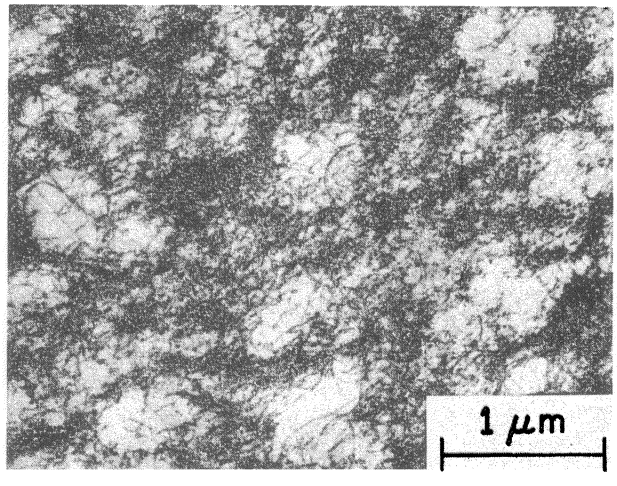
Figure 6. Dislocation structures in Steel A resulting from strain-aging treatments. (2 μm thin foils examined at 1000 kV.)

rise to the higher r_m values obtained in the dynamic-strain-aged specimens. It is known that the orientational changes of the crystals during plastic deformation are facilitated by the formation of the fine cell structure,[12] and that a (111)[110]-type orientation yields the highest r_m values.[13,14]

However, the improvement in r_m from about 1.8 to 2 is apparently not of sufficient magnitude to result in observable changes in texture as determined from x-ray analysis. The most likely reason for this lack of x-ray evidence is



A. Static strain aged



B. Dynamic strain aged

Figure 7. Dislocation structures in Steel C formed on subsequent straining of strain-aged specimens an additional 10 percent at 22°C. (2 μm thin foils examined at 1000 kV.)

that the steels studied have such a strong {111} texture component that small changes in this component cannot be readily distinguished.

SUMMARY

The results of this study show that a dynamic-strain-aging treatment results in about twice the increase in

strength obtained from a static-strain-aging treatment, along with an improvement in r_m value from about 1.8 to 2.0 with only a slight decrease in uniform elongation. The most likely reason for the improved r_m value after the dynamic-strain-aging treatment is that dynamic strain aging produces a polyhedral-type network of dislocation tangles which is expected to make it easier for the crystal lattice to rotate toward the ideal (111)[110]-type end orientation during subsequent tensile deformation.

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