Title

TENSILE PROPERTIES OF 0.05 TO 0.20^ CARBON TRIP STEELS

Permalink

https://escholarship.org/uc/item/1409d2rt

Authors

Chanani, G.R.
Zackay, V.F.
Parker, Earl R.

Publication Date

1970-08-01

Submitted to
Metallurgical Transactions

UCRL-20313
Preprint
c.2

TENSILE PROPERTIES OF 0.05 TO 0.20% CARBON TRIP STEELS

G. R. Chanani, V. F. Zackay,
and Earl R. Parker

August 1970

AEC Contract No. W-7405-eng-48

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

UCRL-20313 c.2

95

TENSILE PROPERTIES OF 0.05 to 0.20% CARBON TRIP STEELS

G. R. Chanani, Graduate Student, University of California
V. F. Zackay and Earl R. Parker, Professors of Metallurgy

Inorganic Materials Research Division, Lawrence Radiation Laboratory
Department of Materials Science and Engineering, College of Engineering
University of California, Berkeley, California

ABSTRACT

The uniaxial tensile properties of a series of TRIP steels of varying carbon contents and processing histories were determined over a wide range of test temperatures.

The yield strengths at room temperature varied both with the deformation temperature (over the range 250° to 550°C) and with the carbon content (0.05 to 0.20%). Possible reasons for these variations are advanced.

For all steels, the -100°C yield strengths were substantially lower than the 100°C yield strengths. The minima and maxima in the yield strengths vs temperatures curves were especially pronounced for the steels processed at the lowest deformation temperatures.

Both the rate of work hardening and the elongation were influenced by the strain-induced austenite-to-martensite transformation. The rate of strain hardening and the rate of production of strain-induced martensite (per unit strain) increased with decreasing temperature.

Tensile Properties of 0.05 to 0.20% Carbon Trip Steels

G. R. Chanani, V. F. Zackay and E. R. Parker

INTRODUCTION

The introduction of high-carbon high-manganese steels by Sir Robert Hadfield over eighty years ago inaugurated the use of strain-induced phase transformations to improve the mechanical properties of steels.(1) Since that time, this phenomenon has been widely investigated with metastable austenitic stainless steels.(2-5) Both Hadfield's manganese steel and metastable austenitic stainless steels have low yield strengths and high elongations in the solution-quenched condition, and in the cold-worked condition they have high yield strengths and low elongations. Both of these combinations of strength and ductility are useful, but it would be better to have high strength combined with high elongation. In recent papers,, Zackay et al.(6,7,8) described a process for producing high-strength steels with high values of elongation. These steels were designed to be thermodynamically unstable so that plastic straining would induce a martensitic transformation. In one of these papers(6) a suggestion was made that steels exhibiting a high degree of transformation induced plasticity be called TRIP steels.

The present investigation was concerned with the effects of warm working temperatures and testing temperatures on the tensile properties of 0.05 to 0.20% carbon TRIP steels. The carbon contents of these steels were chosen to bracket the estimated equilibrium eutectoid carbon content of a base alloy containing 12 Cr, 8 Ni, 4 Mo, 1.5 Si, 0.75 Mn.

In this study, the primary emphasis was placed on correlating the properties of the steels with the warm working procedure.

EXPERIMENTAL PROCEDURE AND RESULTS

Twenty pound vacuum melted ingots were forged to 0.5 in. thickness at 1100°C and subsequently hot rolled to 0.25 in. at 900°C. The plates were solution annealed at 1100°C for one hour and water quenched. Final deformations during warm working (which involved 80% reduction in thickness except where noted) were carried out at temperatures of 250°C, 350°C, 450°C, and 550°C. Preheated rolls were used and temperature control was maintained by returning the pieces to the furnace between passes to re-establish temperature equilibrium. The compositions of the three steels investigated are given in Table I.

Sheet tensile specimens having a one inch gauge length, a thickness of 0.05 in., and a test section width of 0.125 in., were ground from processed sheets. The specimens were loaded by means of pins passing through holes in the enlarged end sections to minimize misalignment. The total elongation was measured between small indentations made on the surface prior to testing. A yield point occurred in most cases (except for the solution-quenched steels), and the yield stress was taken as the stress where the load dropped (upper yield point). When there was no drop in load, the 0.1% offset method was used to obtain the yield stress. True stress-true strain calculations were based on measurements of engineering stress-strain data taken from the Instron recorder. (The total elongation as measured at the end of the test was used as the scaling factor.) The elastic strain of both the specimen and the tensile machine was subtracted from the total strain in computing these curves. The strain

TABLE I

Percentages of Alloying Elements in Steels

C	Cr	Ni	Mo	Si	Mn	Fe
0.05	12.1	7.7	3.9	1.5	1.1	Bal.
0.16	12.1	7.8	3.9	1.5	0.82	Bal.
0.20	12.0	7.9	4.0	1.5	0.80	Bal.

TABLE II

Percentages of Martensite Before and After Tensile Testing
(Condition: 80% Deformation at 250°C)

%C	Testing Temp. °C	% Martensite Before Straining	% Martensite After Fracture
0.05	200	12	18
	100	12	68
	22	12	94
	-78	13	91
	-196	16	92
0.16	200	<1	5
	100	<1	29
	22	<1	78
	-78	<1	84
	-196	<1	95
0.20	200	<1	5
	100	<1	29
	22	<1	82
	-78	<1	80
	-196	<1	80

TABLE III

Elongation Values for Steels Deformed 80% at Various Temperatures and Tested at Room Temperature

% C in Steel	Deformation Temperature, °C	Elongation in 1", %
0.05	250	17
	350	18
	450	23
	550	19
0.16	250	22
	350	19
	450	24
	550	19
0.20	250	26
	350	20
	450	23
	550	23

rate employed was 0.04 per minute; for test temperatures above and below room temperature, the specimen was immersed in a temperature controlled liquid.

The amount of the transformation that occurred during testing was determined quantitatively by measuring the saturation magnetization of tensile specimens before and after testing at various temperatures. The readings were converted to volume percent martensite, with corrections being made for the influence of the alloying elements.(9,10) The results are given in Table II for steels that had been deformed 80% at 250°C.

The three steels had different M_s temperatures because of differences in carbon content. The M_s temperature of the 0.05% carbon steel was above 22°C; this steel contained some martensite after quenching to room temperature as indicated in Table II. This steel was stabilized against further decomposition by room temperature aging. After several weeks at 22°C no additional martensite formed until it was cooled to -35°C. The 0.16 and 0.20% carbon steels contained less than one volume percent of martensite even after cooling to -196°C.

The M_d temperature is a variable depending upon the amount of plastic strain induced in the specimen and upon the amount of martensite produced by a chosen amount of plastic strain. No attempt was made in this work to establish precise values of M_d temperatures, but it can be seen from the data in Table II that some martensite was produced at 200°C in all tensile specimens fractured at 200°C. A more reasonable assignment of M_d temperatures for the 0.16 and 0.20 percent carbon steels would be 100°C, where the percent martensite after fracture was 29 percent in both steels. The comparable M_d for the 0.05 percent carbon steel was somewhat higher, probably around 180°C.

The true stress-true strain curves of two steels (0.05% and 0.20%C) with prior deformations of 80% at 250°C are shown in Figs. 1 and 2 for several test temperatures. (These curves are plotted to the point of <u>maximum load</u>, not to fracture.)

DISCUSSION

In earlier papers, the effect of the amount of deformation on the tensile properties of TRIP steels was reported.(6,7) In the present study, the amount of deformation was held constant (80%), and the deformation temperature was varied from 250°C to 550°C.

The influence of the deformation temperature on the room temperature yield strengths is shown in Fig. 3 and the corresponding elongations are given in Table III. The yield strengths of the 0.16% C steel were not significantly influenced by the deformation temperature, as is shown in Fig. 3. The yield strength of the 0.05% carbon steel was relatively low for prior deformation temperatures of 250°C and 350°C. It rose to a slight maximum for deformation at 450°C and, finally decreased again to a lower value when the processing was carried out at 550°C.

The low yield strengths for the lower deformation temperatures are believed to be due to stress induced martensite which formed during testing at 22°C. At temperatures below the M_d, stresses within the normal elastic range can trigger the formation of martensite.(11) The M_d of this steel was above 200°C, as Table II indicates. This point will be discussed in more detail in a later section.

The somewhat higher strength of the 0.05% carbon steel after deformation at 450°C can be attributed to the presence of untempered martensite that formed during cooling from the deformation temperature. Measurements showed that the total amount of martensite had increased from the 9% in the as-quenched steel to 22 volume percent after the 450°C processing treatment. After processing at 550°C, the amount of martensite was only 14 volume percent, and the yield strength was lower than after the 450°C treatment. In this case, it is thought that more carbon was retained in solution because of the higher solubility of carbon in austenite at the higher temperature and that this carbon retention made the austenite more stable.

A distinctive feature of the plots shown in Fig. 3 is the high yield strength of the 0.20% carbon steel deformed at 250°C. The higher yield strength is presumed to be due to hardening caused by carbide precipitation during the 250°C processing treatment. The undeformed, solution-treated material contained some undissolved carbides (see Fig. 4), revealing that the matrix was saturated with carbon at the solution temperature. Precipitation of carbide particles (presumably Fe_3C) was evidently enhanced by the subsequent deformation at 250°C. The microstructure of this steel after deformation is shown in Fig. 5. An attempt was made to detect the finely dispersed carbides responsible for the high yield strength by transmission electron microscopy but because of the large amount of deformation the structure was too defective to permit resolution of very fine carbide particles.

In general, the yield strength and the ultimate tensile strength increased with carbon content for each deformation temperature studied, but the deformation temperature did not appear to influence the elongation significantly, as shown in Table III.

Test Temperature

The temperature dependence of the tensile properties of TRIP steels is complex. The stability of the austenite as well as the flow characteristics of both austenite and strain-induced martensite are influenced by the temperature of testing.(12-16) The variations of yield strength and elongation with test temperature for the three steels in both the solution quenched and deformed (80% at 250°C) conditions are shown in Figs. 6 and 7. The yield strengths of the solution annealed and quenched steels increase monotonically with decreasing temperature, but the yield strengths of the deformed steels varied irregularly with temperature.

For all steels of the series, regardless of the deformation temperature, the yield strength increased with decreasing test temperature between about -50°C and -196°C. In this temperature range, the increases in yield strength for the deformed steels were greater than for those that were undeformed. In general, the deformed steels exhibited a minimum in yield at about -50°C, with a maximum appearing at about 100°C. These minima and maxima were especially pronounced for the steels deformed at 250°C. Similar trends have been observed for the temperature dependence of the yield strength of solution quenched AISI Type 304 stainless steel and Fe-Ni alloys.(11, 16)

The effects of elastic strains and plastic deformation on martensite formation have long been recognized. It is well known that martensite can be induced to form by plastic straining at temperatures, both above and below the M_s point.(16,17,18) Other investigators have demonstrated that at somewhat lower temperatures where the austenite is less stable, the martensite reaction can be triggered by stresses that are too low to cause plastic deformation by slip.(11)

Plastic deformation can occur by three mechanisms -- slip, twinning, and the martensite reaction. These three independent processes can operate separately, simultaneously, or they can interact. Plastic deformation produces internal stress concentrations wherever slip is blocked. The high stresses associated with such regions can nucleate the martensite reaction. As the temperature of tensile testing is lowered in a metastable austenitic steel, the sequence of events is as follows: Above the M_d temperature no martensite is formed and the shape of the stress strain curve is characteristic of a stable austenitic steel. The 0.20 percent carbon steel in the present series tested at 200°C behaved in this manner. At 100°C martensite formed at the onset of plastic flow and the 0.1% yield stress was thereby increased about 15% above the value measured at the higher temperature. When the test temperature was lowered further to 22°C and -78°C, yielding occurred at stresses about 15% lower than that required for plastic flow by slip. Magnetic measurements confirmed that martensite was induced to form in these cases by the uniform stress provided by the external load. The effects of uniform elastic stress and the effects of local internal stress concentrations induced by plastic flow are reflected by Fig. 6. Also, the extent of the plastic flow due to the martensite transformation was about 5%, as the initial flat portion (Luders strain) of the stress-strain curves in Figs. 2 and 3 indicate. At temperatures below about -50°C the yield strengths of the deformed steels again rise. However, the rate of increase in strength with decreasing temperature is higher for the deformed steels than for the solution quenched steels, evidently because of the formation of strain (or stress) induced martensite in the deformed steels.

A striking feature of TRIP steels is the sharp drop in elongation, as shown in Fig. 7, above the M_d temperature (which is estimated for these steels to be above 100°C). Above the M_d, the austenite no longer transforms to martensite during straining, and the elongation approaches that of highly cold-worked austenite. As several investigators have shown,$^{(19,20)}$ the formation of martensite during straining enhances the work hardening of metastable austenitic steels and necking of tensile test specimens is thereby inhibited.

The ultimate tensile strengths of all three steels in both the solution annealed and deformed conditions exhibited the strong temperature dependence that is characteristic of metastable austenitic steels$^{(21)}$ (see Figs. 8 and 9).

The existence of a wide range of work hardening rates in TRIP steels is revealed by true-stress true-strain curves made at several test temperatures for the 0.05 and 0.20% C steels deformed 80% at 250°C (shown in Figs. 2 and 3). As indicated by the dashed lines, all specimens tested below the M_d deformed initially by the formation and growth of Luders' bands due to the martensitic transformation. Fig. 10 is a photograph of a flat tensile test specimen made at a strain within the initial flat portion of the stress-strain curve and illuminated to show the appearance of the Luders' bands. Following the spread of the Luders' bands throughout the entire gauge length, the steels work-hardened rapidly, with the rate of work-hardening increasing with decreasing test temperature.

The influence of test temperature on the rate of work hardening of both the 0.05% and 0.20% steels, as solution quenched and as deformed, is shown in Fig. 11. The rate of work hardening was determined by measuring the slope of the true-stress true-strain curve at a true strain slightly beyond the Luders' strain (true-stress true-strain curves cannot be drawn for strains within the Luders' strain range). The work-hardening rate increased progressively with decreasing test temperature below the M_d, as shown in Fig. 11. This is a reflection of the increase in the amount of martensite produced per unit strain, as shown in Fig. 12 for the deformed 0.20% C steel. The rate of work hardening was enhanced by prior deformation. At all test temperatures, the deformed, and hence stronger, steels had a higher rate of work hardening than the solution-quenched steels, as is shown in Fig. 11. Apparently the strain induced martensite produced in a deformed austenite matrix is more effective in hardening than that formed in solution-quenched austenite. This may have been due to a finer plate size and/or a higher defect density in the martensite, as was found for ausformed steels(23).

The work-hardening rate for both the deformed and solution annealed steels becomes very low as the amount of martensite produced during straining approaches zero, (i.e., at temperatures above about 100°C), as can be seen in Fig. 11. The low work-hardening rate, however, was not as detrimental to the elongation of the solution quenched steels, (see

Fig. 7), because their lower strengths did not require the higher rates of work hardening to prevent necking.(24) The deformed steels quickly necked and failed at low elongations when they were tested at temperatures at or above the M_d, as shown in Fig. 7. Below the M_d the rates of work hardening of the deformed steels was dependent upon the amount of strain-induced martensite produced per unit strain. The correlation between work-hardening rate and the rate of martensite formation is evident from the plots shown in Figs. 11 and 12. (This behavior is consistent with the observations of Gunter and Reed,(16) Bannerjee, et al,(19) Bressanelli and Markowitz,(20) and Cina(25) among others.)

SUMMARY

The uniaxial tensile properties of a series of TRIP steels of varying carbon content and processing histories were determined over a wide range of test temperatures. The results can be summarized as follows:

The yield strength at room temperature was dependent on deformation temperature. Reasons for this behavior were advanced. The ultimate tensile strengths and the elongations at room temperature were relatively insensitive to the deformation temperature for all the steels of the series.

For all steels of the series, regardless of deformation temperature, the yield strength exhibited a minimum at a test temperature of about -50°C and a maximum at a test temperature of about 100°C. The minima and maxima were most pronounced for steels deformed at 250°C. The ultimate tensile strengths of all three steels in both the solution quenched and deformed conditions exhibited strong temperature dependences.

The rate of work hardening and the elongation were influenced by the strain induced transformation, especially in the deformed steels. Above the M_d temperature, both the rates of work hardening and the elongations of the deformed steels were low. Well below the M_d temperature, the rates of work hardening and the elongations of the deformed steels were high, reflecting the formation of strain-induced martensite. The rate of production of strain-induced martensite per unit strain paralleled that of the rate of strain hardening in that both increased with decreasing temperature. At any temperature below M_d the amount of martensite produced per unit strain was greatest for the lowest carbon (least stable) steel.

REFERENCES

1. R. A. Hadfield, Metallurgy and Influence on Modern Progress, Chapman and Hall, London 1925.
2. E. C. Bain and W. E. Griffiths, "An Introduction to the Fe-Cr-Ni Alloys," Trans. AIME, 75 (1927) 166.
3. V. N. Krivobok and R. A. Lincoln, "Austenitic Stainless Steels," Trans. ASM, 25 (1937) 637.
4. C. B. Post and W. C. Eberly, "Stability of Austenite in Stainless Steels," Trans. ASM., 39 (1947) 868.
5. N. A. Ziegler and P. H. Brace, "Hardening of Austenitic Stainless Steels by Mechanical Working at Sub-Zero Temperatures," Proceedings, ASTM, 50 (1950) 861.
6. V. F. Zackay, E. R. Parker, D. Fahr and R. Busch, "The Enhancement of Ductility in High Strength Steels," Trans, ASM, 60 (1967) 252.
7. J. A. Hall, V. F. Zackay, E. R. Parker, "Structural Observations in a Metastable Austenitic Steel", Trans. Quart. ASM, 62 (1969) 956.
8. W. W. Gerberich, P. L. Hemmings, V. F. Zackay, E. R. Parker, "Interactions Between Crack Growth and Strain-Induced Transformation," 2nd International Conference on Fracture, Brighton, England, April, 1969.
9. R. M. Bozorth, Ferromagnetism, D. Van Nostrand, New York, (1951).
10. K. Hoselitz, Ferromagnetic Properties of Metals and Alloys, Clarendon Press, Oxford (1952).
11. K. Mathieu, "Einfluss von Legierungs gehalt und Versuchsbedingungen auf die $\gamma \longrightarrow \alpha$ Umwandlung bei der Kaltuerformung austenitischer Stähle," Arch. Eisenhüttenewesen, 16 (1942) 215.

12. S. A. Kulin, M. Cohen, and B. L. Averbach, "Effect of Applied Stress on the Martensite Transformation," Trans, AIME, June (1952) 661.

13. E. Scheil, "Uber die Umwandlung des Austenits in Martensite in Eisen-Nickel-legierungen unter Belastung," Ztsch, anorg, allgem, Chemie, 207 (1932) 21.

14. T. Angel, "Formation of Martensite in Austenitic Stainless Steels", JISI, 177 (1954) 165.

15. G. W. Form and W. M. Baldwin, Jr., "The Influence of Strain Rate and Temperature on the Ductility of Austenitic Stainless Steel," Trans. ASM, 48 (1956) 474.

16. S. Floreen and J. R. Michalisin, "High Strength Stainless Steel by Deformation at Low Temperatures," ASTM Special Tech. Publ., No. 369, (1965) 17.

17. C. J. Gunter and R. P. Reed, "The Effect of Experimental Variables Including the Martensitic Transformation on the Low Temperature Mechanical Properties of Austenitic Stainless Steels," Trans. ASM, 55 (1962) 399.

18. B. L. Averbach, S. A. Kulin, and M. Cohen, "The Effect of Plastic Deformation on Solid Reactions: Part II - The Effect of Applied Stress and Strain on the Martensite Reaction". Cold Working of Metals, ASM (1949).

19. A. W. McReynolds, "Effects of Stress and Deformation on Martensite Transformation," Jour. Appl. Phys., 20 (1949) 896.

20. B. R. Banerjee, J. M. Capenos, J. J. Hauser, "Fracture Mechanics of Extra Work-Hardened Type 301 Stainless," in *Application of Fracture Toughness Parameters to Structural Metals*, Gordon and Breach (1966) 373.

21. J. P. Bressanelli and A. Moskowitz, "Effect of Strain Rate, Temperature and Composition on Tensile Properties of Metastable Austenitic Stainless Steel," Trans. ASM, 59 (1966) 223.

22. G. W. Powell, E. R. Marshall and W. A. Backofen, "Strain Hardening of Austenitic Stainless Steel," Trans. ASM, 50 (1958) 478.

23. G. Thomas, D. Schmatz, and W. Gerberich, "Structure and Strength of Some Ausformed Steels," in High Strength Materials, John Wiley (1965) 251.

24. W. J. McGregor Tegart, <u>Elements of Mechanical Metallurgy</u>, Macmillan (1966) 20.

25. B. Cina, "Effect of Cold Work on the $\gamma \longrightarrow \alpha$ Transformation in Some Fe-Ni-Cr Alloys," JISI, 177 (1954) 406.

FIGURE CAPTIONS

Fig. 1. True-stress true-strain curves for the 0.05% C steel (deformed 80% at 250°C) tested at several temperatures. Curves plotted to maximum load only -- not to fracture.

Fig. 2. True-stress true-strain curves for 0.20% C steel (deformed 80% at 250°C) tested at several temperatures. Curves plotted to maximum load only -- not to fracture.

Fig. 3. The room temperature yield strengths of the three steels for several deformation temperatures.

Fig. 4. The microstructure of the 0.20% C steel as solution annealed and quenched to room temperature. Magnification 900X.

Fig. 5. The microstructure of the 0.20% C steel after 80% deformation at 250°C. Magnification 900X.

Fig. 6. The yield strengths of both deformed and solution-quenched steels at several test temperatures.

Fig. 7. Elongations of both deformed and solution-quenched steels at several test temperatures.

Fig. 8. The ultimate tensile strengths of the solution-quenched steels at several test temperatures.

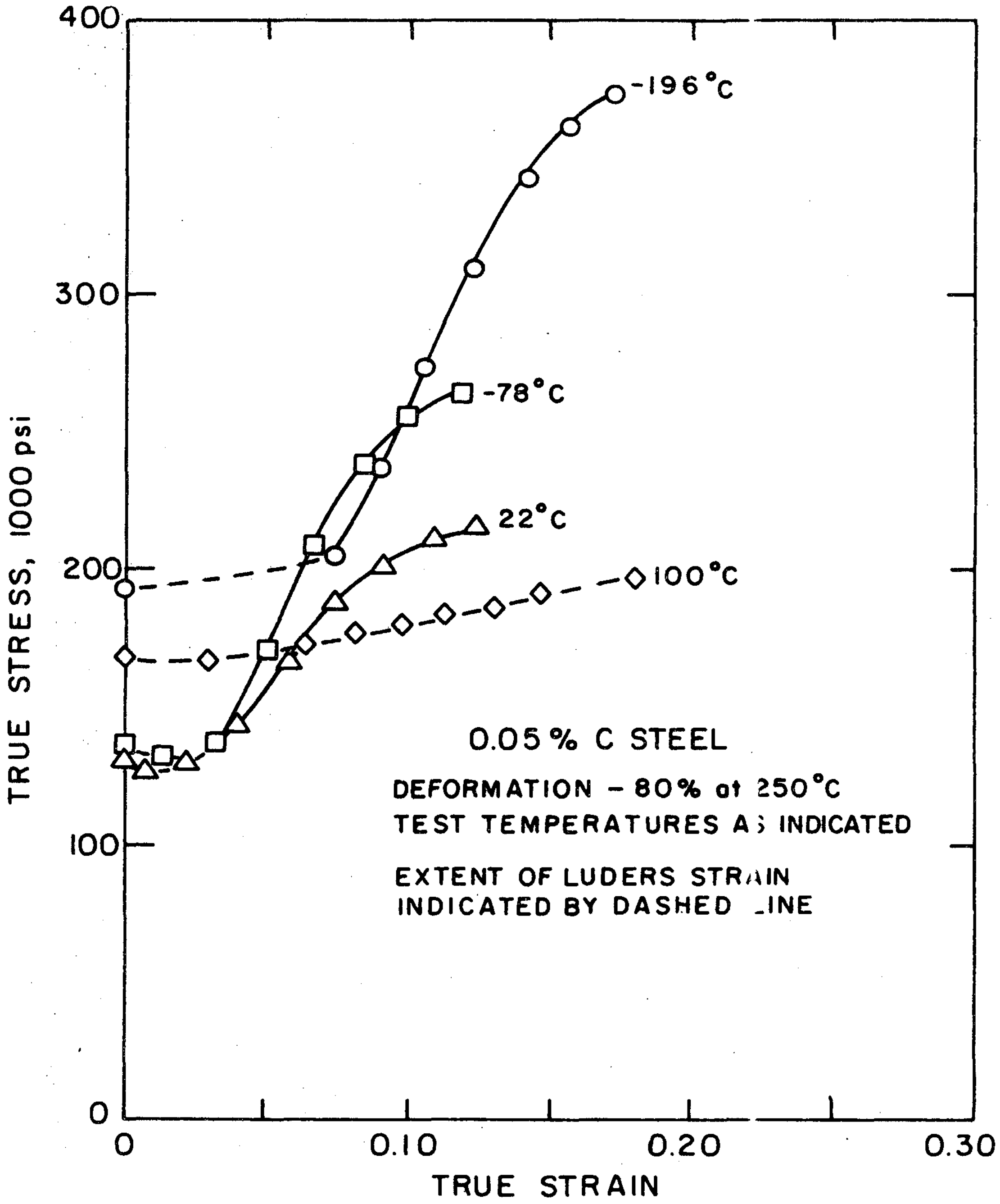
FIGURE CAPTIONS cont.

Fig. 9. The ultimate tensile strengths of the deformed steels at several test temperatures.

Fig. 10. Photograph of a flat tensile specimen tested at room temperature. The test was stopped during the initial flat portion of the stress-strain curve and illuminated to show the appearance of the Luders' bands.

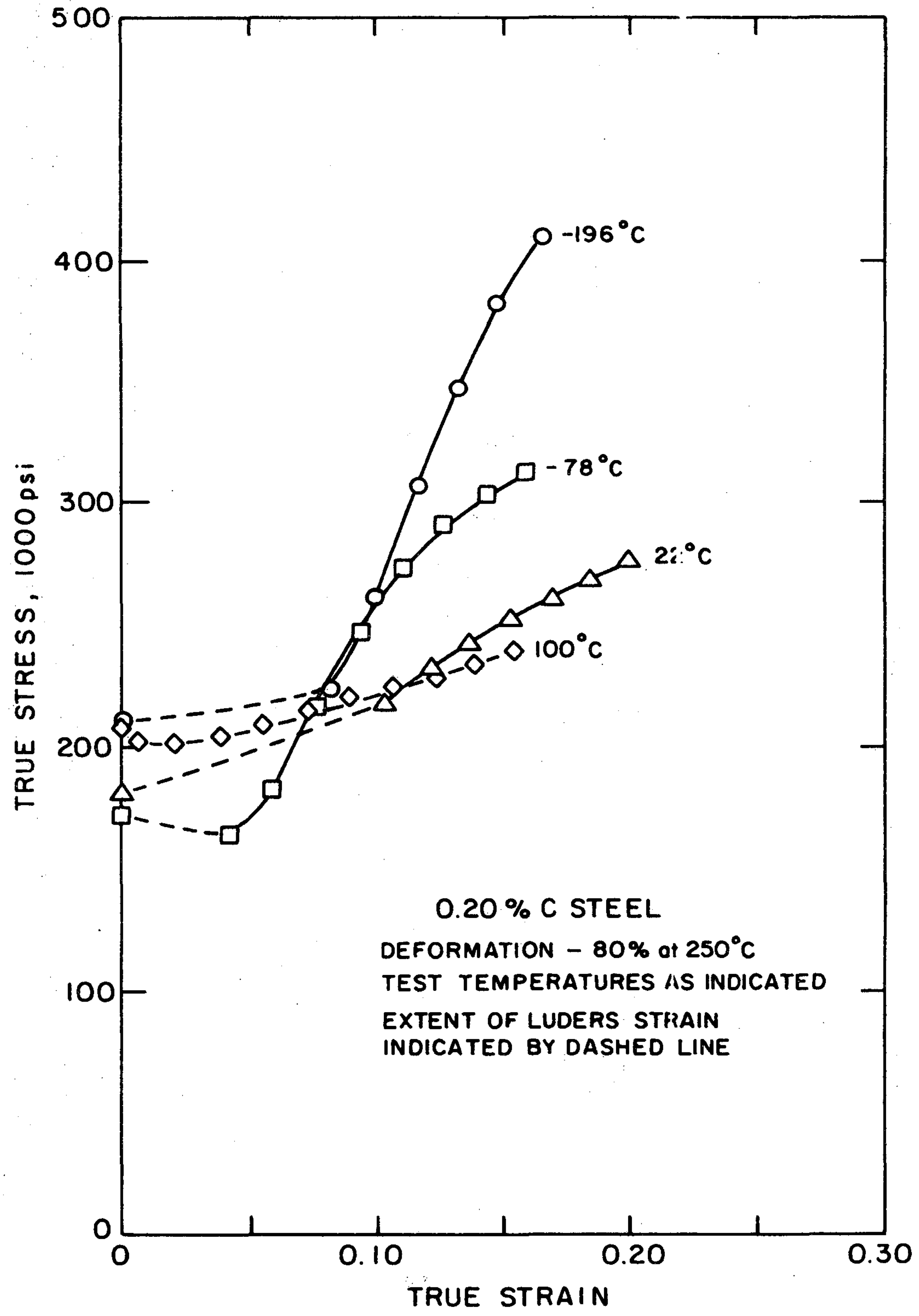
Fig. 11. The rates of work hardening of solution-quenched and of deformed 0.05 C and 0.20 C steels at several test temperatures.

Fig. 12. The rate of martensite production per unit strain for the 0.20 C steel in the deformed condition. (80% at 250°C.)



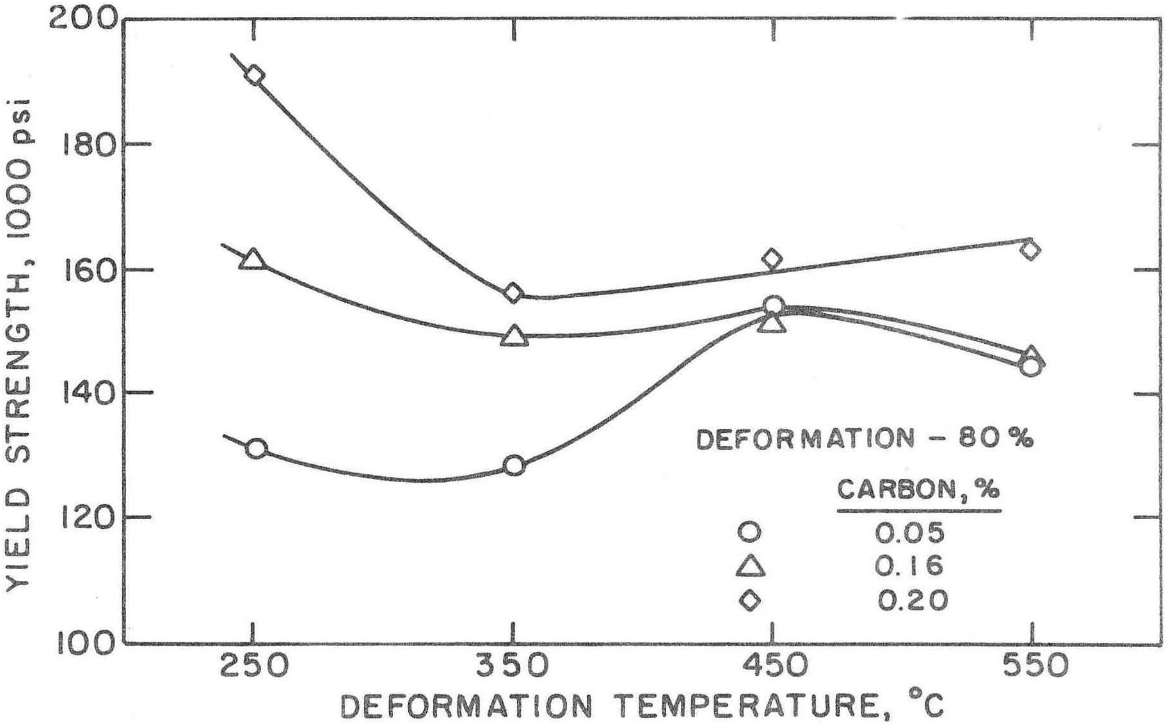
XBL 707-1537

Fig. 1



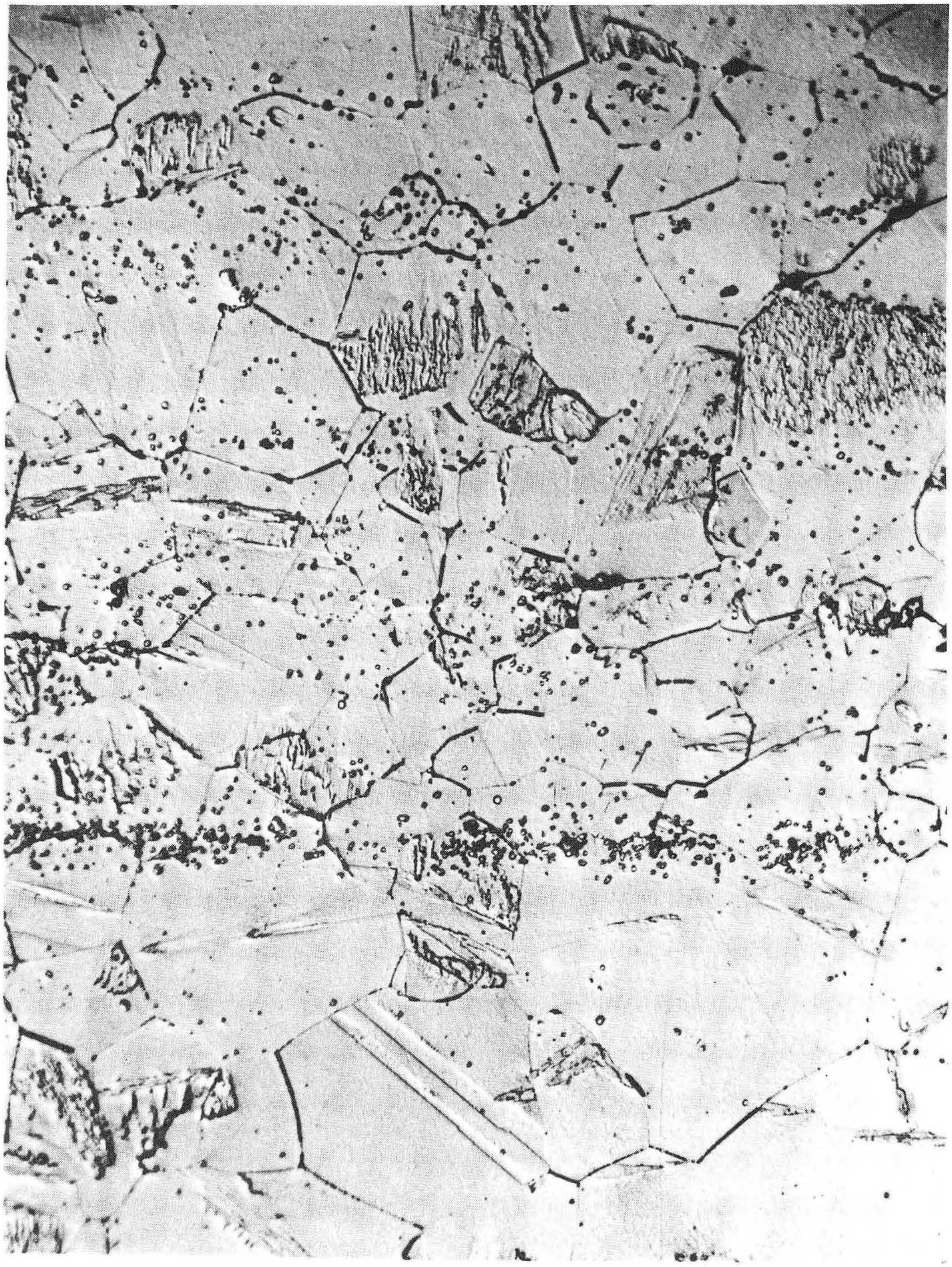
XBL 707-1538

Fig. 2



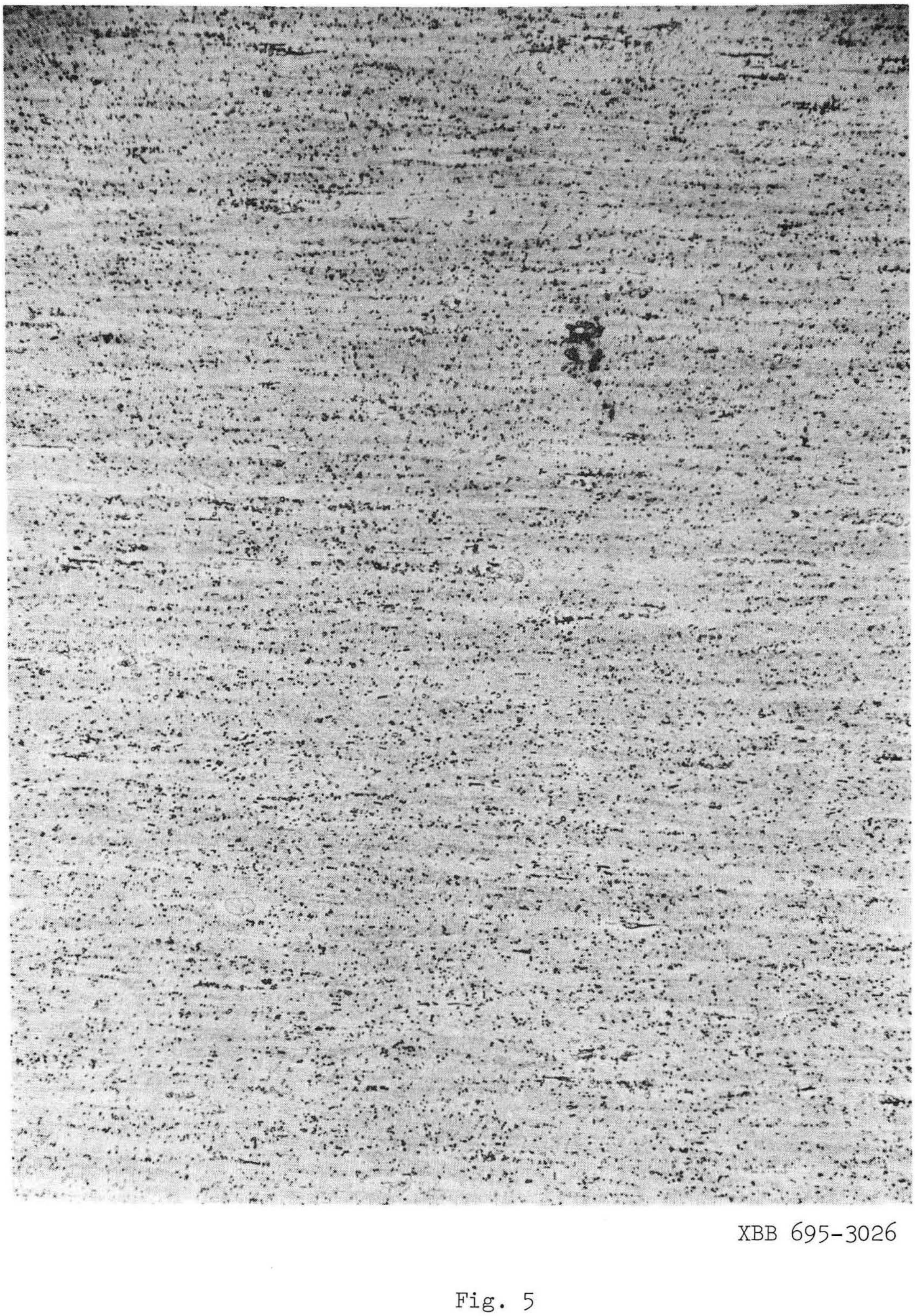
XBL 707-1532

Fig. 3



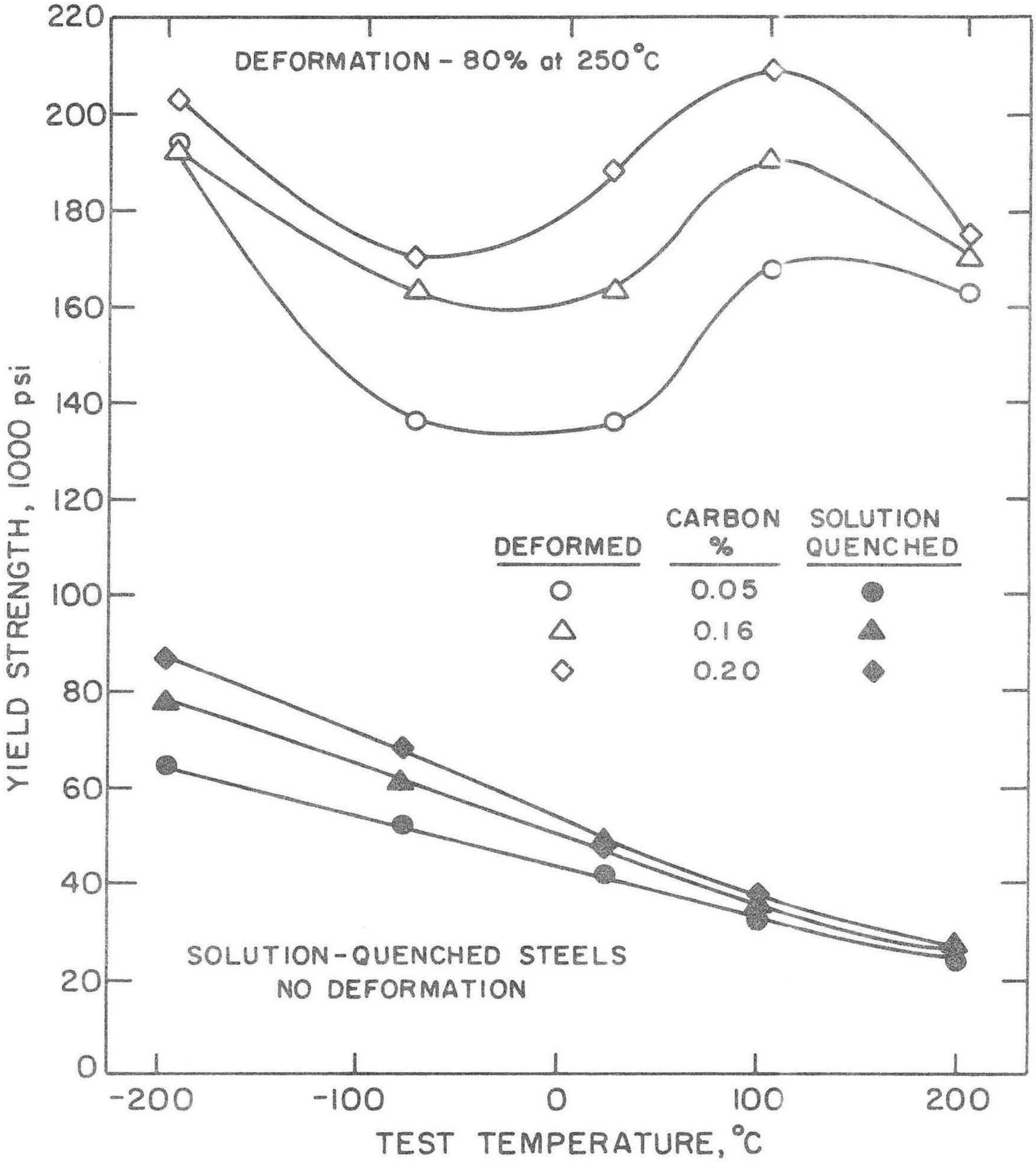
XBB 695-3025

Fig. 4



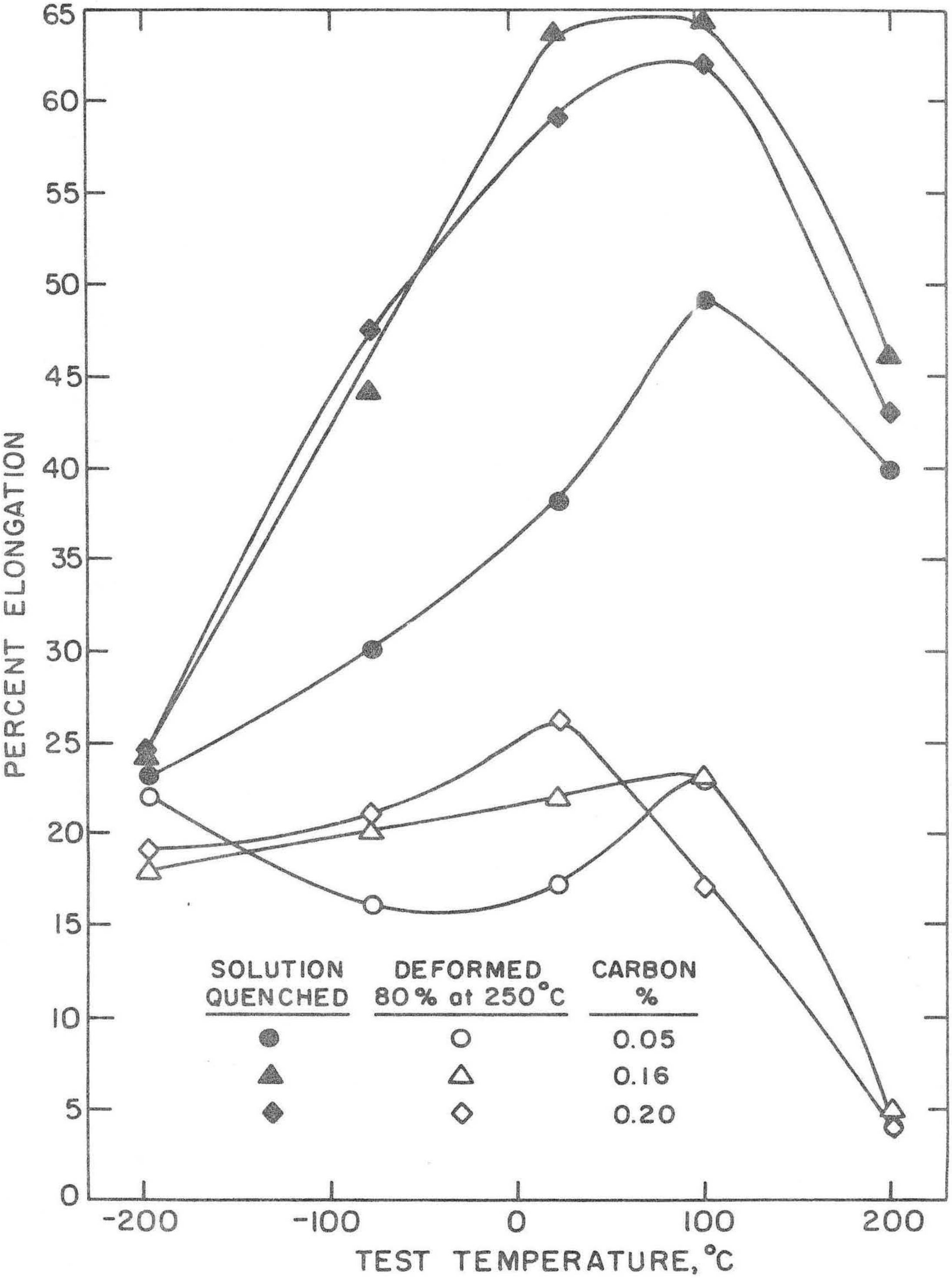
XBB 695-3026

Fig. 5



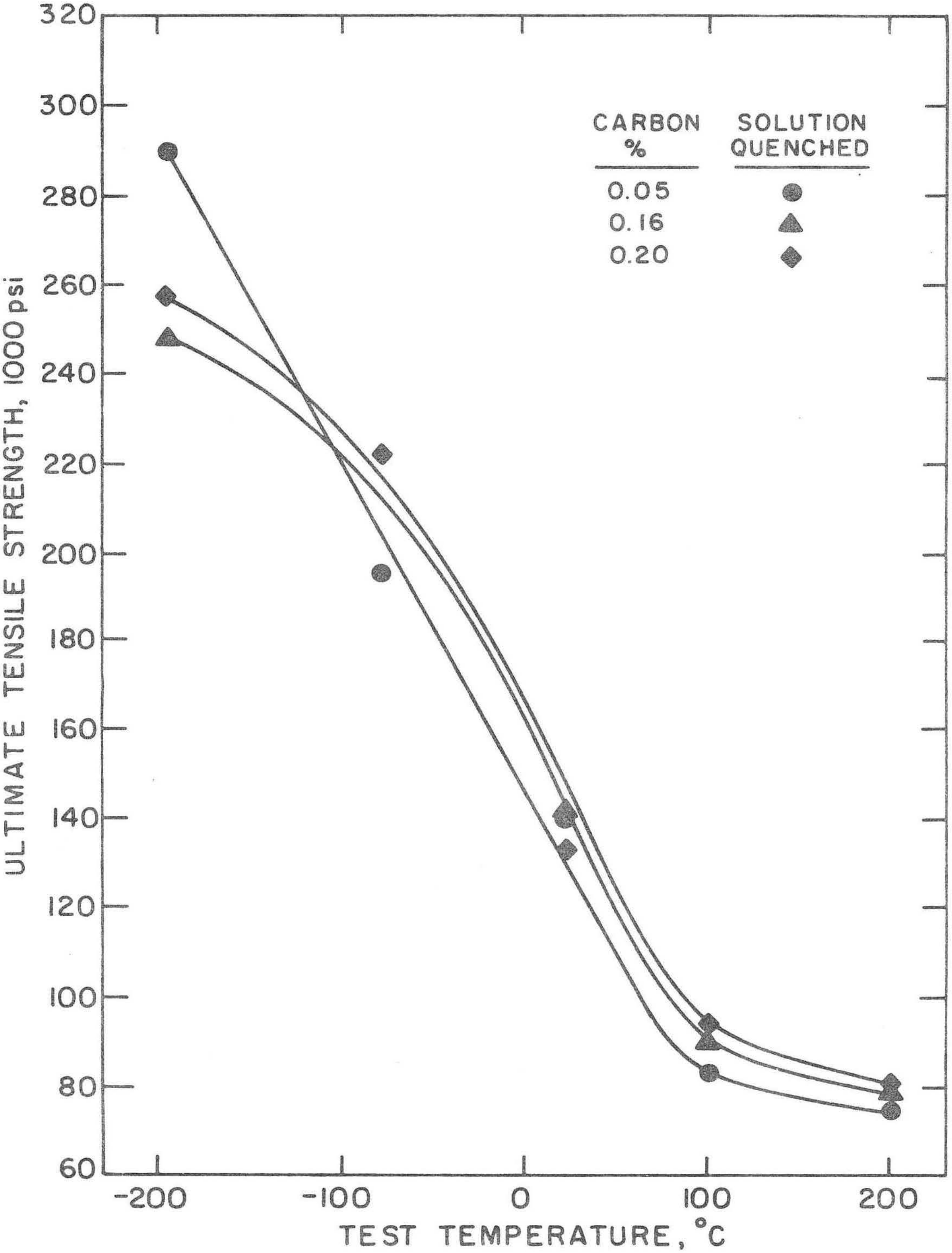
XBL 707-1536

Fig. 6



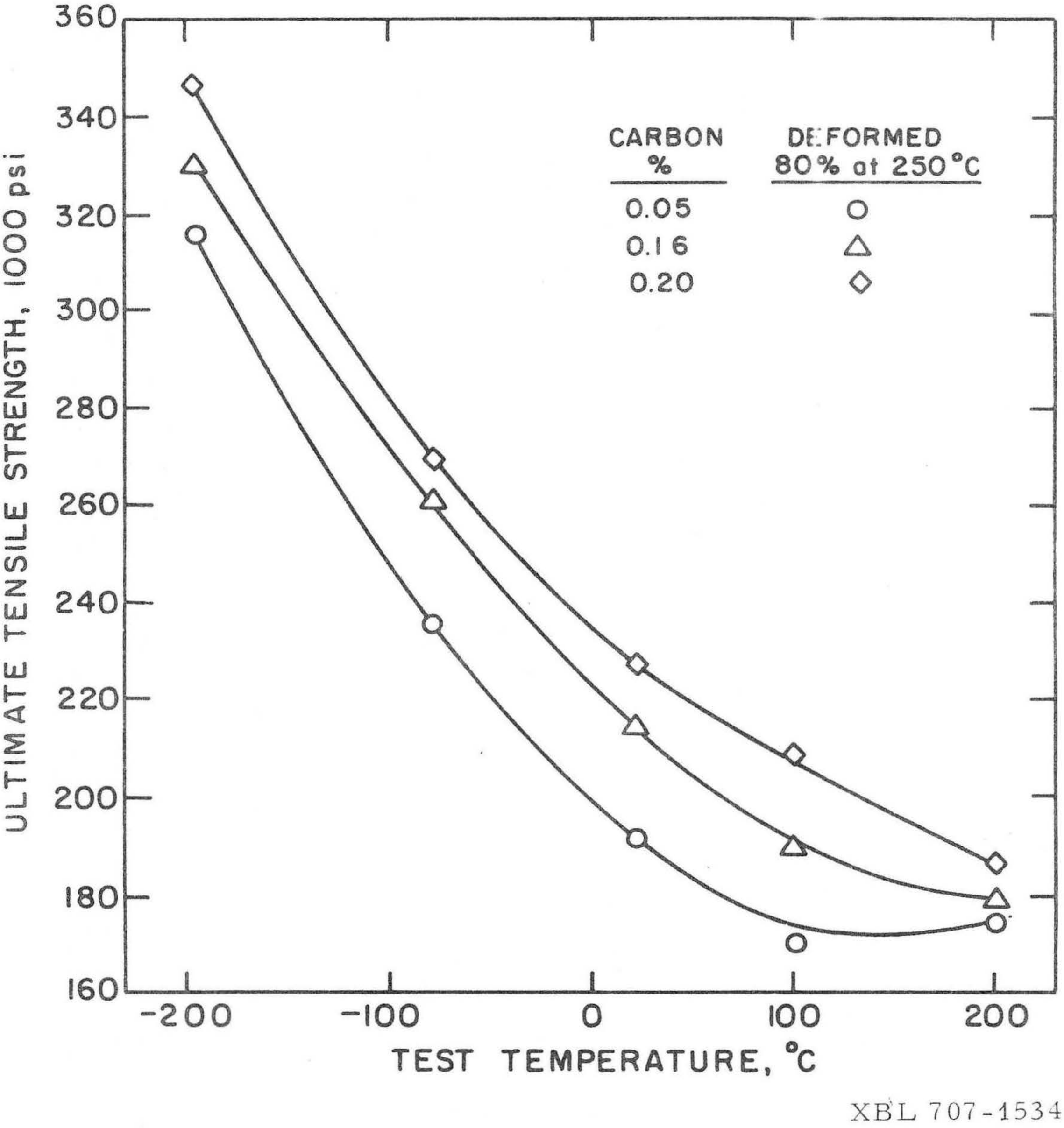
XBL 707-1535

Fig. 7



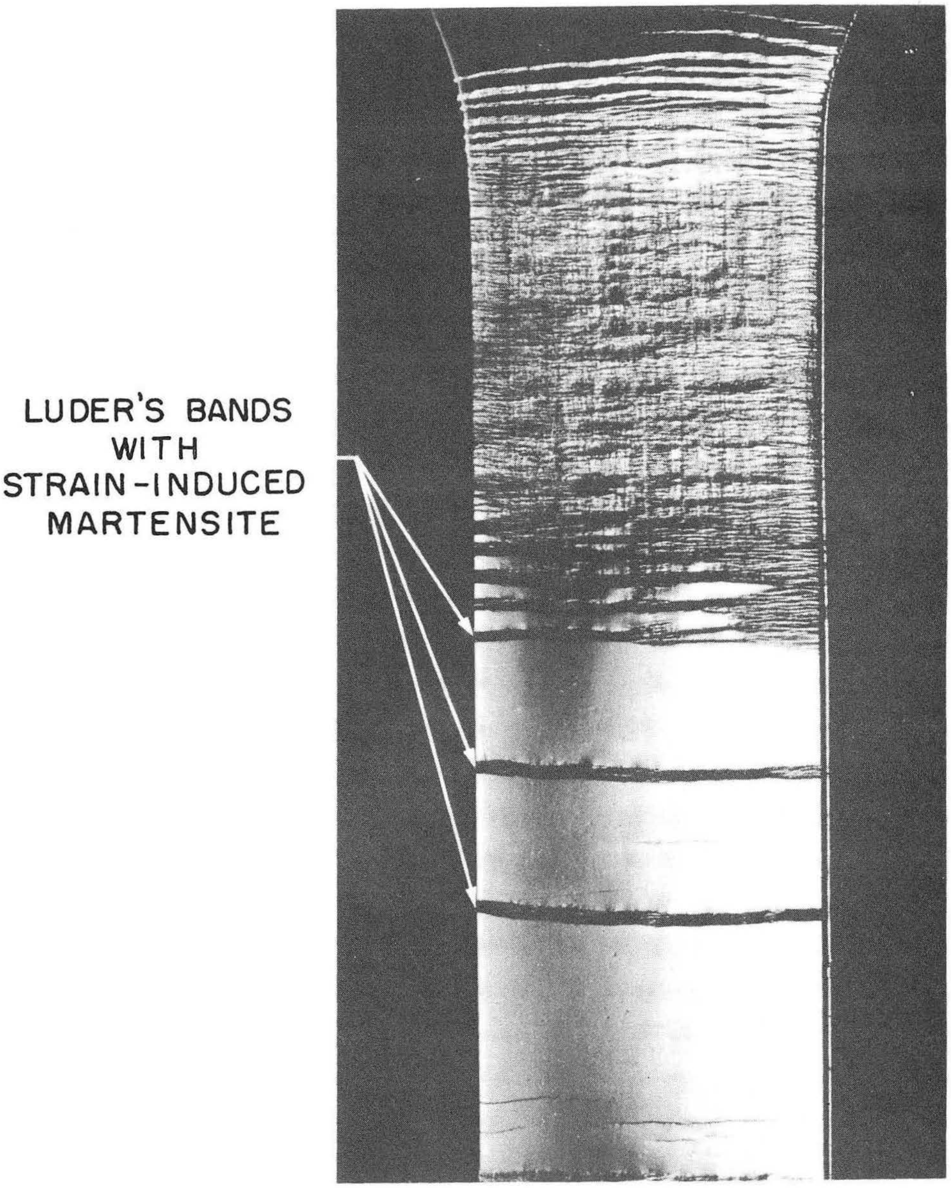
XBL 707-1533

Fig. 8



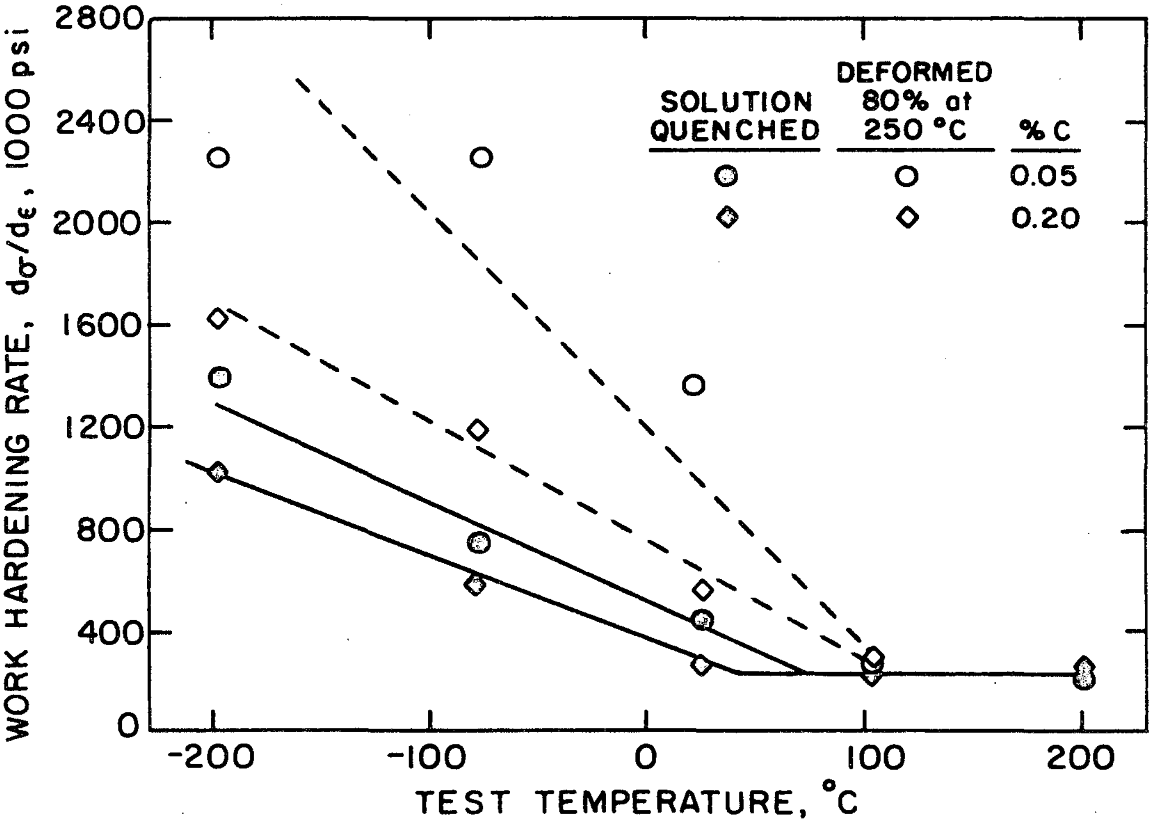
360
340
320
300
280
260
240
220
200
180
160
ULTIMATE TENSILE STRENGTH, 1000 psi
-200
-100
0
100
200
TEST TEMPERATURE, °C
CARBON %
DEFORMED 80% at 250°C
0.05 ○
0.16 △
0.20 ◇
XBL 707-1534

Fig. 9



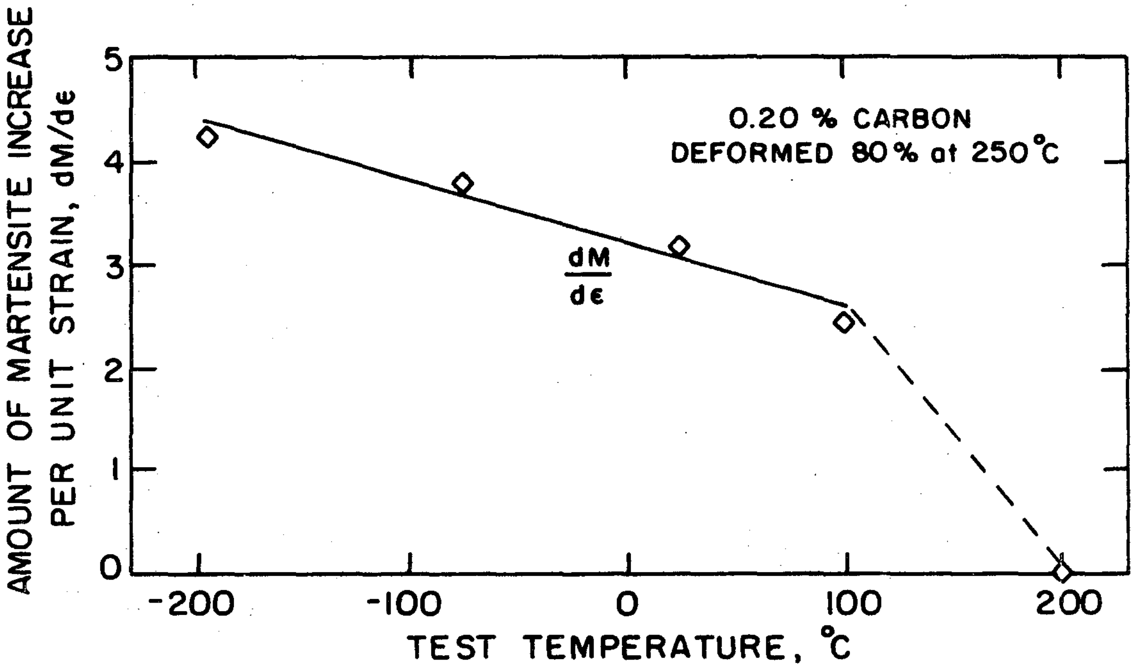
XBB 6811-6879

Fig. 10



XBL 707-1530

Fig. 11



XBL 707-1531

Fig. 12

LEGAL NOTICE

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720