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Lee P. Bendel
Lehigh University

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THE RESISTANCE OF AISI 5160 (POST-TENSIONED CONCRETE TENDONS) TO BRITTLE FRACTURE

by
Lee Powell Bendel

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in

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CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

16 May, 1966
(DATE)

R D Stout
Dean Robert D. Stout

J. F. Libsch
Dr. Joseph F. Libsch

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ABSTRACT

The effect of thermal and mechanical treatments on the tensile and notched tensile properties of post-tensioned concrete tendon material (AISI Type 5160 steel) was studied. The process variables studied included normalizing, proof stressing and stress relieving sequence, stress relieving time and temperature, and tempering temperature of quenched materials. The effect of test temperature on the properties of two conditions was also studied. The fracture toughness parameters, K_{Ic}, were calculated where applicable.

None of the variations in processing, excluding quenching and tempering, improved both the notched and smooth bar properties. The quenched and tempered specimens performed better in either one test or the other, and in some instances better in both. Test temperature had a marked effect on the notched tensile results. Notch severity was also shown to influence the notched tensile strength.

INTRODUCTION

The use of concrete as an engineering material has been increasing at a rather remarkable rate in order to provide civilization with a sufficient number of highways, schools, and places to live and work. The strength demands placed upon the concrete have increased as engineers attempt to keep size and weight to a minimum and architects attempt to improve the aesthetic features of their designs. Concrete performs quite adequately when purely compressive stresses are involved. However, the tensile strength of concrete is only about 10% of the compressive strength. The tensile properties of concrete structures can be improved by the addition of alloy steel tendons. A network of these tendons is constructed and the concrete is poured over them. After the concrete has become hard the tendons are loaded by hydraulic jacks to about 60 to 70% of their ultimate tensile strength. The tensile load is maintained with a gripping wedge or nut which rests on the end plate. Figure 1 illustrates a concrete structure with a tendon under a tensile load. The net result is a concrete structure with uniform properties in both compression and tension. The tendons also provide a method of connecting precast structures.

Knowledge is needed about the relationship between metallurgical factors and the mechanical demands placed upon tendon material, since the use of alloy steel rods to posttension concrete structures is increasing. The practice of positioning and connecting tendons by threaded couplings results in a fairly sharp notch. Also, a bar might be accidentally touched by a weld electrode which would result in a mechanical notch and a metallurgical notch since an area of untempered martensite would be formed.

The effect of specimen geometry on the notched fracture stress; especially where the principles of fracture mechanics apply, has been extensively studied. In order to take full advantage of prior work the specimen geometry used in this investigation was made to conform with those prescribed by a fracture mechanics approach. Thus, it was possible to calculate the"Plane Strain Fracture Toughness Parameter" where all fracture mechanics criteria were fulfilled. This aspect will be discussed further in a later section. Smooth bar tests were also conducted in each heat treated condition using a standard specimen size and geometry. The smooth bar test results provided a method of comparison between notched and unnotched strength levels.

FRACTURE MECHANICS

The basis for sharp crack fracture mechanics was proposed by A. A. Griffith(1) in 1920. His concept of crack-propagation states that an existing crack will propagate in a cataclysmic fashion if the available elastic strain energy release rate exceeds the increase in surface energy of the crack.

Irwin(2) showed that the energy approach is equivalent to a stress-intensity approach developed by Westergaard(3). The stress-intensity approach states that fracture occurs in a given material when a critical stress distribution is reached.

Westergaard developed the following linear elastic stress field equations for cracks:

$$\sigma_x = \frac{K}{(2\pi r)^{1/2}} \cos\frac{\theta}{2} \left(1 - \sin\frac{\theta}{2} \sin\frac{3\theta}{2}\right)$$

$$\sigma_y = \frac{K}{(2\pi r)^{1/2}} \cos\frac{\theta}{2} \left(1 + \sin\frac{\theta}{2} \sin\frac{3\theta}{2}\right)$$

$$\tau_{xy} = \frac{K}{(2\pi r)^{1/2}} \cos\frac{\theta}{2} \sin\frac{\theta}{2} \sin\frac{3\theta}{2}$$

σ_x, σ_y and τ_{xy} are the normal stresses and shear stress on an element at distance r and angle θ from the crack tip.

K is the stress-intensity factor of the elastic stress field in the vicinity of the crack front. K is a function of the applied stress and the crack length (assuming an infinitely sharp crack). For a crack whose length is assigned the value 2a in an infinite plate, the stress intensity factor is given by:

$$K = \sigma(\pi a)^{1/2}$$

The term Kc is used to denote the critical value of K at the point of instability of crack extension; or fracture toughness. The fracture toughness term is used to indicate a measure of the resistance of a material to brittle failure under severe stress condition as introduced by the presence of a flaw. The subscript I of K_I or K_{Ic} refers to the opening mode of crack extension, or plane strain conditions.

The Westergaard equations describe elastic conditions and, therefore in materials which exhibit plastic deformation at the root of the crack, the crack length must be corrected to include the plastic zone size. The plastic zone size is found by equating plastic yield conditions to the elastic stress distribution. Formulas have been developed to determine the plastic zone size for the various test geometries. The formulas used for the notched round test specimens are given in Appendix I. Since the Westergaard formulation is based on elastic conditions it is valid only when the plastic zone size is small in comparison to the specimen diameter or thickness. A common test used to determine if essentially elastic conditions exist is to calculate the ratio of notched tensile strength to the unnotched yield strength. It has been shown(4) that if this value is less than 1.1 the Kc value calculated from the formulas given in Appendix I will be the plane-strain fracture toughness. Plane-strain represents the most severe stress conditions which can be placed on a material, thus the parameter calculated under these conditions is the lower limit of fracture toughness. That is, there is no way in which the stress conditions can be made more severe in their effect on fracture toughness. The plane-strain fracture toughness parameter has become quite useful in the design of thick wall pressure vessels made of high strength materials.

EXPERIMENTAL PROCEDURE

Description of the Steel Tested:

The material tested in this experimental program was an AISI Type 5160 steel. Two heats were tested with slightly varying chemistry. The chemical analyses are given in Table I. The material supplied was 1 1/4 inches in diameter. All specimens including the 0.505 inch diameter smooth bar tensile specimens were taken from this size bar.

Description of Thermal and Mechanical Treatments:

Several specimens were tested in the standard condition or modifications thereof. The standard condition consisted of proof stressing hot rolled bars to about 87% of the ultimate tensile strength and stress relieving at 700°F for about 4 hours. Other specimens were tested in the austenitized quenched, and tempered condition. These specimens were normalized at 1600°F for 1 hour, austenitized at 1550°F for 30 minutes, and tempered at the desired temperature for 4 hours.

The high temperature treatments, austenitizing at 1550°F and normalizing at 1600°F, were conducted in a globar furnace. The specimens were packed in cast iron chips to prevent excessive oxidation and decarburization. A thermocouple was placed next to the specimens to monitor temperature and the time for the specimens to come to the desired temperature. Low temperature treatments; stress-relieving and tempering, were performed in a forced-air furnace. About 20 minutes were allowed for the specimens to come to temperature.

The proof stressing was achieved by loading the specimens to about 87% of the ultimate tensile strength and then immediately releasing the load.

Description of the Smooth Bar Tensile Tests:

The specimen used for this portion of the testing program was 0.505 inches in diameter and had a 2.0 inch gage length. It was a threaded-end round tension test specimen as described in the Metals Handbook(5). The specimens were machined to their proper size before heat treatment except for the gage section which was left about 0.020 inches oversize. The gage section was machined to the proper diameter after heat treating, removing all scale formed plus any possible decarburized material. The specimens were tested in a Universal Testing Machine. An extensometer was attached to the specimens so that a plot of elongation versus load could be recorded which was then used to determine the 0.2% offset yield strength. The ultimate tensile strength, percent reduction in area and percent elongation were determined in the usual manner. Several tests were conducted at temperatures about and below room temperature. The specimens tested above room temperature were heated in a forced-air furnace to about 120°F above the desired test temperature.

The specimens were placed in position in the testing machine and a chromel--alumel thermocouple was welded onto the shoulder of the specimen using an electric discharge welder. The temperature of the cooling specimen was monitored with a direct reading potentiometer. The cooling rate was very slow in the range of temperatures which were tested. The specimens cooled about 5°F every two minutes, and since it only took about two minutes to conduct the tests, the actual test temperature was within ±5°F of the desired temperature.

The tests conducted at 0°F were conducted in a similar manner. The specimens were placed in a cryostat containing dry ice for about 15 minutes. The specimens were removed and placed in the test machine. A thermocouple was attached and the heating rate monitored. The heating rate was similar to the cooling rate. The temperature during the test could not be controlled as closely as for the elevated temperature tests because of the heating due to internal friction as the specimen was loaded. Temperature measurements taken immediately after the test was completed indicated that the specimens were all between 10 and 20°F. The temperature at the point of yielding was probably very close to 0°F, because most of the heating occurred after the specimen began to neck. The frost which formed on the specimen melted only in the region of the neck. The heating rate was thus quite uniform and quite slow until the onset of necking. Since necking takes place after the yield point is reached and after the maximum load, it is reasonable to assume that these properties were measured quite close to the desired temperature. The percent reduction in area and percent elongation were, however, subject to error because these properties depend upon the test temperature at all stages of testing.

Description of the Notched Bar Tensile Tests:

The geometry of the notched bar tensile specimens complied with that recommended by the ASTM Committee on Fracture Testing of High Strength Materials (6). Most of the specimens were 1 1/4 inches round, the one exception will be discussed later. The specimens were 8 inches long with 1 inch of 1 1/4 - 12 N.F. threads machined on each end. The distance from the centrally located notch to the threads was thus 2.4 times the diameter which is greater than the 2D limit set by the ASTM Committee. The specimen geometry is illustrated in Figure AP-1.

The diameter at the root of the notch should be 0.707 times the diameter of the bar, or in this case 0.884 inches. A notch was machined in the center of the specimen to such a depth that the resulting diameter was 0.900 inches. The notch radius was about 0.010 inches. The specimen was then placed in the fatiguing device shown in Figure 2. The machine shown is a Milwaukee Model H end miller. The chuck was fitted with a sleeve to hold the 1 1/4 inch diameter bars. Threads were tapped at the bottom of the sleeve to keep the bars in place. A 2 foot extension arm was made to fit the threads on the other end of the specimen. A bearing was attached to the end of the extension arm so that weights could be hung from the extension arm. The amount of weight which was applied was such that the outermost fibers (at the root of the notch) were loaded to about 90% of the smooth bar yield strength. The load was calculated using the formula:

90% yield strength = KMr/I.

where K is the stress concentration factor = 4.2(7)
M is the moment = load times moment arm
I is the moment of inertia = $r^4/4$
r is the radius at the root of the notch.

The number of cycles required to produce fatigue cracks using loads as calculated above varied from 2800 to 54,000, but was usually about 20,000 to 30,000. The fatigue cracks were visible by means of a 20X eyepiece; however, there was no way of determining the depth of the crack until the specimen had been broken in tension. The depth of the crack was measured after fracture by placing the specimen on a metallograph with a calibrated stage. Six such measurements were made at 60° intervals around the specimen. The crack depth was taken to be the average of the six measurements. In most cases the fatigue crack was very concentric. The net radius was determined by subtracting the average notch depth from 0.450, the machined radius.

The specimens tested at elevated temperature and at

0°F were tested in the same manner as the smooth bar tensile specimens tested at these temperatures. Since the cooling or heating rate was slower for the larger specimens the test temperature could be controlled more closely. The specimens tested at -100°F were placed in a sheet metal container with the threads of the specimen exposed so that it could be placed in the tensile machine. The container was then packed with dry ice. A copper-constantan thermocouple was used to measure the temperature at the ends of the specimen. The temperature reached -100°F in a few minutes.

Specimens from each heat were normalized at 1600°F for 1 hour and air cooled and then given the standard treatment. These bars had to be machined to 1 1/8 inches round so that they could be loaded to 87% of the ultimate tensile strength without failing in the threads. The machined notch in these specimens reduced the net diameter to 0.840 inches. They were then fatigued cracked so that the net diameter was about 0.795 inches, or 0.707 times the gross diameter.

Description of the Hardness Tests:

The hardness tests were conducted just below the fracture surface of the notched bar tensile specimens. After the specimens were fractured a disc was cut from the fractured end. The fracture surface was then ground just enough to allow hardness measurements to be made on the entire surface. Hardness measurements were made near the center, midradius, and surface to make sure there were no differences in structure across the fracture surface. These same specimens were later used for micro-examination.

DISCUSSION OF RESULTS

The test results are divided into four groups to facilitate the discussion. These groups consist of the pearlitic materials, the martensitic materials, the specimens treated by different methods to the same strength level, and the fracture toughness parameters.

Pearlitic Structures:

The results obtained for specimens which had a pearlitic microstructure are given in Table I. It can be seen that changes in the sequence of the standard treatment had almost no effect upon either the smooth bar tensile properties or the notched tensile strength. These variations in process sequence include; cold stretching and stress relief at 700°F (the standard treatment), stress relieving and then cold stretching, or just cold stretching. The specimens which were normalized rather than as rolled prior to the standard treatment had similar smooth bar tensile properties, and had slightly improved notched tensile strength. The specimens which were stress relieved at 1100°F had very good notched fracture properties, but the smooth bar yield strength was so low that such a treatment would be impractical. An attempt was made to relate the smooth bar results with those obtained with the notched bar. Figures 3 and 4 show plots of the notched fracture strength versus smooth bar yield strength and percent reduction in area. There was no correlation between notched and smooth bar strength levels, but there was some indication that the notched tensile strength increases rapidly with increasing smooth bar percent reduction of area between 30 and 45%. At percent reduction of area values greater than 45% and less than 30% there seems to be no correlation between notched fracture stress and percent reduction of area.

The fracture appearance of the notched tensile specimens is shown in Figure 5. It can be seen that there was very little variation in fracture appearance, except for the specimens stress relieved at 1100°F which showed more tearing than the others. Microscopic examination of these specimens revealed that there was little if any difference in microstructure resulting from the treatments. Representative microstructures are shown in Figures 6 to 9.

Three specimens from Heat 1 in the standard condition were tested without a fatigue crack. These specimens had only the machined notch which had a radius of 0.010 inches. They failed at a stress level equal to the smooth bar yield strength. The same specimens with a fatigue crack failed at less than one half the smooth bar yield strength. This demonstrated rather strongly the effect of the notch sharpness on the resultant notched bar fracture strength.

Martensitic Structures:

The results obtained for specimens which had a martensitic microstructure are given in Table II. These specimens displayed a range of smooth bar and notched bar tensile properties. Specimens tempered at the lowest temperature, 800°F, had the highest smooth bar strength and the lowest notched tensile strength. The specimens tempered at the highest temperature, 1200°F, behaved oppositely. The effect of tempering temperature on the various properties tested is shown in Figures 10 to 13. The optimum balance of smooth bar properties and notched bar tensile strength occurred at the intermediate tempering temperature, 1000°F. The results obtained for the two heats varied only slightly. The heat with higher alloy content had higher smooth bar properties, but lower notched properties.

The plots of notched fracture strength versus smooth bar yield strength and percent reduction in area are shown in Figures 3 and 4. There was an inverse relationship between notched fracture strength and smooth bar yield strength. At a yield strength of 175 KSI the notched fracture strength changed quite rapidly. A similar relationship existed between notched fracture strength and smooth bar percent reduction in area in the martensitic specimens as that in the pearlitic specimens. The notched fracture strength increased with increasing smooth bar ductility.

The fracture surface of the notched bar specimens is shown in Figure 14. The specimens tempered at the higher temperatures had very unusual fracture surfaces. In addition to the fracture normal to the tensile axis, there was failure in a direction parallel to the tensile axis. This can be seen in Figure 14. It is generally accepted that a triaxial stress state exists below the root of a notch in a circumferentially notched bar loaded in tension(8). Thus there are forces trying to pull the bar apart in all three directions. The unusual fracture which occurred in the specimens tempered at high temperatures was caused by the fact that the strength in the axial direction of these ductile materials has been increased by the plastic constraint caused by the notch. If the radial stress reaches a high enough value, failure may also occur in a direction parallel to the axis of the bar. It was originally believed that the longitudinal failure occurred first; relieving the plastic constraint so that the failure perpendicular to the axis could proceed. Several specimens were loaded to a point just below which failure should occur. The specimens were then split apart and examined for transverse failure. Since there was none, the failures in both directions must have occurred at the same load.

<u>Specimens Treated to the Same Strength Level:</u>

Two process conditions from one heat were tested at several temperatures above and below room temperatures. The conditions tested were (1) the standard cold stretched and stress-relieved treatment and (2) austenitized, quenched and tempered to the same strength level as the first condition.

The quenched and tempered specimens were not quite as strong as the standard treatment, but, the difference was too small to affect the general purpose of the tests. The tempering temperature selected to give a strength level comparable with the standard condition was 1130°F. The test results which were obtained are reported in Table III. The data are also shown graphically in Figures 15 and 16. It can be seen that with decreasing temperature the smooth bar strength levels increase, while the ductility decreases. The ductility values should be used only to indicate trends because as was indicated in EXPERIMENTAL PROCEDURE these values may be subject to error. The expected result for a condition of increasing strength and decreasing ductility is that the material would be more susceptible to brittle failure. This was indeed the case with the material in the standard condition. The specimens tested at 200°F had a notched fracture strength which almost equaled the yield strength, whereas at 0°F the ratio of notched fracture stress to yield stress was less than 0.5. There was no significant difference between the ratio of notched fracture stress to yield stress at 75°F and 0°F; thus there was a lower limit for the strength ratio.

There was no point in testing at temperatures greater than 75°F because the specimens in the quenched and tempered condition were notch strengthened even at temperatures down to -100°F. The tempered martensite was shown to be quite ductile and resistant to brittle fracture even at -100°F. Although there was no change in the fracture strength, there was a change in the fracture appearance as is shown in Figure 17. The fracture in a direction parallel to the specimen axis disappeared at the lower temperatures and the amount of fibrous fracture (the dark areas which have probably failed in a ductile manner) decreased. Thus, the fracture appearance indicates that a transition from ductile failure to brittle failure may occur, although the fracture strength does not reflect this.

The morphology of brittle fracture in a pearlitic and martensitic steel containing 0.56% Carbon has been investigated by Turkalo(10). She found that the fracture facet size is dependent upon the size of ferrite areas with a given crystallographic orientation. Hillert(11) has shown that the crystallographic orientation of the ferrite in a pearlite colony is the same throughout since the cementite and ferrite plates are actually interpenetrating single crystals. In addition the orientation of the proeutectoid ferrite is quite often the same as adjacent pearlitic ferrite. Thus, the fracture facets should be at least as large as the pearlite colonies. Turkalo found them to vary in size between the average pearlite colony size and the prior austenite grain size. The fracture facet size of tempered martensite was equal to the martensite needle size which was quite small in comparison to the pearlite colony size. Turkalo has suggested that fracture toughness is related to the fracture facet size, so that a given steel treated to have similar strength levels but different microstructures will show a dependence of fracture toughness on microstructure. The results obtained in this work have substantiated Turkalo's suggestion.

Fracture Toughness Parameters:

Up to this point little mention has been made of the fracture toughness parameters because some of the notched bar failures did not occur under plane strain conditions. Thus, it was better to discuss the results based on notched fracture strength alone. Many of the specimens did fail in plane strain conditions and the Plane Strain Fracture Toughness Parameters, K_{Ic}, are reported in the Tables for these specimens.

It was mentioned in the section on FRACTURE MECHANICS that if the notched fracture strength to smooth bar yield strength ratio is less than 1.1 plane strain conditions exist. A fracture toughness value was calculated using the procedure outlined in Appendix I for all specimens which had a notched strength to yield strength ratio less than 1.1.

The notched fracture strength to yield strength ratio obtained for the specimens given the standard treatment and tested atvarious temperatures were all less than 1.1. This indicated that plane strain conditions existed for all test temperatures. The data demonstrate that the fracture toughness parameter is temperature dependent. The values obtained at 75°F and 0°F were quite similar, so there is probably a limiting lower value. A plot of K_{Ic} versus test temperature is shown in Figure 15.

CONCLUSIONS

1. At the same strength level microstructures produced by oil quenching produced superior notch fracture strength to that shown in bars that were cold stretched and stress relieved.

2. There was no relationship between smooth bar yield strength and notched fracture strength for the pearlitic materials. There was an inverse relationship between these two strength values for the martensitic materials. Above a critical value of 170 to 180 ksi in yield strength the notched fracture strength dropped rapidly.

3. There was a marked increase in notched fracture strength with increasing smooth bar ductility over the range of 30 to 45% reduction in area.

4. Changes in the commercial process sequence and variables had very little effect upon properties. The one exception, stress relief at 1100°F, was impractical because the yield strength was drastically reduced.

5. Increasing tempering temperature lowered smooth bar strength levels and raised smooth bar ductility and notched fracture strength.

6. Test temperature may have an effect on the notched

tensile strength. Notched tensile strength and K_{Ic} values decreased with decreasing test temperature to some limiting lower value.

7. Bars given the standard treatment were not severly embrittled at room temperature by a charpy notch, whereas those specimens which had a fatigue crack were embrittled. Thus, notches produced by proper threading will not improve the load carrying capacity, while notches produced by fatigue will have a detrimental effect.

APPENDIX I

The general configuration of the fracture toughness specimen used in this experimental program is shown in Figure AP-1. The specimen had an overall length of 8 inches. One inch of threads (1 1/4 - 12 N. K.) were machined on each end. The major diameters used were 1.250 and 1.125 inches.

K_{Ic}^2 was calculated from the following equation:

$$K_{Ic}^2 = \frac{1.63\ P^2 D}{d^4}\left((.172 - .8\ (d/D - 0.65)^2\ )\right) \quad . \quad 1.$$

The factor in brackets varied from 0.1697 to 0.1720 for the d values determined for the specimens tested. Thus, an average value of 0.171 was used. If D is assumed equal to 1.250, equation 1 reduces to:

$$K_{Ic}^2 = 0.348\ (1/d^4)P^2 \quad \ldots\ldots\ldots\ldots\ldots \quad 2.$$

The d used in this formula is d_o, the actual diameter at the root of the notch, plus the plastic zone size which is calculated from:

$$d_p = \frac{K_{Ic}^2(1 - \nu^2)}{3\pi\sigma^2_{y.s.}} \quad \ldots\ldots\ldots\ldots\ldots \quad 3.$$

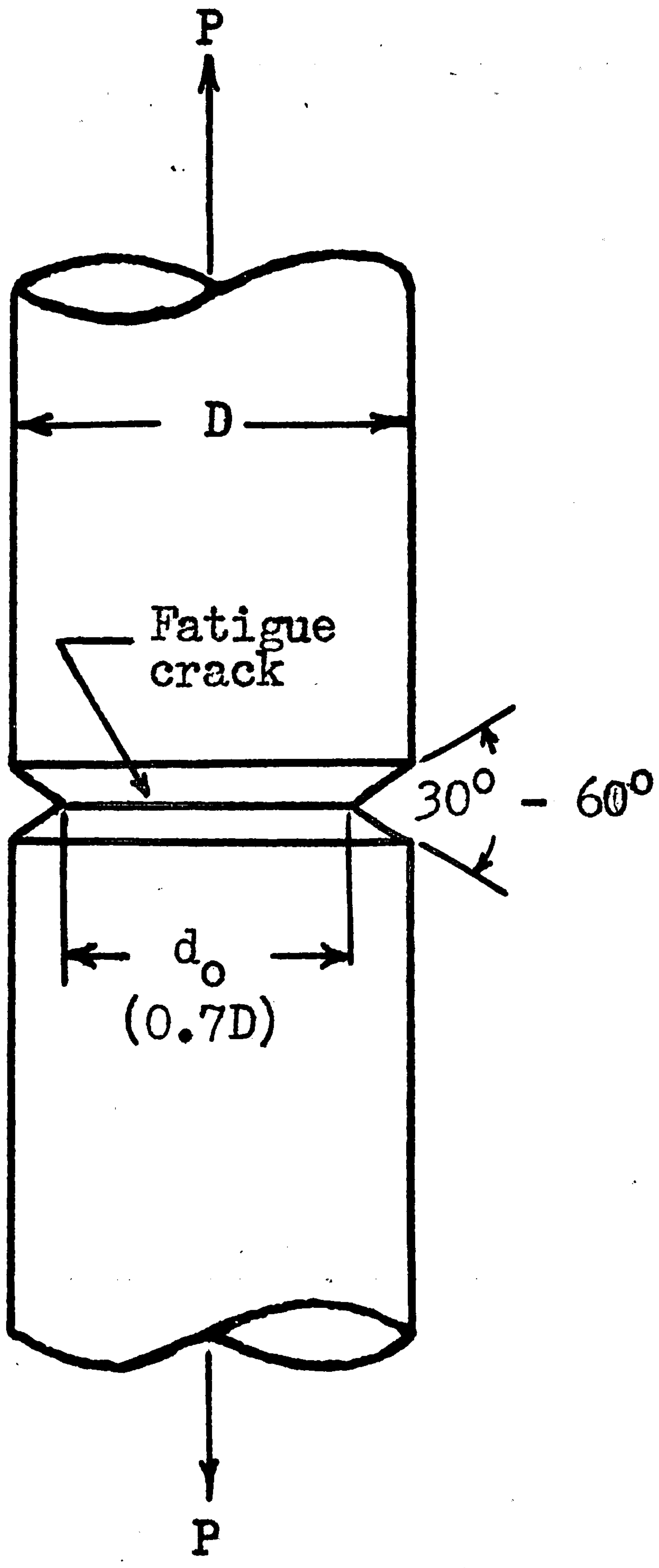
If ν is assumed equal to 0.33, equation 3 reduces to:

$$d_p = 0.0943 K_{Ic}^2/\sigma^2_{y.s.} \quad \ldots\ldots\ldots\ldots \quad 4.$$

Further:

$$d = d_o - d_p \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 5.$$

K_{Ic} is found by successive approximations. That is, a value for K_{Ic} is used in equation 5. The value of d calculated is then used in equation 2 to determine a new K_{Ic}. The advantage gained by repeating this process more than once is minute.



For plane-strain tests only:

d_o is the minimum diameter of the fatigue crack at the root of the notch. It is measured after the specimen has been fractured.

$$\frac{EG_{Ic}}{(1-\nu^2)} = K_{Ic}^2 =$$

$$\frac{1.63\,P^2D}{d^4}\left((0.172 - 0.8(\tfrac{d}{D} - 0.65)^2\right))$$

= Poisson's ratio

E = Elastic modulus

P = Load at fracture in pounds

$d = d_o - (K_{Ic}^2/3\pi\sigma_{ys}^2)$

The equation may be reduced to $K_{Ic} = 0.414\sigma_n\sqrt{D}$ if d_o is approximately equal to 0.707D and if the term $K_{Ic}^2/3\pi\sigma_{ys}^2$ is very small compared to d_o.

σ_n = Notched strength based on the area $d^2/4$

FIGURE AP-1 Circumferentially Notched and Fatigue-Cracked Round Bar for Plate, Bar Stock, and Forgings(9)

Note: D should be larger than $4(K_{Ic}/\sigma_{ys})^2$.

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TABLE I

CHEMICAL ANALYSIS OF THE MATERIAL TESTED

	C	Mn	P	S	Si	Cr	Fe
Heat 1	0.69	1.20	0.012	0.024	0.30	1.04	Balance
Heat 2	0.63	1.02	0.011	0.021	0.27	0.95	Balance

TABLE II

RESULTS OF TESTS CONDUCTED ON SPECIMENS WITH PEARLITIC MICROSTRUCTURES

HEAT 1 - SMOOTH BAR TEST RESULTS:

Condition	0.2% Offset Yield Str. (Psi.)	Tensile Strength (Psi.)	% R. A.	% Elong.	Hardness Rc
Cold Stretched + Stress Rel.	150,800	164,900	29.2	10.5	
at 700°F, 4 hrs.	149,200	163,500	29.8	11.5	
Ave.	150,000	164,200	29.5	11.0	35
Cold Stretched + Stress	125,500	163,700	32.1	13.0	
Rel., 700°F, 8 hrs.	127,700	163,800	29.8	11.5	
Ave.	126,600	163,800	31.0	12.3	34
Normalized at 1600°F, 1 hr.	129,800	149,000	16.6	6.6	
Cold Stretched + Stress	131,100	149,200	16.8	6.2	
Rel. at 700°F, 8 hrs.					
Ave.	130,500	149,100	16.7	6.4	32
Stress Rel., 700°F, 4 hrs.,	134,800	164,100	31.8	13.5	
+ Cold Stretched	134,000	161,700	28.2	10.5	
Ave.	134,400	162,900	30.0	12.0	33
Cold Stretched	133,700	163,700	27.9	11.5	
	134,700	164,200	27.4	10.5	
Ave.	134,200	164,000	27.6	11.0	33
Cold Stretched + Stress	81,100	138,900	33.0	13.5	
Rel., 1100°F, 2 hrs.	81,200	137,600	32.8	14.0	
Ave.	81,200	138,300	32.9	13.8	24

Cold Stretched specimens were loaded to about 87% of the Ultimate Tensile Strength.

Stress Relieved specimens were Air Cooled.

TABLE II - CONT'D

RESULTS OF TESTS CONDUCTED ON SPECIMENS WITH PEARLITIC MICROSTRUCTURES

HEAT 2 - SMOOTH BAR TEST RESULTS:

Condition	0.2% Offset Yield Str. (Psi.)	Tensile Strength (Psi.)	% R. A.	% Elong.	Hardness Rc
Cold Stretched + Stress	133,700	149,400	39.5	13.0	
Rel., 700°F, 8 hrs.	134,200	149,200	36.1	13.5	
Ave.	134,000	149,300	37.8	13.3	30
Normalized at 1600°F, 1 hr.	130,000	146,500	20.5	6.2	
Cold Stretched + Stress	127,500	144,500	20.5	6.8	
Rel. at 700°F, 8 hrs.					
Ave.	128,800	145,500	20.5	6.5	29
Stress Rel., 700°F, 4 hrs.,	126,500	147,900	38.9	12.0	
+ Cold Stretched	125,000	147,200	38.7	13.0	
Ave.	125,800	147,600	38.8	12.5	28
Cold Stretched	129,600	147,800	36.9	13.0	
	137,800	148,900	35.7	11.0	
Ave.	133,700	148,400	36.3	12.0	28
Cold Stretched + Stress	81,200	137,200	43.7	16.0	
Rel., 1100°F, 2 hrs.	81,400	137,800	41.4	14.0	
Ave.	81,300	137,500	42.6	15.0	26.5

Cold Stretched specimens were loaded to about 87% of the Ultimate Tensile Strength.

Stress Relieved specimens were Air Cooled.

TABLE II - CONT'D

RESULTS OF TESTS CONDUCTED ON SPECIMENS WITH PEARLITIC MICROSTRUCTURES

HEAT 1 - NOTCHED BAR TEST RESULTS:

Condition		Notched Fracture Stress (Psi.)	Ave. 0.2% Offset Yield Str. (Psi.)	K_{Ic} Psi$\sqrt{in}$	Notched Stress to Yield Str. Ratio
Cold Stretched + Stress Rel. at 700°F, 4 hrs.		51,100		23,800	
		85,400		40,100	
		51,200		23,800	
		79,300		37,200	
		62,600		29,300	
Condition (1)	Ave.	65,900	150,000	30,800	0.44
Condition (1) with no fatigue crack.		169,800			
		152,500			
		153,300		N. A.	
	Ave.	158,500	150,000		1.06
Cold Stretched + Stress Rel., 700°F, 8 hrs.		81,100		38,200	
		68,900		32,300	
		63,200		29,600	
	Ave.	71,100	126,600	33,400	0.56
Normalized at 1600°F, 1 hr., Cold Stretched + Stress Rel., 700°F, 8 hrs.		88,600		41,900	
		77,600		36,500	
	Ave.	83,100	130,500	39,200	0.64
Stress Rel., 700°F, 4 hrs. + Cold Stretched		74,400		34,900	
		69,400		32,500	
	Ave.	71,900	134,200	33,700	0.54
Cold Stretched		61,200		28,600	
		67,700		31,600	
		74,200		34,800	
		70,200		33,000	
	Ave.	68,300	134,200	32,000	0.51

TABLE II - CONT'D

RESULTS OF TESTS CONDUCTED ON SPECIMENS WITH PEARLITIC MICROSTRUCTURES

HEAT 1 - NOTCHED BAR TEST RESULTS:

Condition	Notched Fracture Stress (Psi.)	Ave. 0.2% Offset Yield Str. (psi.)	K_{Ic} Psi$\sqrt{in}$	Notched Stress to Yield Str. Ratio
Cold Stretched + Stress Rel., 1100°F, 2 hrs.	140,000 123,000 153,800		N. A.	
Ave.	138,900	81,200		1.71

Cold Stretched specimens were loaded to about 87% of the Ultimate Tensile Strength.

Stress Relieved specimens were Air Cooled.

N. A. = Not Applicable.

TABLE II - CONT'D

RESULTS OF TESTS CONDUCTED ON SPECIMENS WITH PEARLITIC MICROSTRUCTURES

HEAT 2 - NOTCHED BAR TEST RESULTS:

Condition	Notched Fracture Stress (Psi.)	Ave. 0.2% Offset Yield Str. (Psi.)	K_{Ic} Psi$\sqrt{in}$	Notched Stress to Yield Str. Ratio
Cold Stretched + Stress Rel., 700°F, 8 hrs.	103,400		49,300	
	83,600		39,500	
	76,900		36,100	
Ave.	88,000	134,000	41,600	0.66
Normalized at 1600°F, 1 hr., Cold Stretched + Stress Rel., 700°F, 8 hrs.	115,700		55,400	
	140,900		68,400	
Ave.	128,400	128,800	61,900	1.00
Stress Rel., 700°F, 4 hrs. + Cold Stretched	87,100		41,400	
	93,800		44,700	
	103,000		49,300	
Ave.	94,700	125,800	45,100	0.75
Cold Stretched	74,500		35,000	
	82,500		38,800	
	95,100		45,100	
Ave.	84,000	133,700	39,600	0.63
Cold Stretched + Stress Rel., 1100°F, 2 hrs.	61,100		29,100	
	75,400		36,400	
	99,400		49,500	
Ave.	78,600	81,300	38,300	0.97

Cold Stretched specimens were loaded to about 87% of the Ultimate Tensile Strength.

Stress Relieved specimens were Air Cooled.

TABLE III

RESULTS OF TESTS CONDUCTED ON SPECIMENS WITH MARTENSITIC MICROSTRUCTURES

HEAT 1 - SMOOTH BAR TEST RESULTS:

Condition		0.2% Offset Yield Str. (Psi.)	Tensile Strength (Psi.)	% R. A.	% Elong.	Hardness Rc
Quenched and Tempered		215,000	237,200	31.6	6.5	
at 800°F, 4 hrs.		210,500	232,400	32.9	9.0	
	Ave.	212,800	234,900	32.3	7.8	49
Quenched and Tempered		177,300	200,000	33.1	10.0	
at 1000°F, 4 hrs.		185,900	207,200	35.4	10.0	
	Ave.	181,600	203,600	34.3	10.0	43
Quenched and Tempered		135,300	156,500	45.1	15.0	
at 1130°F, 4 hrs.		134,100	155,500	44.0	15.0	
	Ave.	134,700	156,000	44.6	15.0	29
Quenched and Tempered		126,600	146,700	47.3	18.0	
at 1200°F, 4 hrs.		123,800	140,700	49.7	18.0	
	Ave.	125,200	143,700	48.5	18.0	26

Quenched and Tempered specimens were Normalized at 1600°F, 1 hr., Air Cool; Austenitized at 1550°F, 30 min., Oil Quench; and Tempered at the temperature indicated for 4 hrs., Air Cool.

TABLE III - CONT'D

RESULTS OF TESTS CONDUCTED ON SPECIMENS WITH MARTENSITIC MICROSTRUCTURES

HEAT 2 - SMOOTH BAR TEST RESULTS:

Condition		0.2% Offset Yield Str. (Psi.)	Tensile Strength (Psi.)	% R. A.	% Elong.	Hardness Rc
Quenched and Tempered at 800°F, 4 hrs.		177,800	201,100	39.4	10.4	
		179,300	204,200	38.8	10.2	
	Ave.	178,600	202,700	39.1	10.3	43.5
Quenched and Tempered at 1000°F, 4 hrs.		167,200	185,800	41.7	13.5	
		161,200	181,900	42.7	12.5	
	Ave.	164,200	183,900	42.2	13.0	38
Quenched and Tempered at 1100°F, 4 hrs.		138,400	257,300	44.9	16.0	
		140,200	157,900	44.3	17.0	
	Ave.	139,300	157,600	44.6	16.5	31
Quenched and Tempered at 1200°F, 4 hrs.		119,300	132,000	54.3	18.5	
		118,600	132,300	53.2	18.5	
	Ave.	119,000	132,200	53.8	18.5	26

Quenched and Tempered specimens were Normalized at 1600°F, 1 hr., Air Cool; Austenitized at 1550°F, 30 min., Oil Quench; and Tempered at the temperature indicated for 4 hrs., Air Cool.

TABLE III - CONT'D

RESULTS OF TESTS CONDUCTED
ON SPECIMENS WITH MARTENSITIC MICROSTRUCTURES

HEAT 1 - NOTCHED BAR TEST RESULTS:

Condition		Notched Fracture Stress (Psi.)	Ave. 0.2% Offset Yield Str. (Psi.)	K_{Ic} Psi$\sqrt{in}$	Notched Stress to Yield Str. Ratio
Quenched and Tempered at 800°F, 4 hrs.		74,200 60,300 68,300		34,500 28,100 31,900	
	Ave.	67,600	212,800	31,500	0.31
Quenched and Tempered at 1000°F, 4 hrs.		179,100 158,800 188,100		87,600 76,100 90,800	
	Ave.	175,300	181,600	84,800	0.96
Quenched and Tempered at 1130°F, 4 hrs.		203,100 185,800 192,200		N. A.	
	Ave.	193,700	134,700		1.44
Quenched and Tempered at 1200°F, 4 hrs.		191,200 199,600 196,500		N. A.	
	Ave.	195,800	125,200		1.56

Quenched and Tempered specimens were Normalized at 1600°F, 1 hr., Air Cool; Austenitized at 1550°F, 30 min., Oil Quench; and Tempered at the temperature indicated for 4 hrs., Air Cool.

N. A. = Not Applicable.

TABLE III - CONT'D

RESULTS OF TESTS CONDUCTED
ON SPECIMENS WITH MARTENSITIC MICROSTRUCTURES

HEAT 2 - NOTCHED BAR TEST RESULTS:

Condition		Notched Fracture Stress (Psi.)	Ave. 0.2% Offset YieldStr. (Psi.)	K_{Ic} Psi$\sqrt{in}$	Notched Stress to Yield Str. Ratio
Quenched and Tempered at 800°F, 4 hrs.		101,900		47,900	
		93,000		41,900	
		95,700		42,700	
		88,800		41,700	
	Ave.	94,900	178,600	43,600	0.53
Quenched and Tempered at 1000°F, 4 hrs.		206,700		103,400	
		212,200		106,600	
		226,600		114,900	
	Ave.	215,200	164,200	105,000	1.31
Quenched and Tempered at 1100°F, 4 hrs.		214,200			
		212,300		N. A.	
		212,300			
	Ave.	212,900	139,300		1.52
Quenched and Tempered at 1200°F, 4 hrs.		179,200			
		191,200		N. A.	
		213,200			
	Ave.	194,500	119,000		1.64

Quenched and Tempered specimens were Normalized at 1600°F, 1 hr., Air Cool; Austenitized at 1550°F, 30 min., Oil Quench; and Tempered at the temperature indicated for 4 hrs., Air Cool

N. A. = Not Applicable.

TABLE IV

RESULTS OF TESTS CONDUCTED ON SPECIMENS HEAT TREATED TO 150 KSI YIELD STRENGTH AND TESTED AT VARIOUS TEMPERATURES

HEAT 1 - SMOOTH BAR TEST RESULTS:

Condition		0.2% Offset Yield Str. (Psi.)	Tensile Strength (Psi.)	% R. A.	% Elong.	Hardness Rc
Cold Stretched + Stress Rel. at 700°F, 4 hrs.		150,800	164,900	29.2	10.5	
		149,200	163,500	29.8	11.5	
Condition (1)	Ave.	150,000	164,200	29.5	11.0	35
Condition (1) tested at 0°F		- -	169,900	26.9	10.5	
		152,900	169,600	29.8	9.5	
	Ave.	152,900	169,800	28.4	10.0	—
Condition (1) tested at 140°F		146,800	160,000	31.4	10.0	
		147,700	163,700	31.6	11.0	
	Ave.	147,300	162,200	31.5	10.5	—
Condition (1) tested at 200°F		141,100	158,900	31.4	11.0	
		141,800	157,700	31.2	11.0	
	Ave.	141,500	158,300	31.3	11.0	—
Quenched and Tempered at 1130°F, 4 hrs.		135,300	156,500	45.1	15.0	
		134,100	155,500	44.0	15.0	
Condition (2)	Ave.	134,700	156,000	44.6	15.0	29
Condition (2) tested at 0°F		142,900	158,700	42.3	14.5	
		137,000	151,600	46.9	16.5	
	Ave.	140,000	155,200	45.2	15.5	—

Cold Stretched specimens were loaded to about 87% of the Ultimate Tensile Strength.

Quenched and Tempered specimens were Normalized at 1600°F, 1 hr., Air Cool; Austenitized at 1550°F, 30 min., Oil Quench; and Tempered at the temperature indicated for 4 hrs., Air Cool.

TABLE IV - CONT'D

RESULTS OF TESTS CONDUCTED ON SPECIMENS HEAT TREATED TO 150 KSI YIELD STRENGTH AND TESTED AT VARIOUS TEMPERATURES

HEAT 1 - NOTCHED BAR TEST RESULTS:

Condition		Notched Fracture Stress (Psi.)	Ave. 0.2% Offset YieldStr. (Psi.)	K_{Ic} Psi$\sqrt{in}$	Notched Stress to Yield Str. Ratio
Cold Stretched + Stress Rel. at 700°F, 4 hrs.		51,100		23,800	
		85,400		40,100	
		51,200		23,800	
		79,300		37,200	
		72,600		29,300	
Condition (1)	Ave.	65,900	150,000	30,800	0.44
Condition (1) tested at 0°F,		68,200		32,000	
		77,200		36,200	
	Ave.	72,600	152,900	34,100	0.47
Condition (1) tested at 140°F		84,600		39,900	
		89,400		42,200	
		99,000		46,800	
	Ave.	91,000	147,300	43,000	0.62
Condition (1) tested at 200°F.		126,300		60,800	
		135,400		65,700	
	Ave.	130,900	141,500	63,300	0.93
Quenched and Tempered at 1130°F, 4 hrs.		203,100			
		185,800		N. A.	
		192,200			
Condition (2)	Ave.	193,700	134,700		1.44
Condition (2) tested at 0°F.		205,000			
		188,400		N. A.	
		181,400			
	Ave.	191,600	140,000		1.37

TABLE IV - CONT'D

RESULTS OF TESTS CONDUCTED ON SPECIMENS HEAT TREATED TO 150 KSI YIELD STRENGTH AND TESTED AT VARIOUS TEMPERATURES

HEAT 1 - NOTCHED BAR TEST RESULTS:

Condition		Notched Fracture Stress (Psi.)	Ave. 0.2% Offset Yield Str. (Psi.)	K_{Ic} Psi$\sqrt{in}$	Notched Stress to Yield Str. Ratio
Condition (2) tested at -100°F.		187,500 204,000 201,200		N. A.	
	Ave.	197,600	------		----

Cold Stretched specimens were loaded to about 87% of the Ultimate Tensile Strength.

Quenched and Tempered specimens were Normalized at 1600°F, 1 hr., Air Cool; Austenitized at 1550°F, 30 min., Oil Quench; and Tempered at the temperature indicated for 4 hrs., Air Cool.

N. A. = Not Applicable.

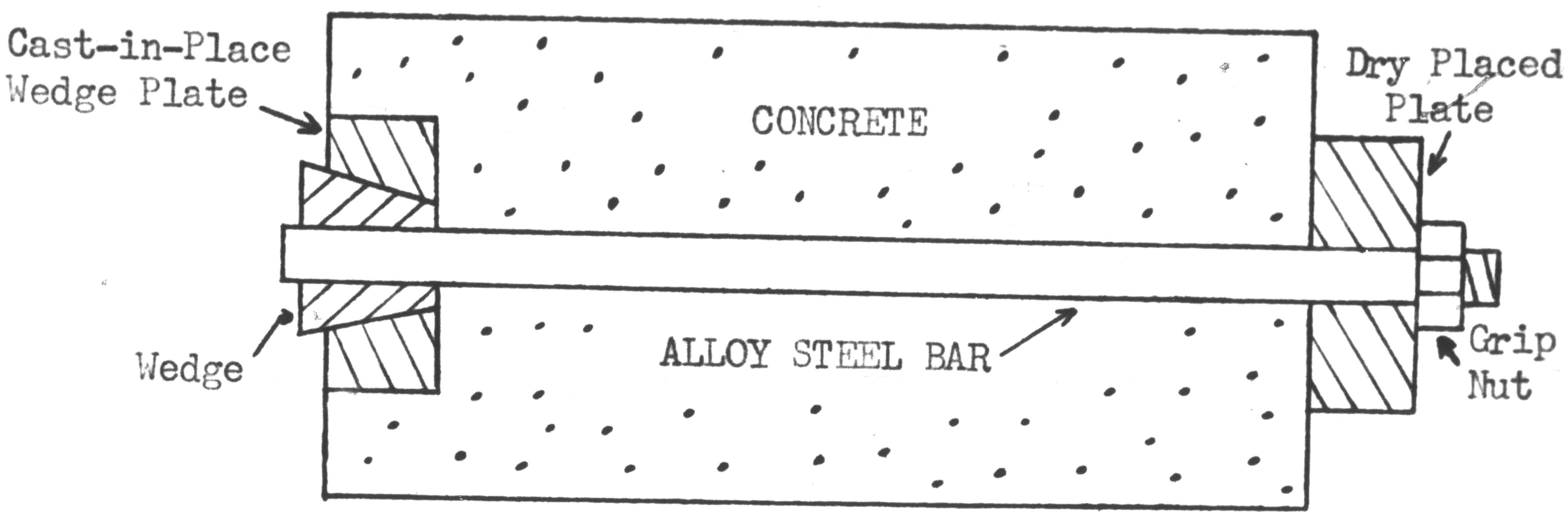

FIGURE 1 - CUTAWAY VIEW OF A CONCRETE BEAM WITH AN ALLOY STEEL TENDON HELD IN PLACE BY VARIOUS METHODS

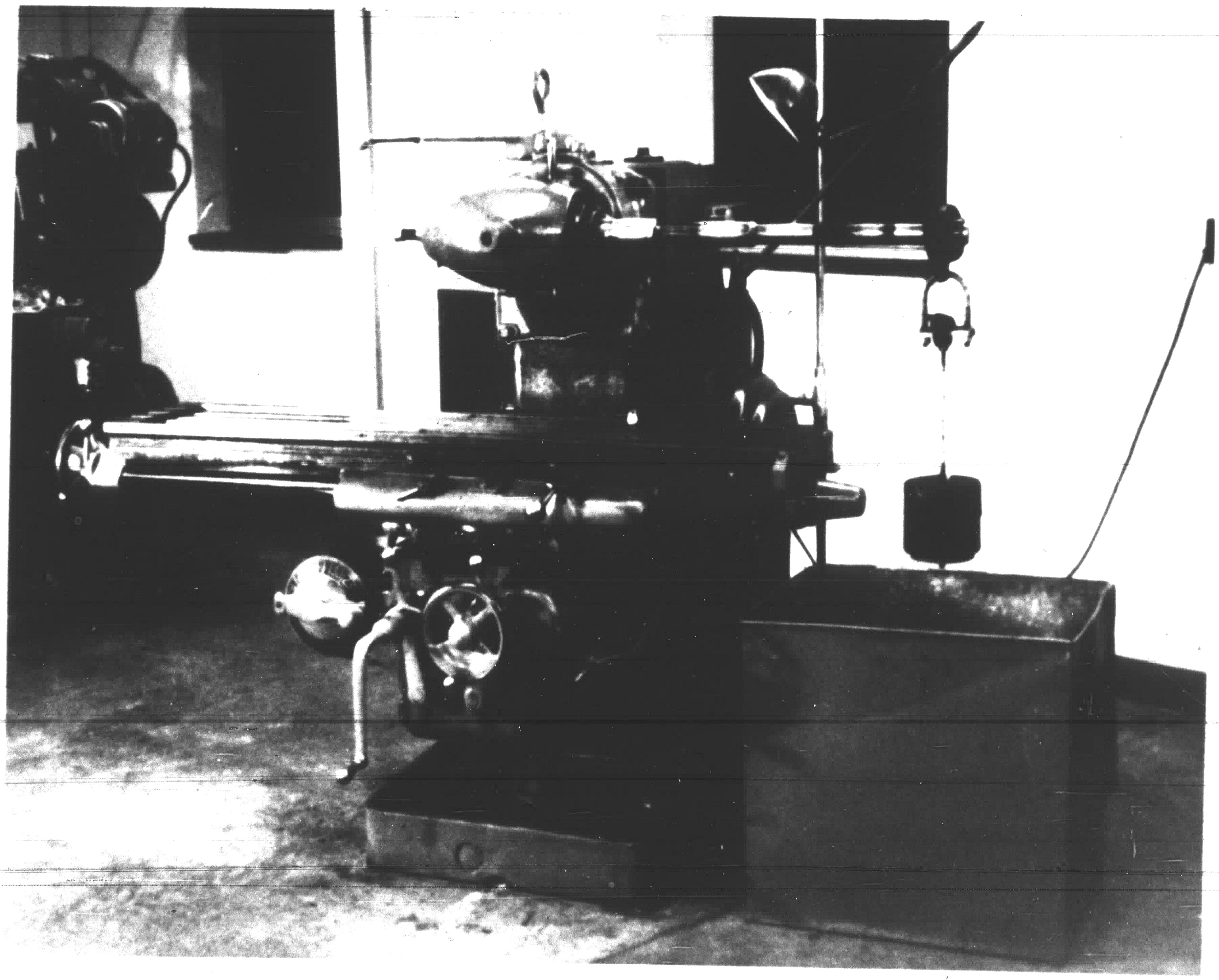

FIGURE 2 - THE FATIGUING MACHINE

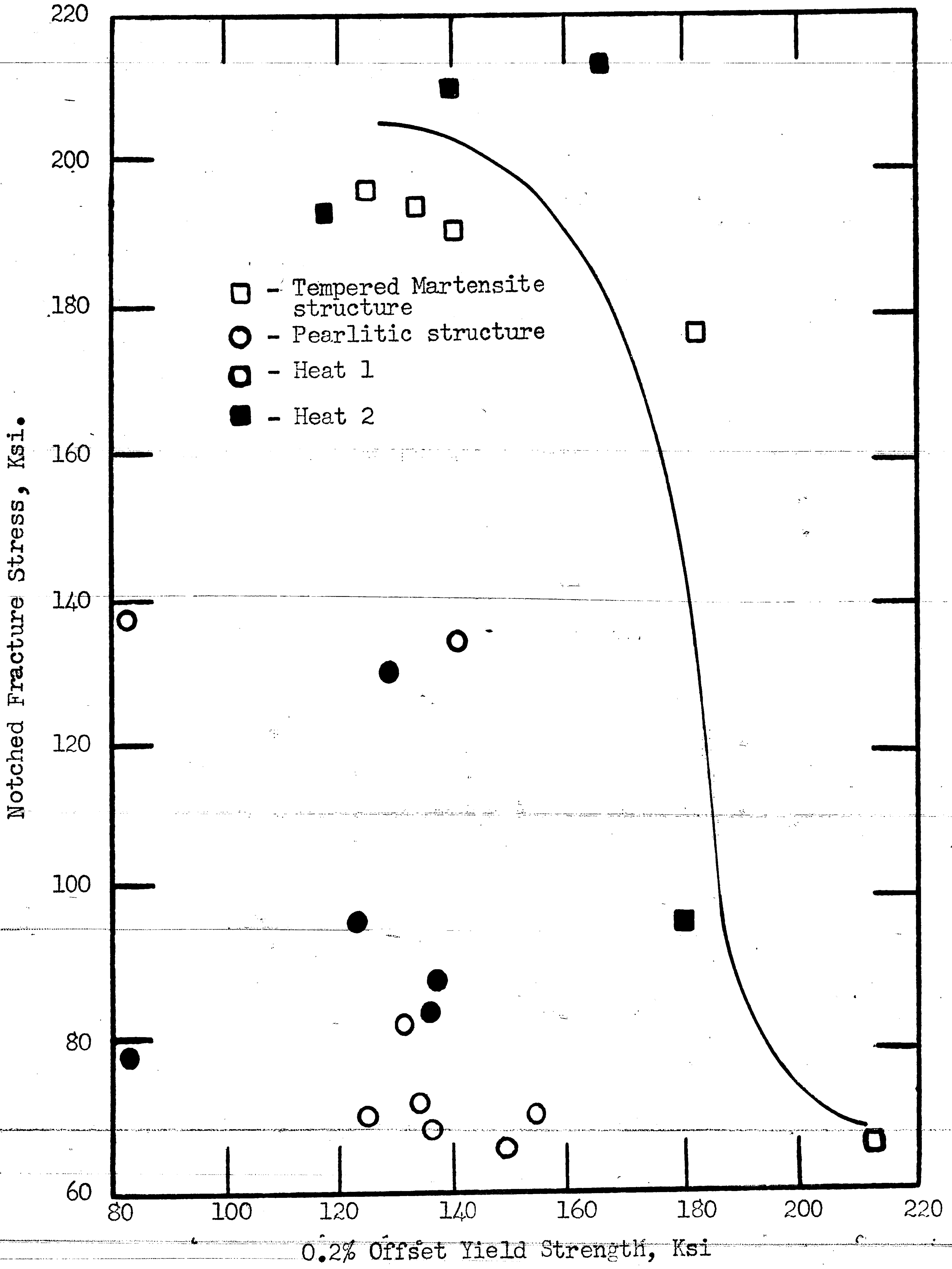

FIGURE 3 - Plot of Notched Fracture Stress versus the smooth bar 0.2% Offset Yield Strength of all the conditions tested.

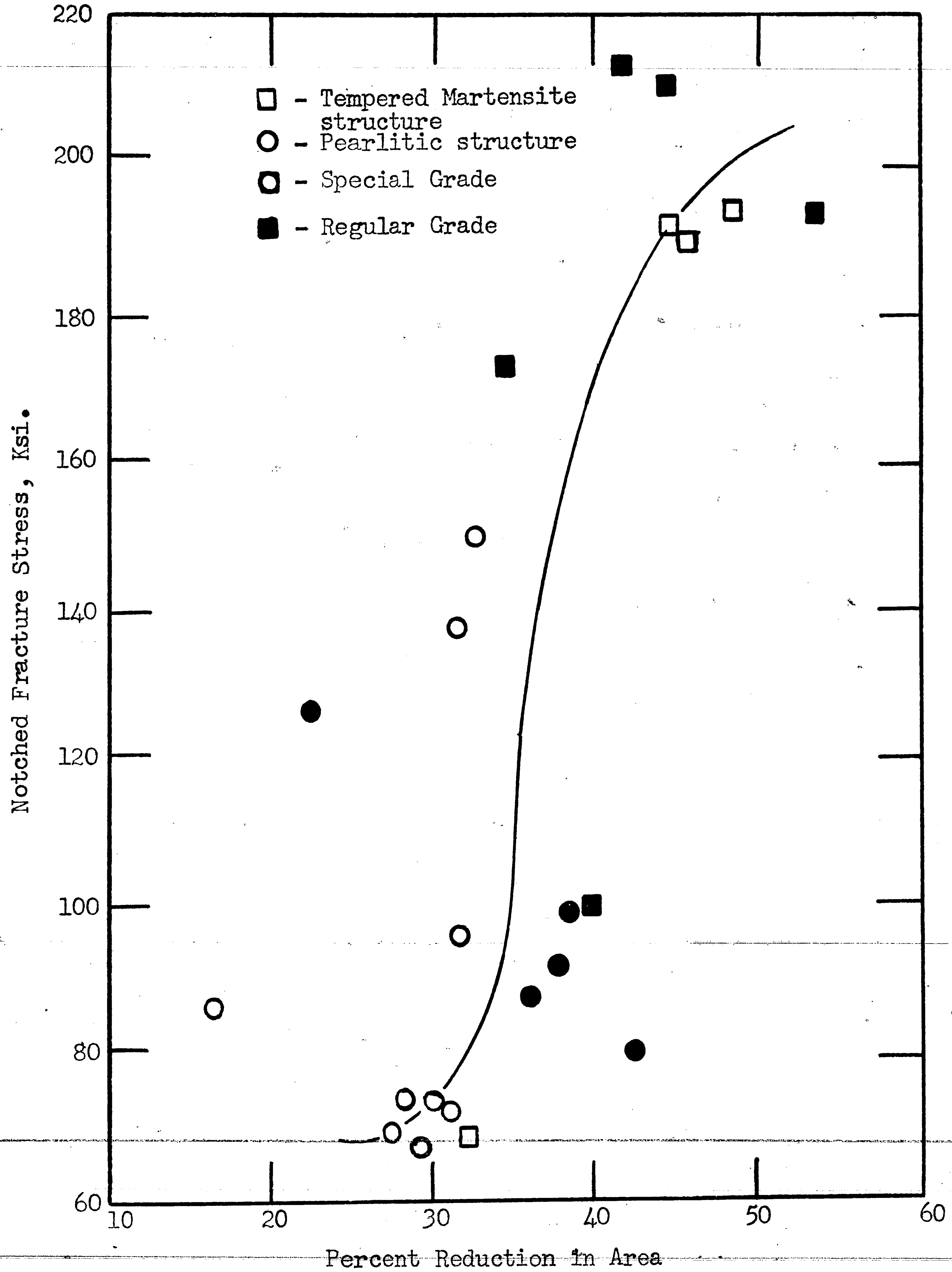

FIGURE 4 - Plot of Notched Fracture Stress versus smooth bar Percent Reduction in Area of all the conditions tested.

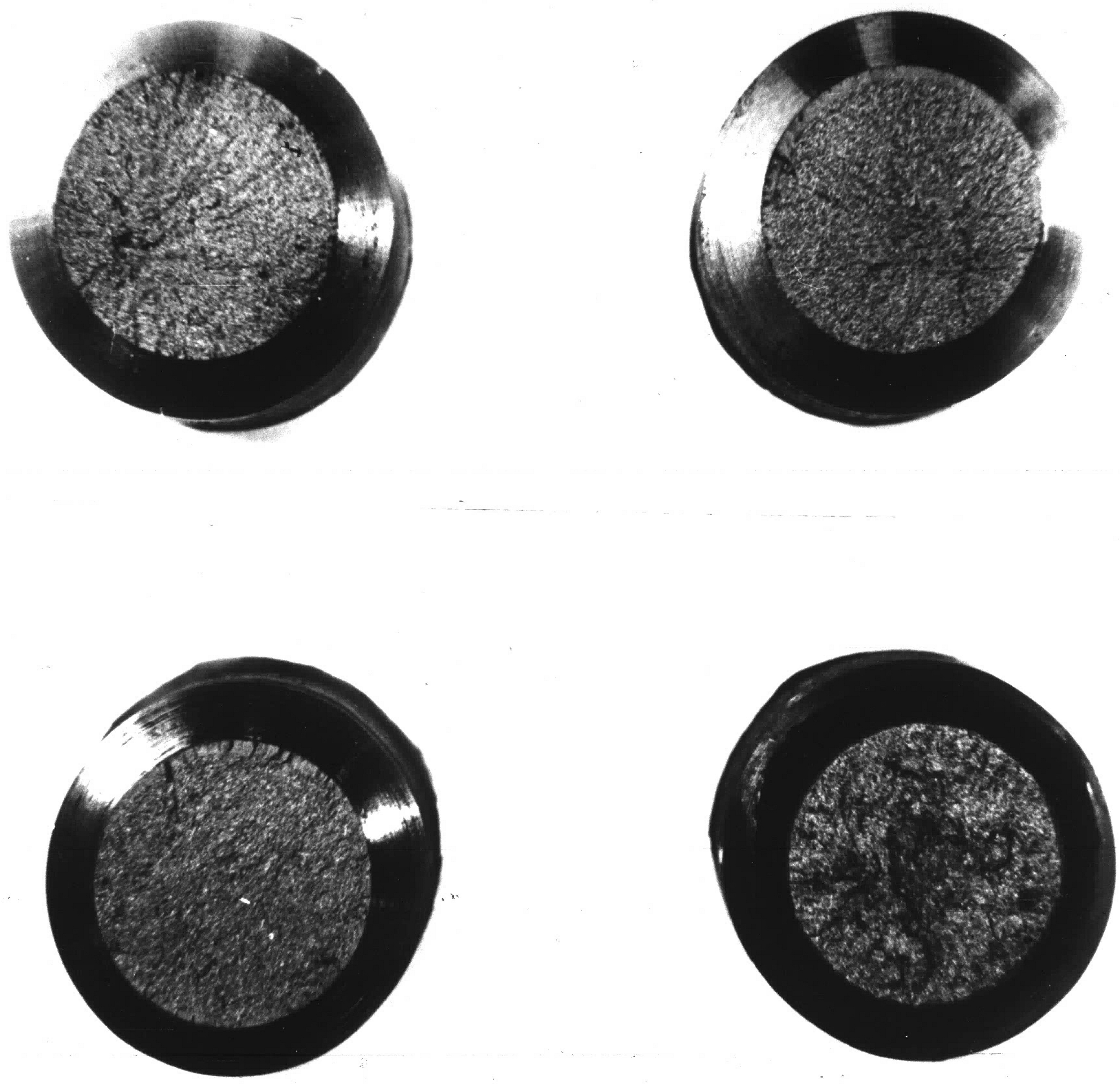

FIGURE 5 - TYPICAL FRACTURE APPEARANCE OF SPECIMENS WITH A PEARLITIC MICROSTRUCTURE - HEAT 1

Mag: 1.5X

Upper Left	Hot rolled to 1.25 inches round; Proof Stressed to 87% UTS, Notched Fracture Stress = 68,300 psi.
Upper Right	Hot rolled to 1.25 inches round; Stress Relieved at 700°F, 4 hrs., Air Cool; Proof Stressed to 87% UTS, Notched Fracture Stress = 71,900 psi.
Lower Left	Hot rolled to 1.25 inches round; Proof Stressed to 87% UTS; Stress Relieved at 700°F, 8 hrs., Air Cool, Notched Fracture Stress = 71,100 psi.
Lower Right	Hot rolled to 1.25 inches round; Proof Stressed to 87% UTS; Stress Relieved at 1100°F, 2 hrs., Air Cool, Notched Fracture Stress = 138,900 psi.

FIGURE 6 Etch: 1% Nital
Mag: 250X

Stress Relieved 700°F,
4 hrs., A. C., Proof
Stressed to 87% UTS

FIGURE 7 Etch: 1% Nital
Mag: 250X

Proof Stressed to
87% UTS, Stress Relieved
700°F, 8 hrs., A.C.

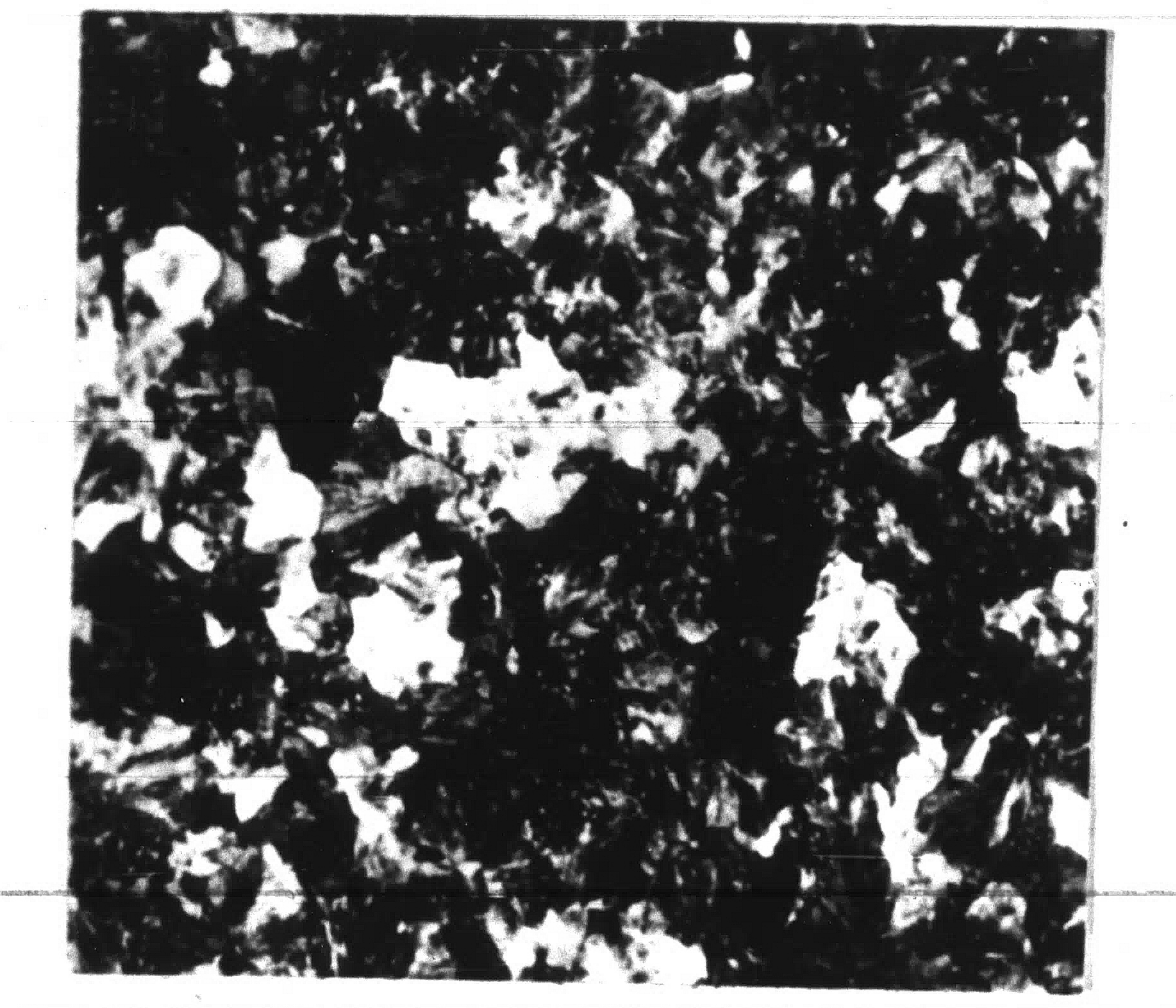

FIGURE 8 Etch: 1% Nital
Mag: 250X

Proof Stressed to
87% UTS

FIGURE 9 Etch: 1% Nital
Mag: 250X

Proof Stressed to
87% UTS, Stress Relieved
700°F, 4 hrs., A. C.

FIGURES 6 TO 9 - TYPICAL PEARLITIC MICROSTRUCTURES OF THE SPECIMENS GIVEN VARIATIONS OF THE STANDARD TREATMENT - HEAT 1

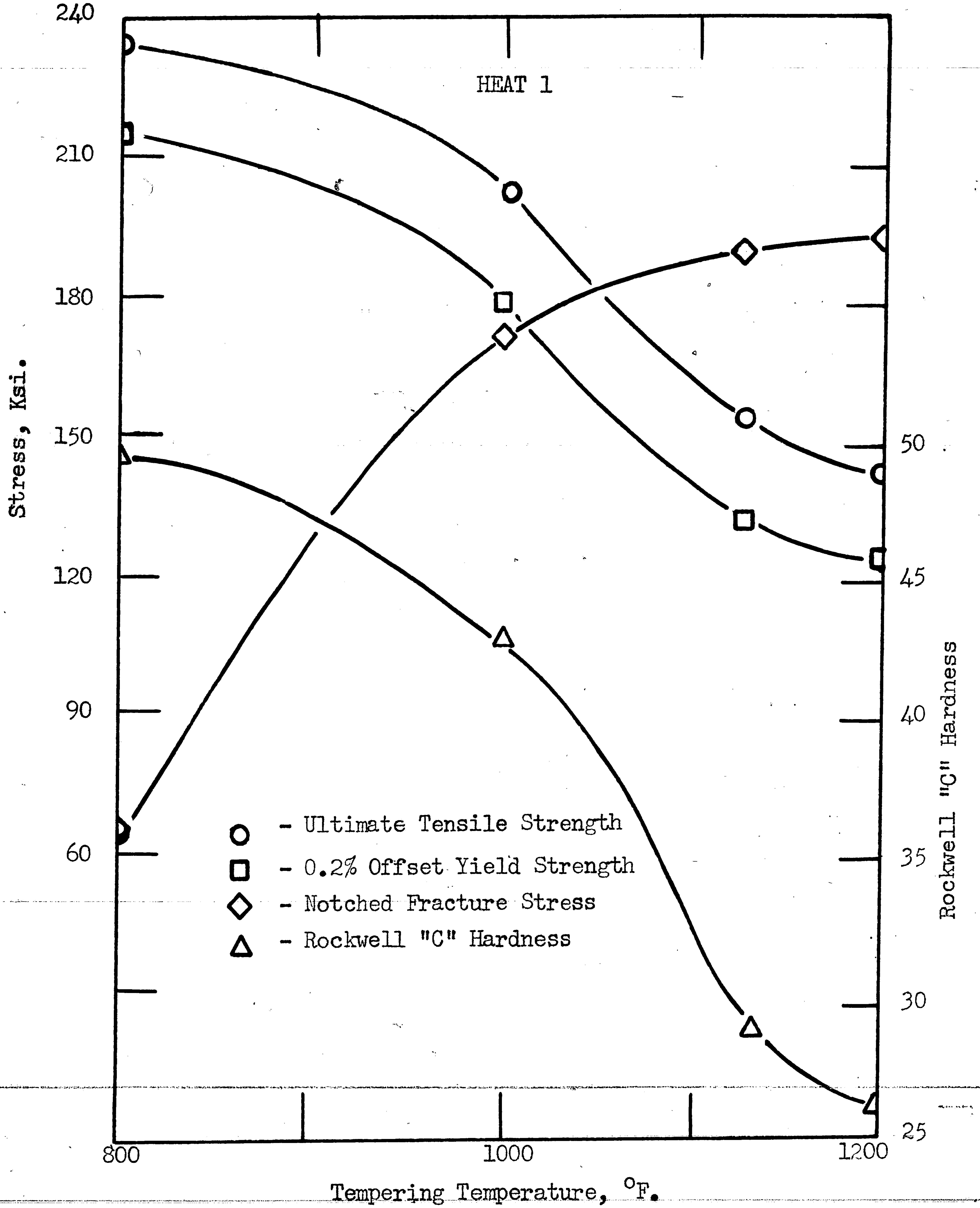

FIGURE 10 - The effect of tempering temperature on notched and unnotched strength and hardness - Heat 1. Specimens were normalized at 1600°F, 1 hr., Air Cool; hardened at 1550°F, 30 min., Oil Quenched; and tempered at the temperature indicated for four hrs., Air Cool.

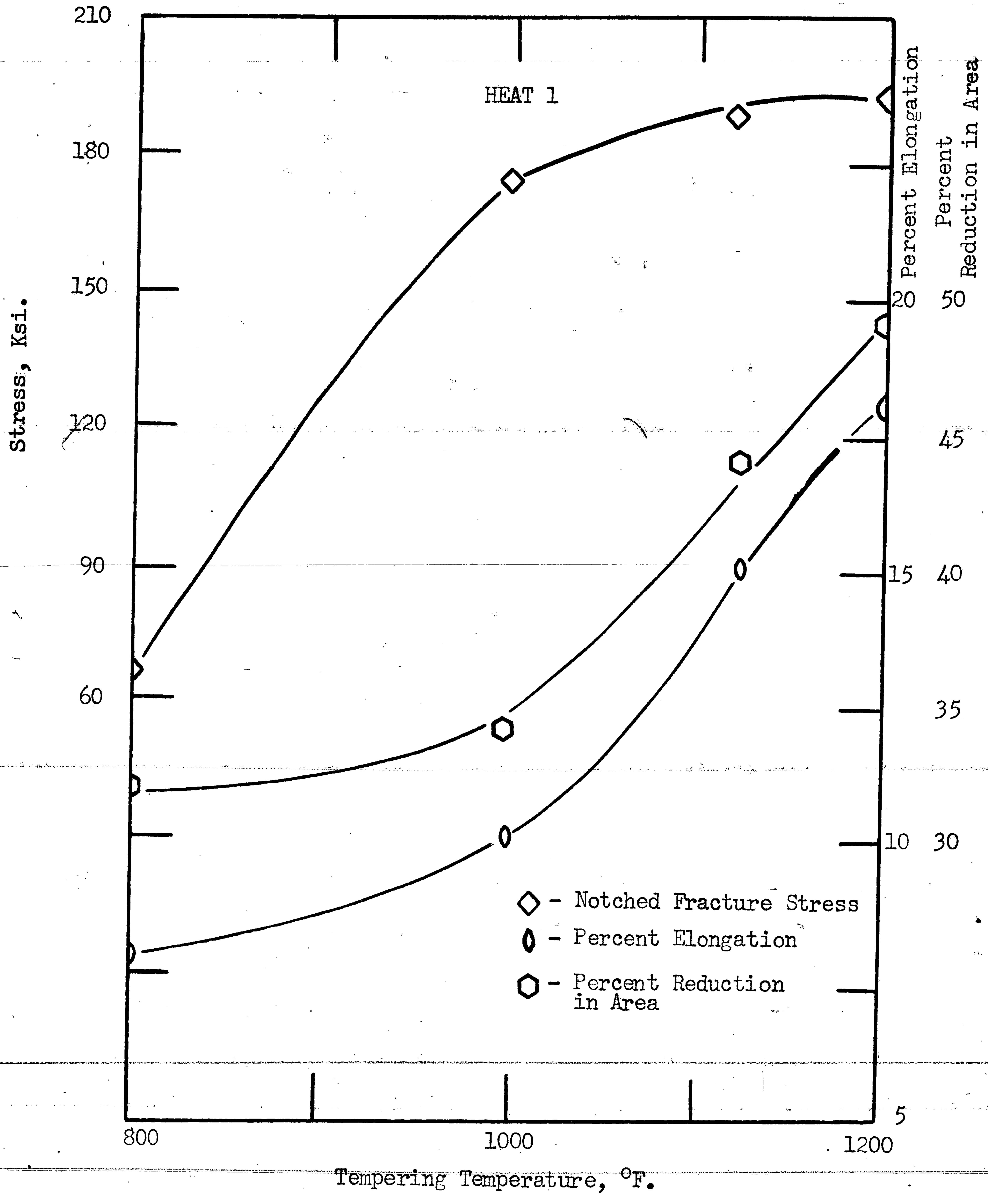

FIGURE 11 - The effect of tempering temperature on the notched fracture stress and smooth bar ductility - Heat 1. Specimens were normalized at 1600°F, 1 hr., Air Cool; hardened at 1550°F, 30 min., Oil Quench; and tempered at the temperature indicated for 4 hrs., Air Cool.

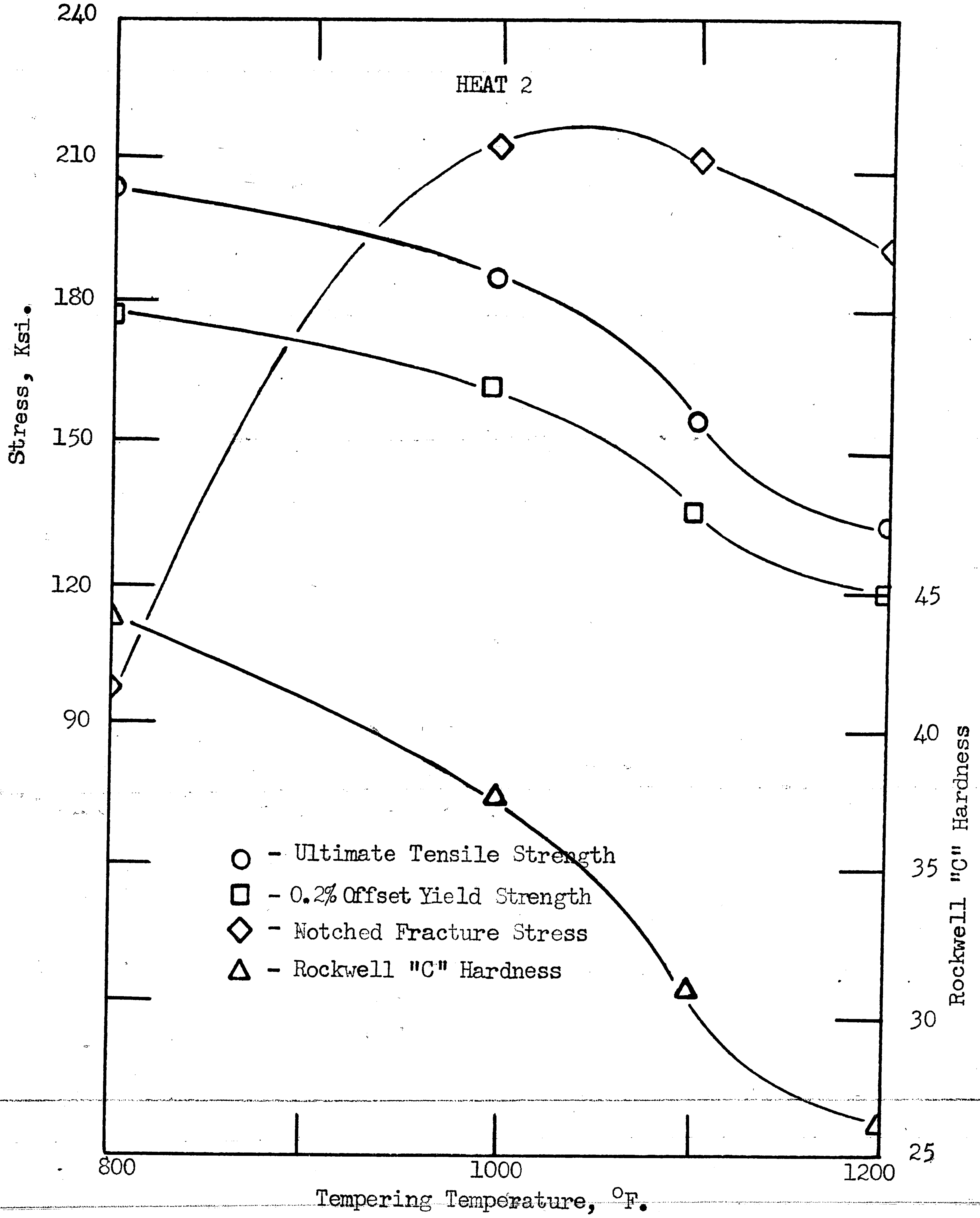

FIGURE 12 - The effect of tempering temperatureon notched and unnotched strength and hardness - Heat 2. Specimens were normalized at 1600°F, 1 hr., Air Cool; hardened at 1550°F, 30 min., Oil Quench; and tempered at the temperature indicated for four hrs., Air Cool.

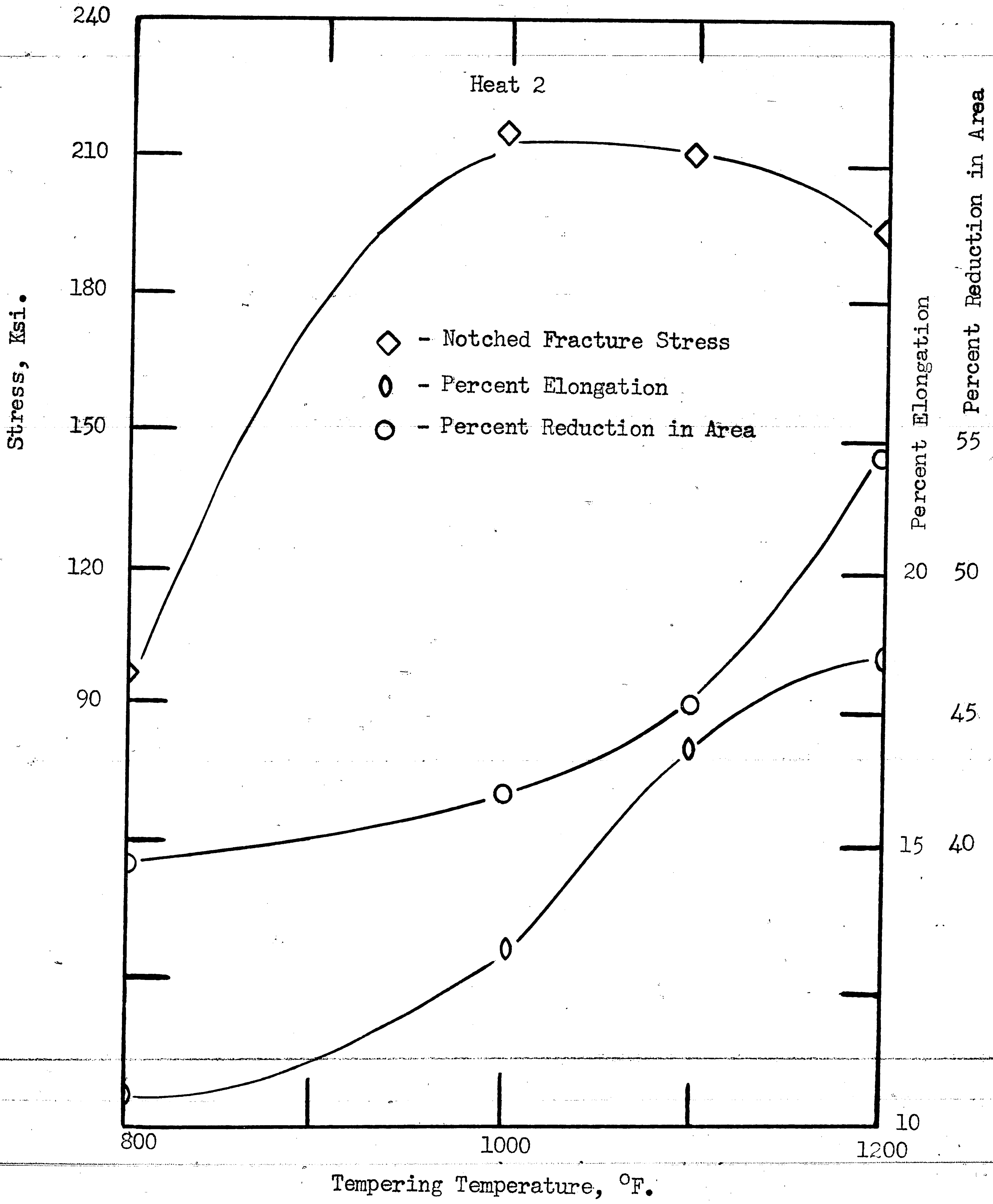

FIGURE 13 - The effect of tempering temperature on notched fracture stress and smooth bar ductility - Heat 2. Specimens were normalized at 1600°F, 1 hr., Air Cool; hardened at 1550°F, 30 min., Oil Quench; and tempered at the temperature indicated for 4 hrs., Air Cool.

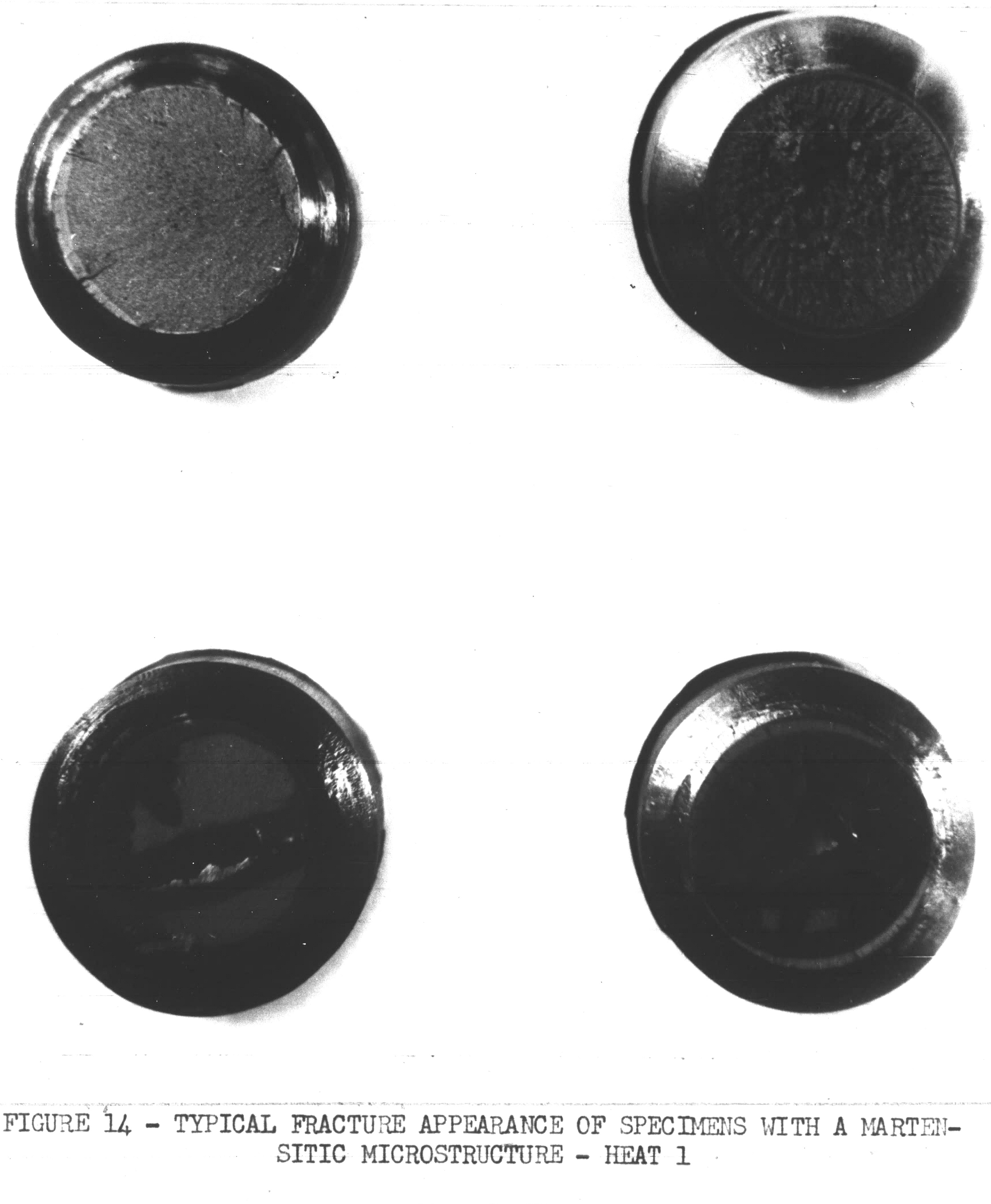

FIGURE 14 - TYPICAL FRACTURE APPEARANCE OF SPECIMENS WITH A MARTENSITIC MICROSTRUCTURE - HEAT 1

Mag: 1.5X

Normalized at 1600°F, 1 hr., Air Cool; Austenitized at 1550°F, 30 min., Oil Quench; Tempered 4 hrs. at the temperature indicated, Air Cool.

Upper Left - Tempered at 800°F, Notched Fracture Stress = 67,600 psi.
Upper Right - Tempered at 1000°F, Notched Fracture Stress = 175,300 psi.
Lower Right - Tempered at 1130°F, Notched Fracture Stress = 193,700 psi.
Lower Left - Tempered at 1200°F, Notched Fracture Stress = 195,800 psi.

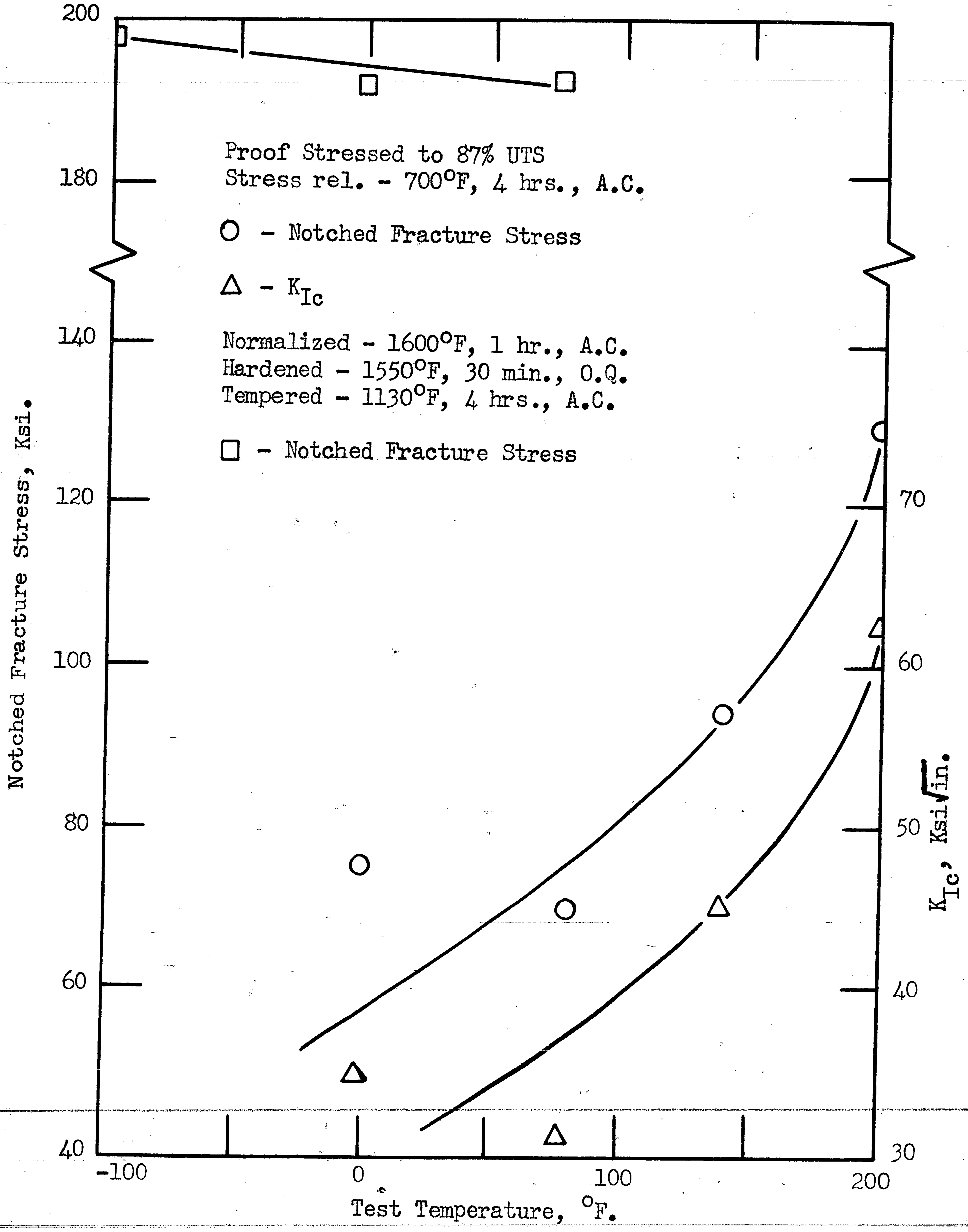

FIGURE 15 - The effect of Test Temperature on the Notched Fracture Stress and K_{Ic} to the same strength level of Pearlitic and Martensitic steels heat treated to the same strength levels - Heat 1.

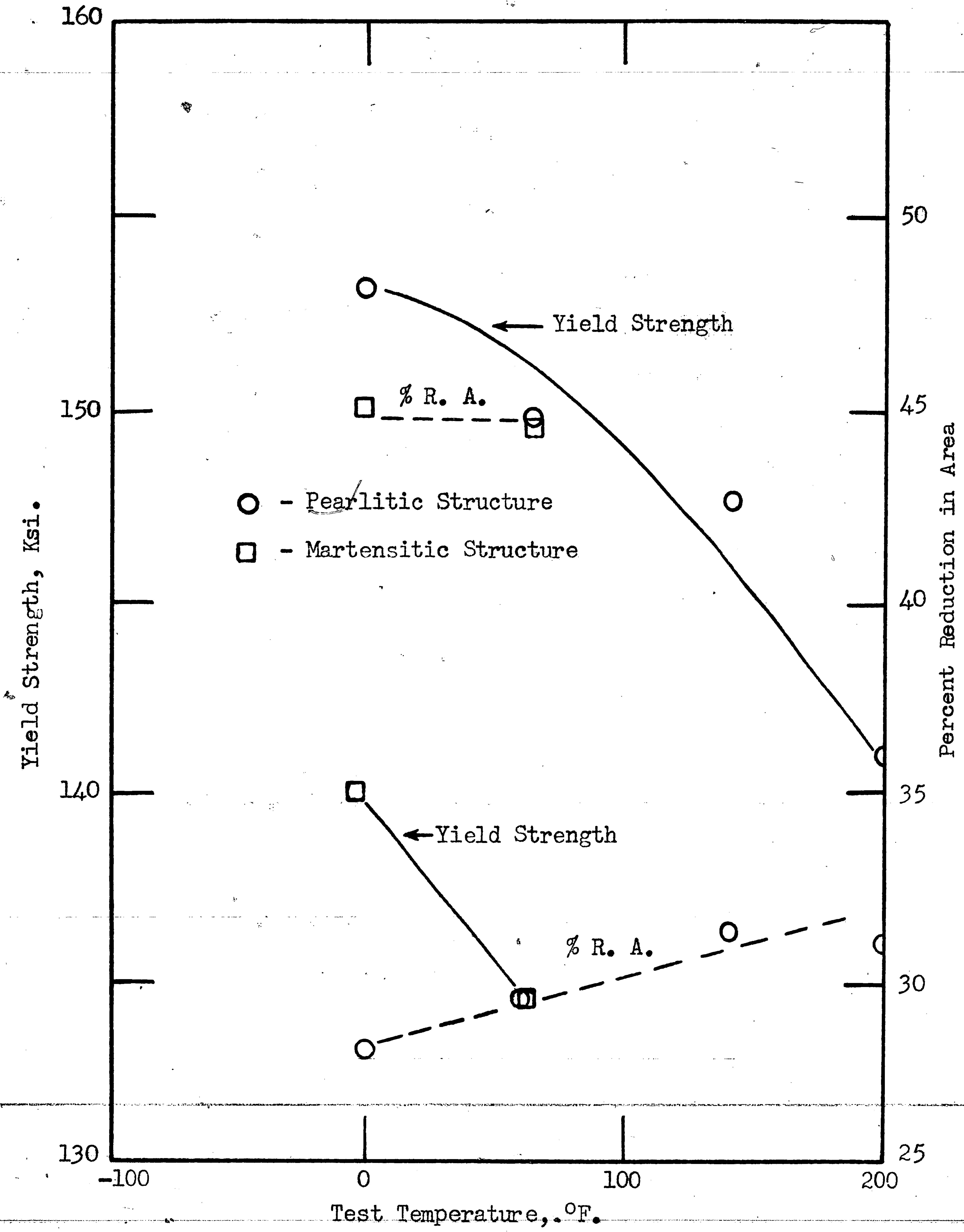

FIGURE 16 - The effect of test temperature on the yield strength and percent reduction in area of pearlitic and martensitic steels heat treated to the same strength levels - Heat 1.

FIGURE 17 - TYPICAL FRACTURE APPEARANCE OF SPECIMENS WITH A MARTENSITIC MICROSTRUCTURE, TESTED AT VARIOUS TEMPERATURES - HEAT 1

Mag: 1.5X

Normalized at 1600°F, 1 hr., Air Cool; Austenitized at 1550°F, 30 min., Oil Quench; Tempered at 1130°F, 4 hrs., Air Cool.

Upper - Tested at 75°F, Notched Fracture Stress = 193,700 psi.
Lower Left - Tested at 0°F, Notched Fracture Stress = 191,600 psi.
Lower Right - Tested at -100°F, Notched Fracture Stress = 197,600 psi.

VITA

The author is the son of Evelyn M. and the late Clair W. Bendel. He was born on January 29, 1941 in Reading, Pennsylvania. After graduation from Reading Senior High School in 1958, the author matriculated to Lehigh University where he was awarded a Bachelor of Science degree in Metallurgical Engineering in 1962. From June 1962 to January 1965 he was affiliated with The Carpenter Steel Company of Reading, Pennsylvania in the position of Assistant Metallurgist - Stainless Steel Research. In January 1965 the author took a 13-month leave of absence to study toward a Master of Science degree in Metallurgical Engineering at Lehigh University. The author is a member of the American Society for Metals and the American Institute of Mining, Metallurgical, and Petroleum Engineers.