AN INVESTIGATION OF THE EFFECT OF TIME AND TEMPERATURE ON THE PROPERTIES OF A NORMALIZED STEEL

by

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ABSTRACT

AN INVESTIGATION OF THE EFFECT OF TIME AND TEMPERATURE ON THE PROPERTIES OF A NORMALIZED STEEL

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A steel used for both API normalized grades E and N-80 tubular products was normalized at three different temperatures (793, 849, and 904°C) and for four different times (5 min., 20 min., 1 hour, and 2 hours) at each temperature. The samples were then evaluated for impact toughness, yield and tensile strength, elongation, hardness, fatigue strength and microstructure.

The lowest normalizing temperature of 793°C produced significant improvements in yield and tensile strength, impact toughness and fatigue strength over the samples normalized at 849 and 904°C. The superior mechanical properties of the samples normalized at 793°C were attributed to their finer grain size and more uniform carbide dispersion that were observed in the metallographic study.

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ACKNOWLEDGMENTS

The assistance of Mr. G. S. Drigel is gratefully acknowledged and the fine photographic work of Mr. H. R. Walsh was definitely appreciated. The author also wishes to express appreciation to Armco Steel Corporation for the material and use of their facilities to conduct this study.

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CHAPTER I

Introduction

Two commonly used oil country tubular products designated grade E and N-80 grade by the American Petroleum Institute (API), have a yield strength range of 517 MPa - 724 MPa (75 - 105 ksi) and 552 MPa - 758 MPa (80 - 110 ksi) respectively. N-80 grade pipe is used as oil well casing or tubing and may be subjected to high static stresses such as the weight of the casing string or pressures due to fluid columns such as the drilling fluids. Grade E pipe is used for drill pipe and is subjected to cyclical loading due to the flexing of the pipe during drilling. One of the heat treating techniques used to achieve these desired yield strength ranges is normalizing. Normalizing is basically a homogenization process consisting of austenitizing a part and then allowing it to cool in air.

Section size is important in normalizing in that the dimensions and shape of a part determine its cooling rate in still air and, therefore, its resulting microstructure.

A typical alloy used to attain both the N-80 and grade E yield strength ranges contains .30 - .40 carbon, 1.40 - 1.90 manganese, .10 - .35 silicon, .03 - .10 vanadium and .10 - .20 molybdenum. The microstructure of this alloy after normalizing is predominantly ferrite and bainite. Forced air cooling of this alloy is not sufficient to produce martensite.[1] Therefore, the ferrite - bainite microstructure is retained for most rates of air cooling and most section sizes that would be encountered in tubular products.

Since normalizing is usually considered to be a homogenization or pre-heat treat process rather than a process to attain a specified yield strength or hardness, there has not been a great deal of effort to determine an optimum normalizing time or temperature. Normalizing can be a cost savings over quenching and tempering in that only one heating cycle is required and for a two furnace heat treating line out put is doubled when compared to quenching and tempering.

Several researchers [2,3] have investigated the effect of austenitizing temperature along with time at temperature for quenching and tempering of alloy steels.

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[1]B. A. Cole, "Tubular Products - Effects of Different Cooling Rates on Normalized AMB 08 Material" (Internal Report S. I. No. 75-275, Armco Steel Research Center, April 25, 1975).

[2]P. Dembowski and R. Griffin, "Effect of Austenitization Soak Times on Mechanical Properties of Low Alloy Steel", Industrial Heating, (March, 1976), p. 34 - 39.

[3]E. R. Parker, "Interrelations of Compositions, Transformation Kinetics, Morphology, and Mechanical Properties of Alloy Steels", Metallurgical Transactions A, 8 A - No. 7 (July, 1977), p. 1025 - 1053.

P. Dembowski and R. Griffin studied the effect of austenitization times on the mechanical properties of quenched and tempered modified AISI 4337 steel. In this study it was reported that very little change in mechanical properties occurred with different austenitizing times and temperatures other than slight changes attributable to grain size variations. However, E. R. Parker[3] while examining the effect of austenitizing temperature on the mechanical properties of quenched and tempered AISI 4130 and 4340, reported a marked improvement in fracture toughness when quenching from 1200°C instead of 870°C. The improvement was attributed to undecomposed austenite between the martensite laths.

A study that included an investigation of the effect of austenitizing temperature on normalized bainitic steels was conducted by K. J. Irvine and F. B. Pickering.[4] Here a series of 1½% Mo - B high carbon bainitic steels were heat treated by normalizing and tempering. The results of this investigation showed a pronounced effect of the austenitizing temperature on the transformation characteristics of bainite due to the undissolved carbides in the higher carbon steels.

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[3]E. R. Parker, Metallurgical Transactions A, pp. 1025 - 1053.

[4]K. J. Irvine and F. B. Pickering, "High-Carbon Bainitic Steels", Physical Properties of Martensite and Bainite, Special Report 93, The Iron and Steel Institute, London, (1965), p. 110.

The study included austenitizing at Ac_3 + 30°C and from a temperature sufficiently high enough to dissolve all the carbides. It was reported that for carbon levels up to .4% there was no difference in yield strength or ultimate tensile strength between the samples normalized at the two different temperatures because there were no undissolved carbides.

G. S. Drigel[5] evaluated the effect of normalizing temperature and time on a steel similar to that used in this investigation. Normalizing temperatures of 816°, 871°, and 927°C and soak times of five minutes and fifteen minutes were used. In this study, it was found that yield strength and tensile strength properties decreased with increasing normalizing temperature. The effect of time at normalizing temperature on mechanical properties was found to be statistically insignificant. In addition, an increase in prior austenite grain size along with a coarsening of the general microstructure resulted as the normalizing temperature increased.

The purpose of this study is to determine the influence of normalizing temperature and holding time at temperature on the mechanical (fatigue, tensile, hardness and toughness tests) and microstructural properties of a steel used for both Grades N-80 and E tubular products.

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[5]G. S. Drigel, "Normalizing Temperature and Time for N-80", (Internal Report S. I. 77 - 398, Armco Steel Research Center, May 27, 1977).

This study will also evaluate the validity of the familiar rule for heating of one hour per inch of section thickness. Any possible reduction of normalizing temperature and time without sacrifice of mechanical properties would benefit energy conservation, improve furnace output and reduce heat treating costs.

CHAPTER II

Testing Procedure

To obtain samples for normalizing, a length of 19.38 cm O.D. x 58.1 Kg/m (7-5/8 in. x 39#/ft.) N-80 grade seamless pipe was cut into 46 cm long sections. The pieces were cut from one pipe of a single heat of steel melted in a basic oxygen furnace. The analysis of this pipe (.35 C, 1.78 Mn, .016 P, .015 S, .12 Si, .06 V and .17 Mo) is typical of that used to attain 517 MPa - 758 MPa (75 - 110 ksi) yield strength in the normalized condition. Rather than simply choosing different normalizing temperatures, it was decided to use Ac_3 as a base temperature and determine the effects of various increments of temperature above Ac_3 along with different lengths of time at that temperature.

In determining Ac_3 standard dilatometric techniques were used along with a heating rate similar to the normalizing furnace used in this investigation. Ac_3 was found to be 777°C.

The sections were then normalized at three different temperatures and for four different periods of time as shown in table I. In order to monitor the temperature of each test piece, a chromel-alumel thermocouple was imbedded in each section at approximately mid-wall.

Time at normalizing temperature was started when the sample reached 5°C below the desired temperature. At the end of the time cycle, the sample was removed from the furnace and allowed to air cool.

Mechanical tests were then performed on the normalized sections. Test specimens were cut from each section as depicted in figure 1. The series of tests performed on each section is listed in table II. Duplicate tensile strips (254 mm wide x 508 mm gauge length) were cut from each section according to API specification 5 A and tested in accordance with ASTM specification A 370. Three longitudinal full size charpy specimens were cut from each section with the notch being perpendicular to the longitudinal direction and were tested in accordance to ASTM A 370 at -32°C. Twelve rotating beam fatigue specimens (machined according to figure 2) were cut from each section and tested in a standard rotating beam fatigue testing machine.

Preparation of samples used for light and scanning electron microscopy was done using standard metallographic techniques. Light microscopy samples were etched in a 2% nital solution and the scanning electron samples were etched in a 3% nital solution.

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CHAPTER III

Test Results

Toughness

Impact values of the grade E or N-80 steel at -32°C (figure 3) were found to be slightly higher for the samples normalized at 793°C than for the samples normalized at 849°C and 904°C. Impact values of those normalized at 849°C were approximately the same as those normalized at 793°C for times up to one hour. The sample normalized for two hours at 849°C had a lower impact value than the two hour sample at 793°C. Samples normalized at 904°C displayed an overall lower impact value than the samples normalized at both 849°C and 793°C. Lateral expansion values as shown in figure 4 followed essentially the same pattern as the impact values for all the samples.

Hardness

Average Brinell hardness numbers (figure 6) for all the samples fell in a range of 229 to 245 BHN. The samples normalized at 793°C had a slightly higher hardness than those normalized at 849°C and 904°C. Also, the samples displayed a slightly lower hardness after normalizing for two hours at each temperature.

Yield Strength

The samples normalized at 793°C generally had the highest overall yield strength (an average of 606.7 MPa (88 ksi)) and displayed only a slight drop in yield strength with increasing time at temperature as shown in figure 7. The sample normalized for 5 minutes at 849°C had a comparable yield strength to those normalized at 793°C. As the normalizing time at 849°C increased, the yield strength decreased to a minimum of 561 MPa (81 ksi) for the sample normalized for two hours. All of the samples normalized at 904°C had lower yield strengths (an average of 544.6 MPa (79 ksi)) with the samples normalized for times up to one hour having approximately equal yield strengths. The sample normalized for two hours at 904°C had a lower yield strength (an average of 525.3 MPa (76.2 ksi)) than all of the other samples tested.

Tensile Strength

The tensile strengths of all the samples tested followed essentially the same pattern as the yield strengths as shown in figure 7. A fairly uniform tensile strength was observed for the samples normalized at 793°C and a decreasing tensile strength with increasing time was noted for the samples normalized at 849 and 904°C.

Elongation

The elongation values for most samples fell in a narrow range of 23.7 to 27.5% as shown in figure 5.

The samples normalized at 793°C had slightly higher elongation values than those normalized at 849°C and 904°C. The samples normalized at 793°C and 849°C displayed very little change in elongation with increasing time up to two hours. The sample normalized at 904°C for two hours had a considerably lower elongation value (20%) than all of the other samples tested.

Fatigue

The samples normalized at 793°C had an overall endurance limit that was higher (an average of 400.7 MPa (58.1 ksi)) than those normalized at either 849 or 904°C. The endurance limit for all normalizing temperatures displayed little variation with increasing time at temperature as shown in figure 8. The samples normalized at 904°C, while demonstrating more erratic endurance limits had approximately comparable endurance limits to those normalized at 849°C. Individual S - N curves for all the samples are shown in figures 9 through 11.

Metallography

The photomicrographs in figures 12 through 17 showed a distinct coarsening of the microstructure with increasing normalizing temperature. The samples normalized at 793°C (figures 12 and 13) had a very fine structure of ferrite and bainite with little difference being shown with longer time at normalizing temperature. The samples normalized at

849°C (figures 14 and 15) had a coarser structure than the 793°C samples. As the time increased, at 849°C the ferrite grains became more distinct and more acicular as shown in figure 15. The samples normalized at 904°C (figures 16 and 17) had a very coarse structure of acicular ferrite and bainite. Increasing time at 904°C again led to more distinct and larger acicular ferrite grains as shown in figure 17.

SEM Analysis

The SEM photographs (figures 18 through 23) depict the same results as were described by light microscopy. At 2000x the coarsening of the ferrite grains with increasing time at each temperature is more apparent. With increasing time at temperature, the ferrite grains are seen to become more distinct with less carbide present within the ferrite grains as shown in figures 19, 21, and 23.

CHAPTER IV

Discussion of Results

Toughness

The samples of the grade E or N-80 steel normalized at 793°C had an average of 4 J and 8 J (figure 3) higher impact value than the samples normalized at 849°C and 904°C respectively. This higher impact value is attributed to the finer grain size of the samples as shown in figures 12 and 13. The samples normalized at 849°C and for times up to one hour retained a fine grain structure (figures 14 and 20) and, therefore, had approximately equal impact values to those normalized at 793°C as shown in figure 3. The lower impact value (19 J) of the sample normalized at 849°C for two hours would be due to the coarser structure and larger ferrite grain size as shown in figures 15 and 21. The still larger austenitic and hence larger ferrite grain size of the samples normalized at 904°C (figures 16 and 17) accounts for the lower impact values of the samples normalized at that temperature. K. J. Irvine and F. B. Pickering[6] demonstrated

[6] K. J. Irvine and F. B. Pickering, Low Carbon Steels with Ferrite-Pearlite Structures, Journal of the Iron and Steel Institute, Vol. 201, (1963), p. 944.

the adverse effect of large austenitic grain size on Charpy V - notch values of a steel (.11 C, .49 Mn, .3 Si) normalized at temperatures from 900°C to 1200°C.

Hardness

The samples normalized at 793°C were approximately 5 BHN points harder than the 849°C samples and 7 BHN points harder than the 904°C samples as shown in figure 6. The higher hardness can be attributed to finer grain size and carbide dispersion as can be seen in figures 20 and 21. The 10 BHN point decrease in hardness at all temperatures for normalizing times of two hours would be due to a coarsening of the carbide dispersion and grain size as is illustrated in figures 19, 21, and 23.

Yield and Tensile Strength

Due to the fact that the yield strength to tensile strength ratio displayed little variation (.70 - .77) for all the samples tested the factors affecting yield strength would also be responsible for the observed differences in tensile strength. The small variation in yield and tensile strength observed for all of the samples normalized at 793°C (figure 7) is due to the fact that only slight coarsening of the structure occurred as can be seen in figures 12 and 13. For the samples normalized at 849°C a more distinct lowering of the yield and tensile strength occurred with increasing time at temperature. Analysis of the microstructure in figure 20 for the sample normalized for five minutes shows a fine structure with a uniform carbide dispersion very similar to the microstructure of the samples normalized at 793°C (figures 18 and 19). After two hours at 849°C, figure 21 depicts a much coarser structure with larger ferrite grains and greater agglomeration of the carbides that would account for the lower yield and tensile strength as shown in figure 7. F. B. Pickering[7] studied the relationship between the number of carbide particles and tensile strength of low carbon bainitic steels. It was reported that as the number of carbide particles decreased a corresponding decrease in tensile strength occurred. The results encountered in this investigation are also in agreement with those of N. J. Petch[8] whose studies have shown that the yield strength of a material increases with decreasing grain size.

The overall lower yield and tensile strengths (an average of 545 MPa and 761 MPa respectively) observed for the samples normalized at 904°C (figure 7) is attributable to still larger grain size and further carbide coarsening.

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[7] F. B. Pickering, "The Structure and Properties of Bainite in Steels", Transformation and Hardenability in Steels Symposium: (February, 1967), Climax Molybdenum Co. of Michigan, Inc. 1967.

[8] N. J. Petch, "The Cleavage Strength of Polycrystals", Journal of the Iron and Steel Institute, (1953) vol. 174, p. 25.

Analysis of figure 17 reveals that considerable growth of the ferrite grains occurred in the sample normalized at 904°C for two hours accounting for its much lower yield and tensile strength.

Elongation

The elongation values for the samples normalized at 793°C fell within a narrow range in line with yield and tensile properties as shown in figure 5. The higher elongation values of the samples normalized at 793° versus those of the samples normalized at 904°C may reflect the more uniform dispersion of carbides at the lower normalizing temperature. The sample normalized at 904°C for two hours is noted to have a very acicular ferrite and bainite structure (figure 17) that is primarily responsible for the lower elongation observed in that sample. The increase in elongation that occurred in the sample normalized at 849°C for two hours would be due to the larger ferrite grains (figure 15) without the large acicularity that was observed in the sample normalized at 904°C for two hours.

Fatigue

The higher endurance limit (an average of 58 MPa) observed in the samples normalized at 793°C follows the trend of higher strength properties found for these samples. The relatively uniform fatigue ratio (.42 - .52) of all the samples tested reflects the influence of grain size on the tensile properties and, therefore, on the endurance limits. It is also known that fatigue strength of annealed steel increases with decreasing grain size[9] as would be the case with the samples normalized at 793°C.

Metallography

Normalizing at 793°C produced a very fine grain size without a great deal of coarsening being encountered at times up to two hours (figures 12 and 13). The sample normalized at 849°C for five minutes (figure 15) also displayed a relatively fine structure comparable to the 793°C samples. The samples normalized at 793°C and 849°C for five minutes probably had some undissolved vanadium carbides during austenitization that accounted for nucleation of bainite throughout the structure. H. B. Aaron and G. R. Kotler[10] and P. Dembowski and R. Griffin[11] have determined that vanadium carbides are rapidly dissolved during austenitization. At 843°C, the time necessary for complete solution of fine vanadium carbides was reported to be approximately 16 minutes. The clear ferrite

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[9]George E. Dieter, Jr., Mechanical Metallurgy New York McGraw-Hill Book Company, Inc., 1961), p. 329.

[10]H. B. Aaron and G. R. Kotler, "Second Phase Dissolution", Metallurgical Transactions, vol. 2 (1971), p. 393.

[11]P. Dembowski and R. Griffin, Austenitization Soak Times, p. 34 - 39.

grains observed in figures 19, 21, and 23 would suggest that solution of the carbides had taken place and that nucleation of the bainite occurred predominantly at the prior austenite grain boundaries.

Applications

The preceding results indicate that current normalizing procedures used to obtain grade E or N-80 properties may be modified at the benefit of steel properties and energy conservation. Consider a current practice consisting of normalizing at 871°C for 30 minutes at temperature according to the well known rule of one hour soaking time per inch of section thickness. This cycle could be changed to normalizing at 793°C for 10 minutes which would increase furnace output, conserve a considerable amount of fuel by virtue of the lower furnace temperature and shorter cycle time, and yield a product with better mechanical properties.

CHAPTER V

Conclusions

The effect of normalizing temperature and time were evaluated for a steel used for N-80 and E grade tubular products. The study included comparison of impact toughness, hardness, tensile properties, fatigue life and microstructure. Based on this investigation the following conclusions were reached:

1. Normalizing at a temperature 16°C above Ac_3 (793°C) and for a short period of time resulted in mechanical properties that were better than those of samples normalized at 849°C or 904°C.

2. Normalizing at 793°C for 5 minutes produced a more uniform microstructure than normalizing at 849°C or 904°C for 2 hours.

3. It would be economically advisable to use lower normalizing temperatures and shorter normalizing times.

4. The rule of one hour soaking time per inch of section thickness does not appear to be necessary for normalizing tubular products.

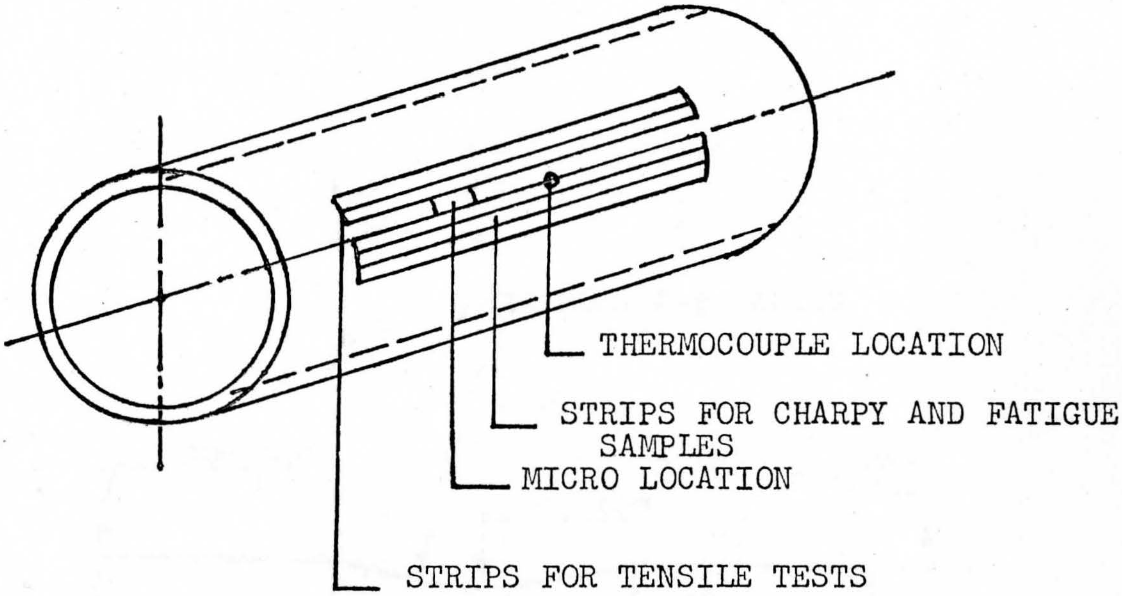

Figure 1.--Test specimen location in normalized sections.

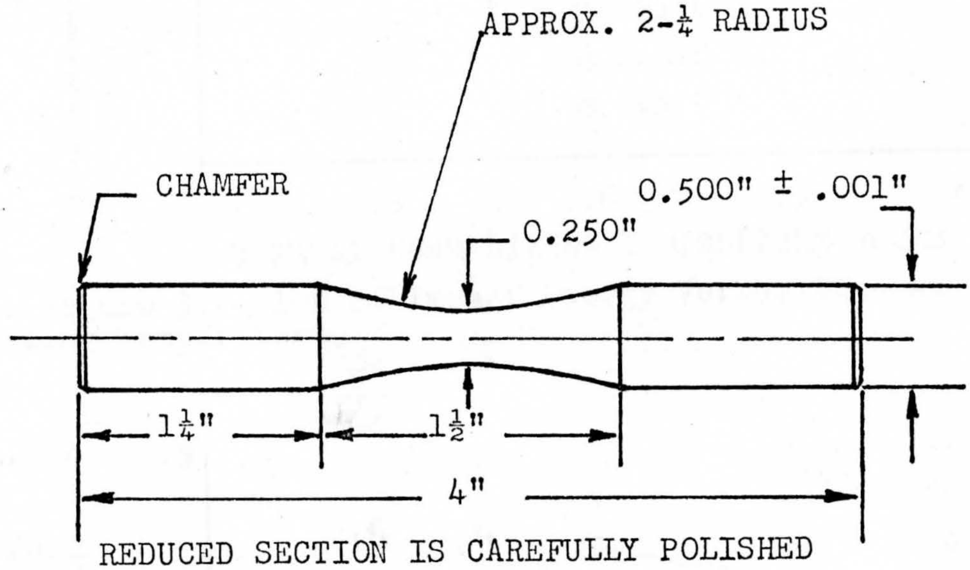

Figure 2.--Rotating Beam Fatigue Test Specimen

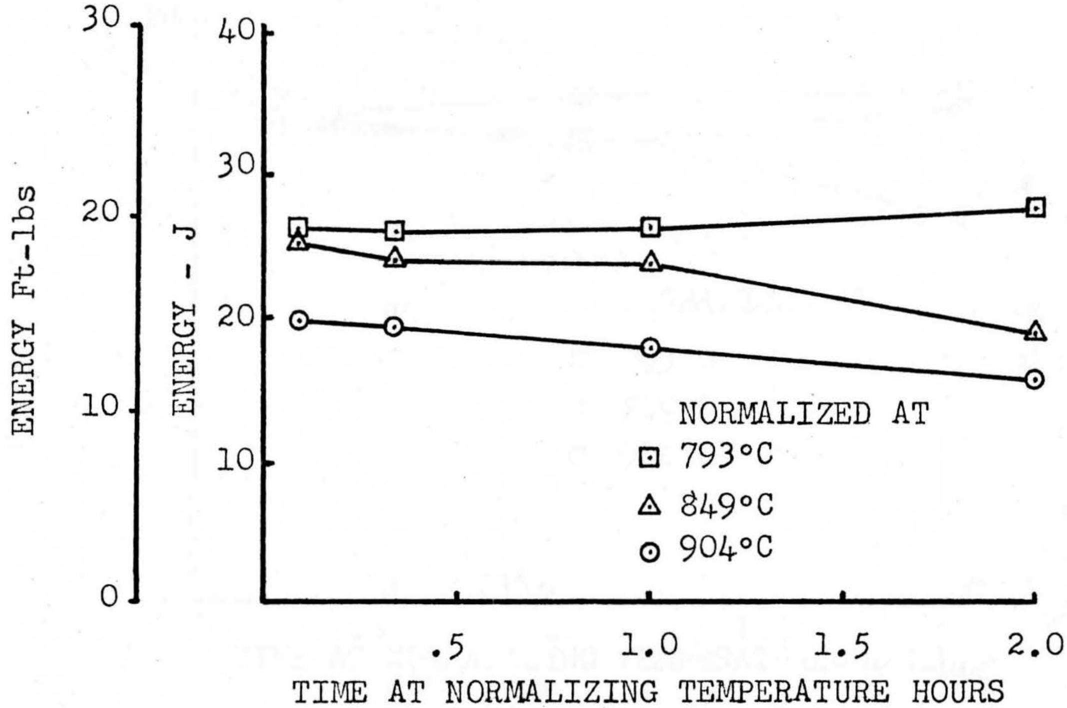

Figure 3.--Plot of Impact Energy Versus Time at Normalizing Temperature.

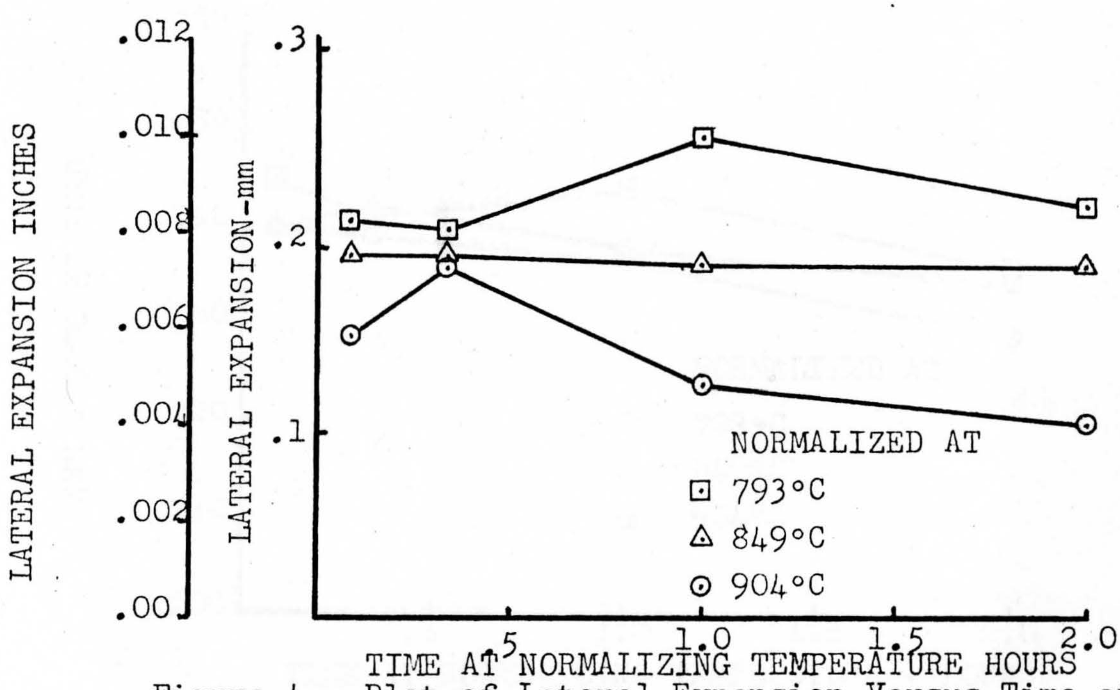

Figure 4.--Plot of Lateral Expansion Versus Time at Normalizing Temperature.

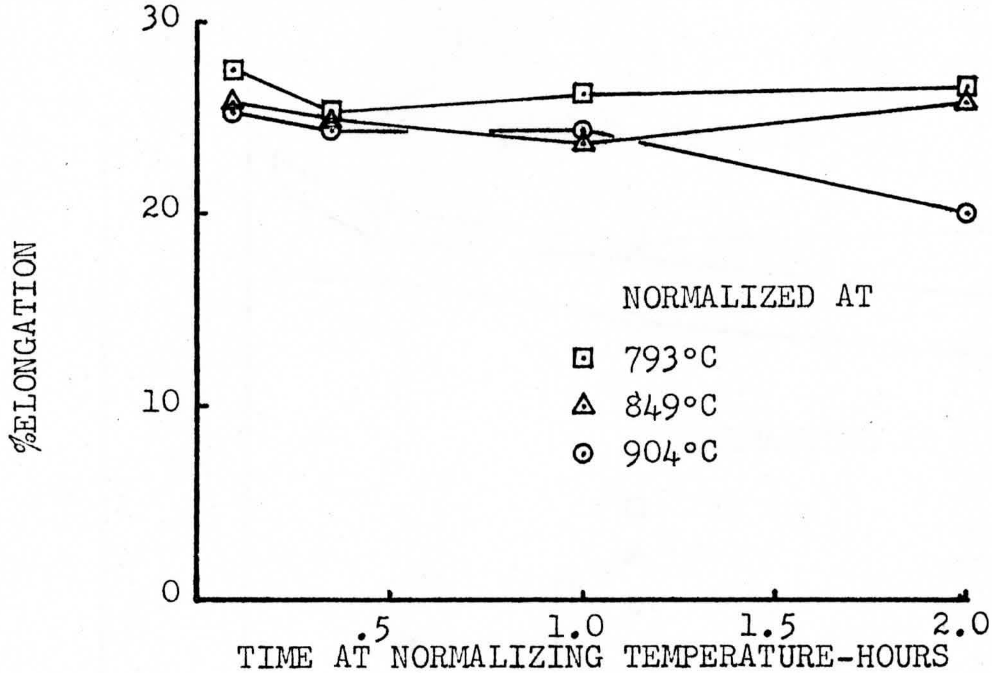

Figure 5.--Plot of Percent Elongation Versus Time at Normalizing Temperature.

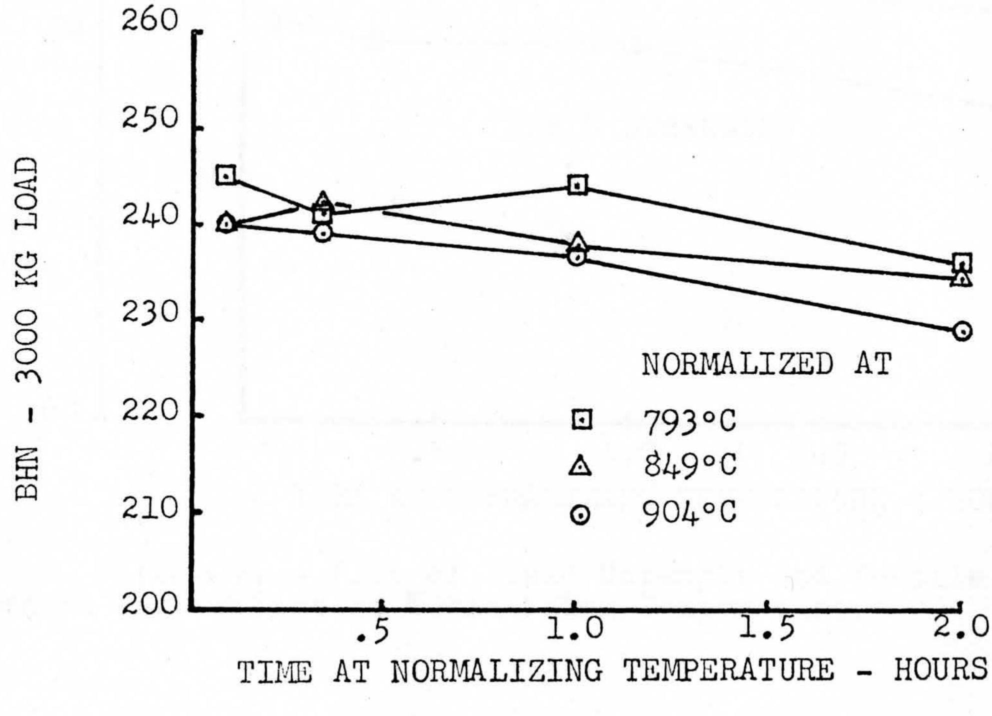

Figure 6.-- Plot of Brinell Hardness Versus Time at Normalizing Temperature.

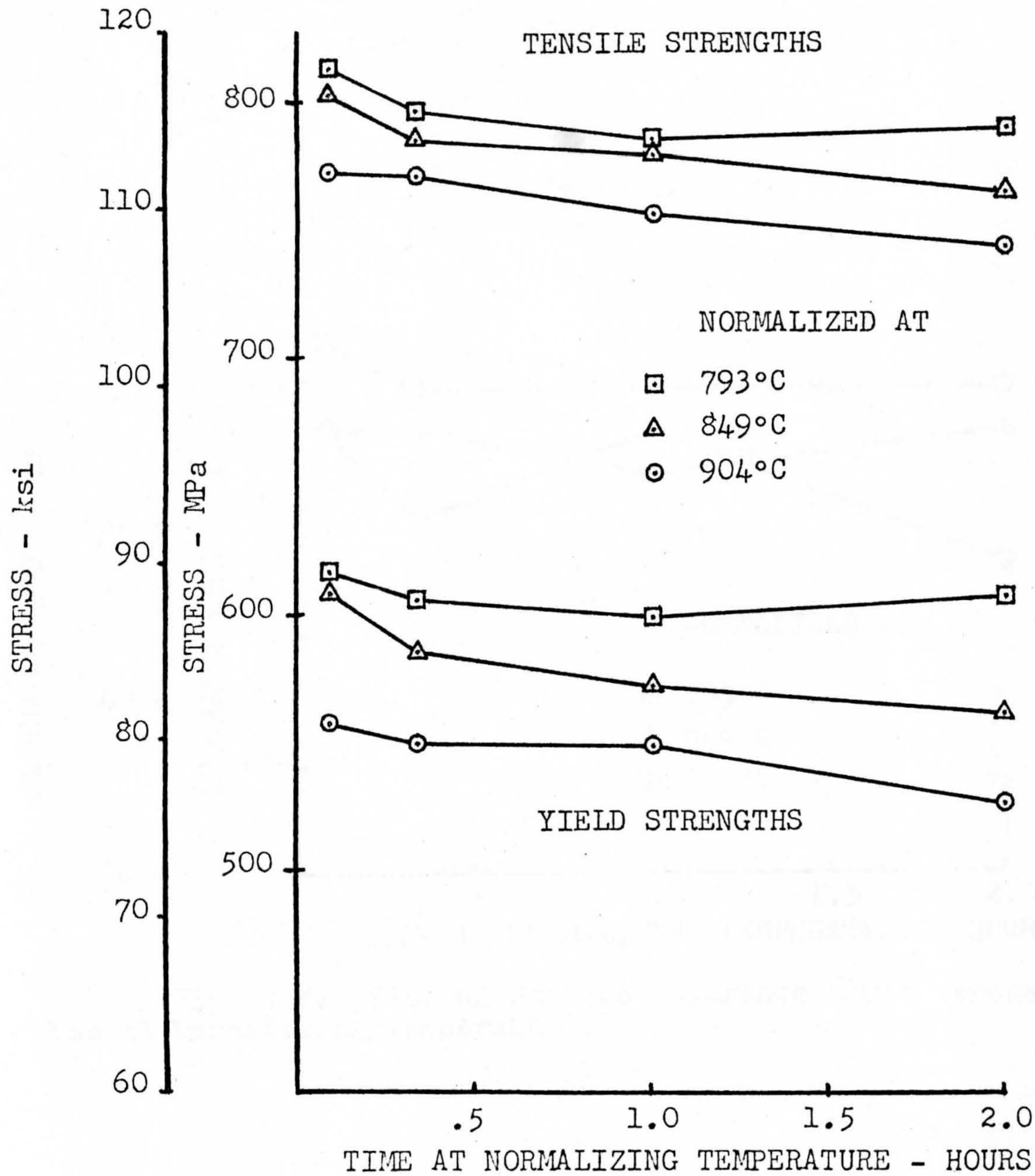

Figure 7.-- Plot of Yield Strength and Tensile Strength Versus Time at Normalizing Temperature.

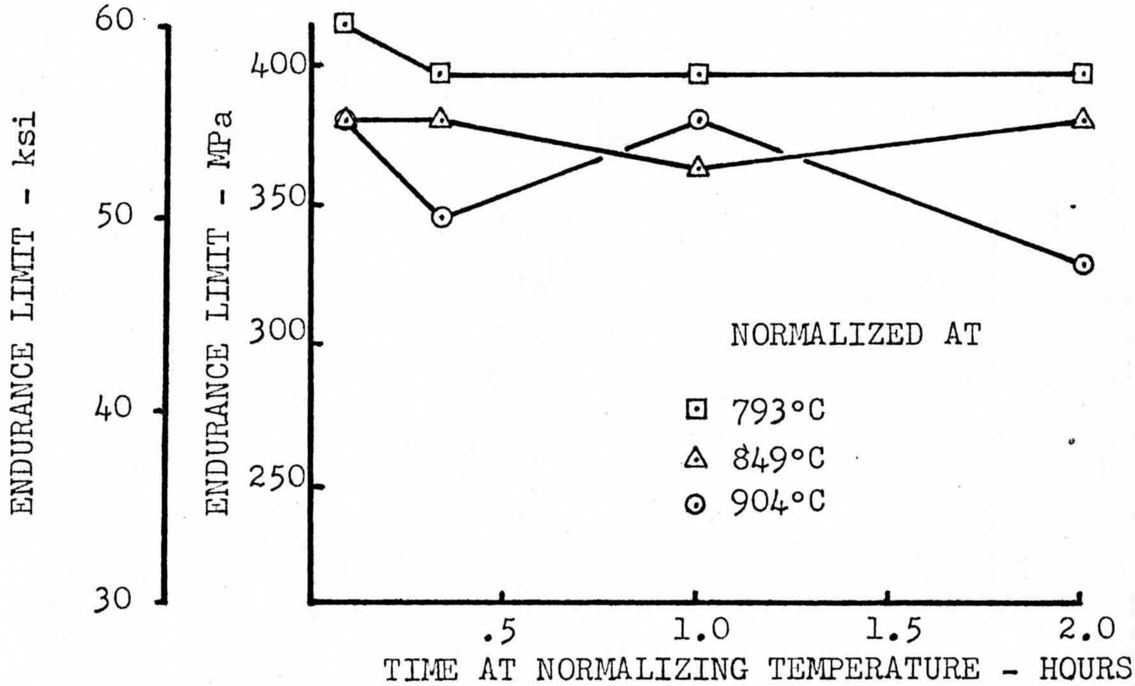

Figure 8.--Plot of Fatigue Endurance Limit Versus Time at Normalizing Temperature.

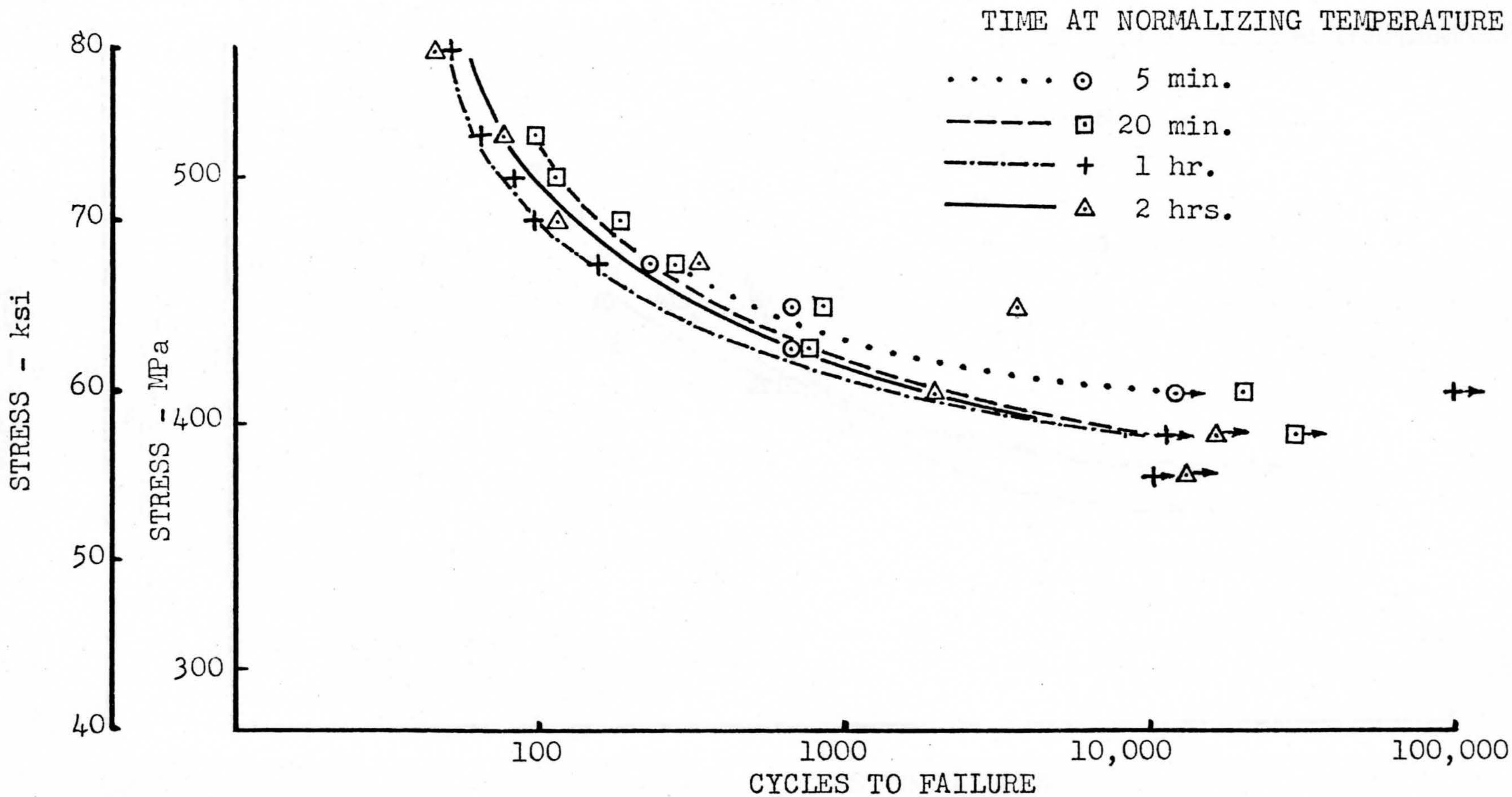

Figure 9.--Plot of Stress Versus Cycles to Failure for Samples Normalized at 793°C.

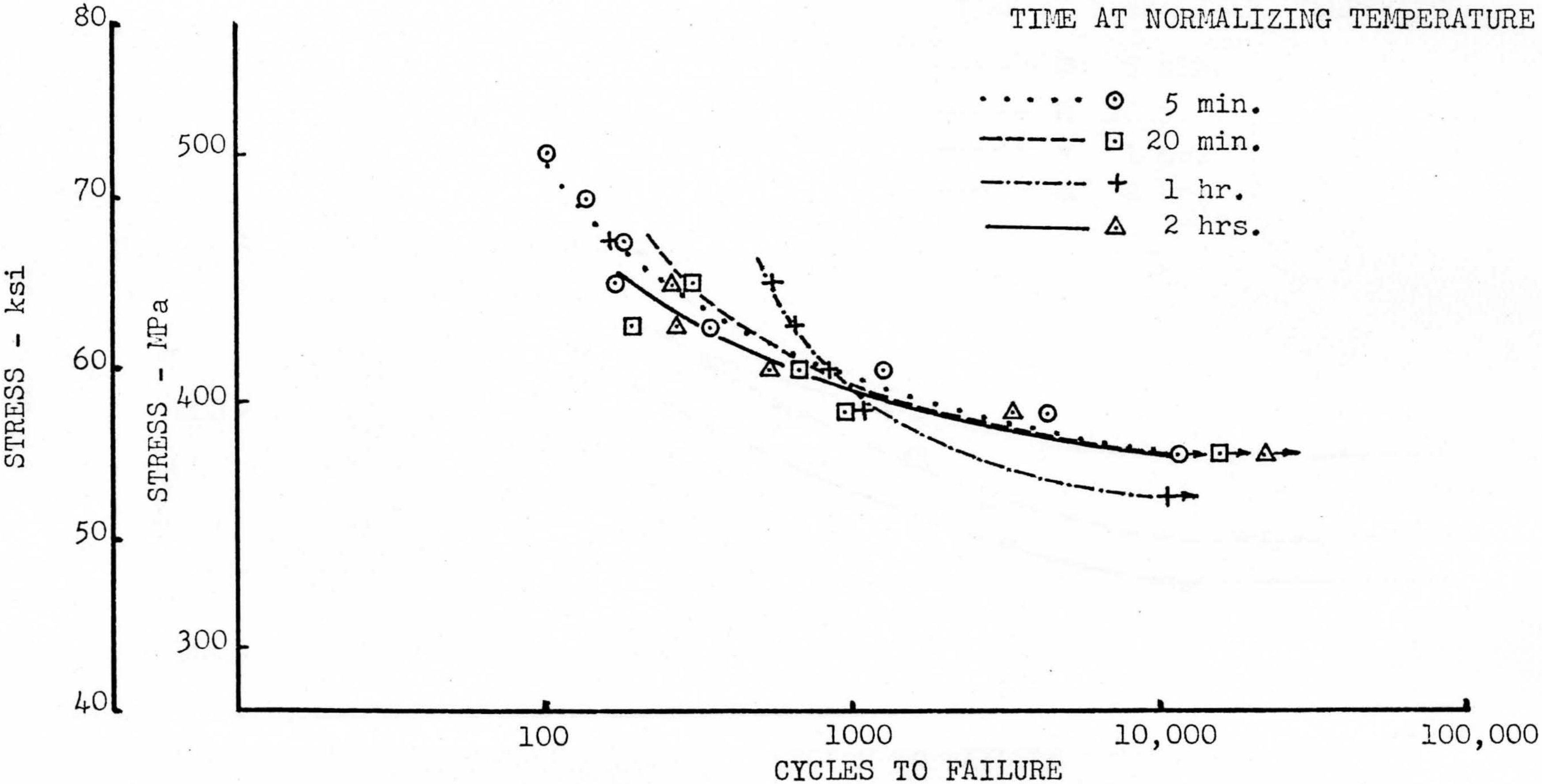

Figure 10.--Plot of Stress Versus Cycles to Failure for Samples Normalized at 849°C.

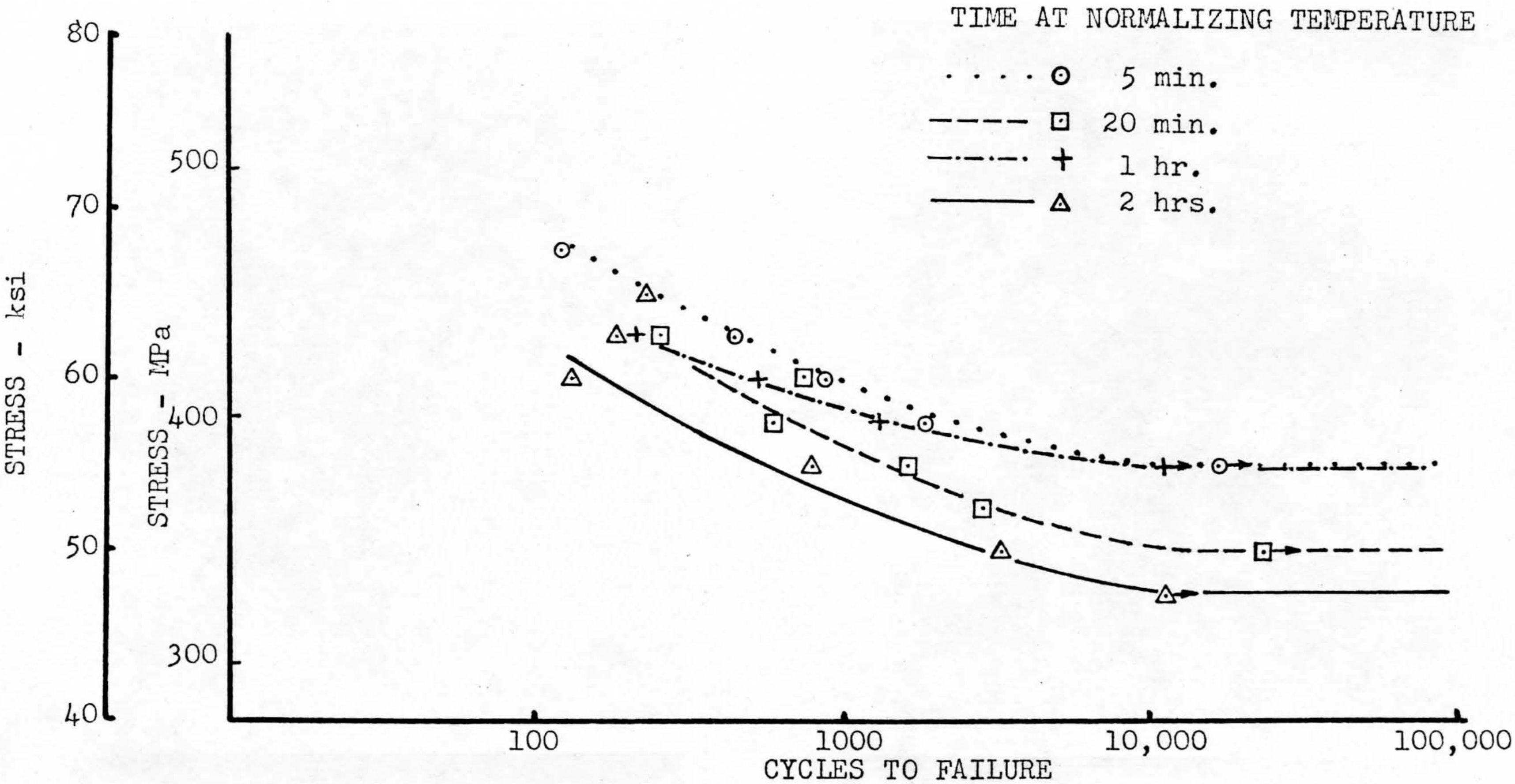

Figure 11.--Plot of Stress Versus Cycles to Failure for Samples Normalized at 904°C.

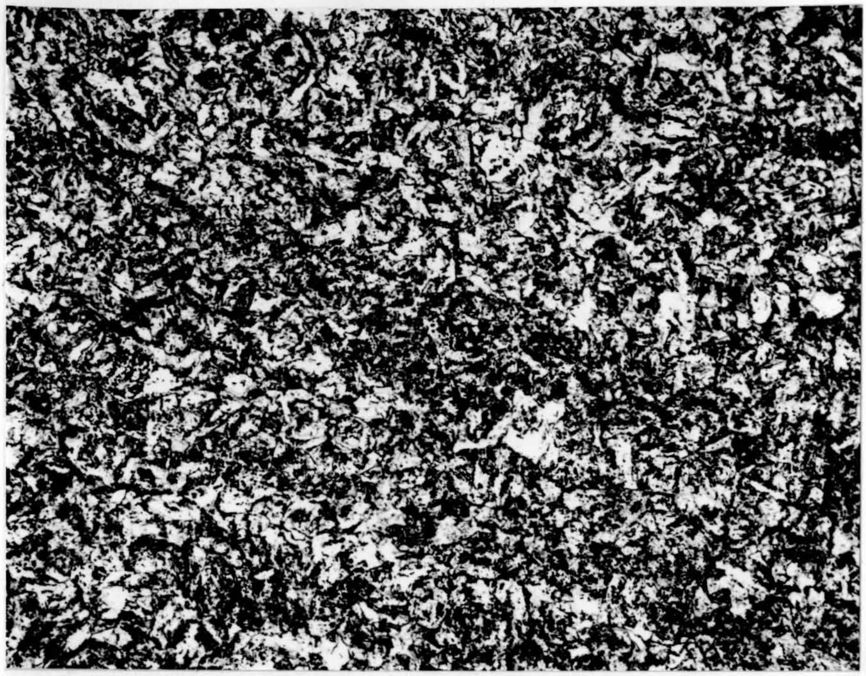

Fig. 12 -- Photomicrograph of Sample Normalized at 793°C for 5 Minutes (500x)

Fig. 13 -- Photomicrograph of Sample Normalized at 793°C for 2 Hours (500x)

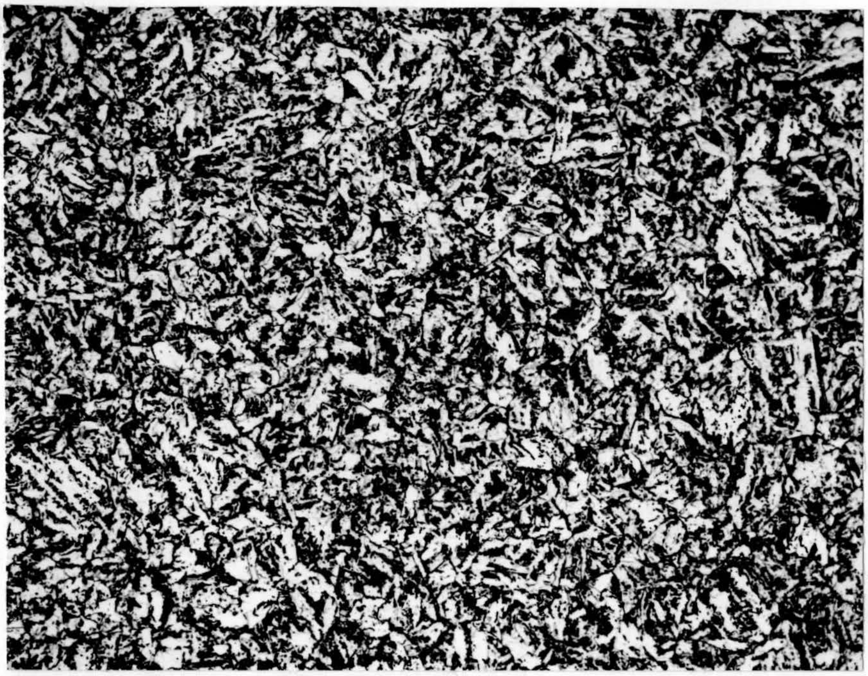

Fig. 14 -- Photomicrograph of Sample Normalized at 849°C for 5 Minutes (500x)

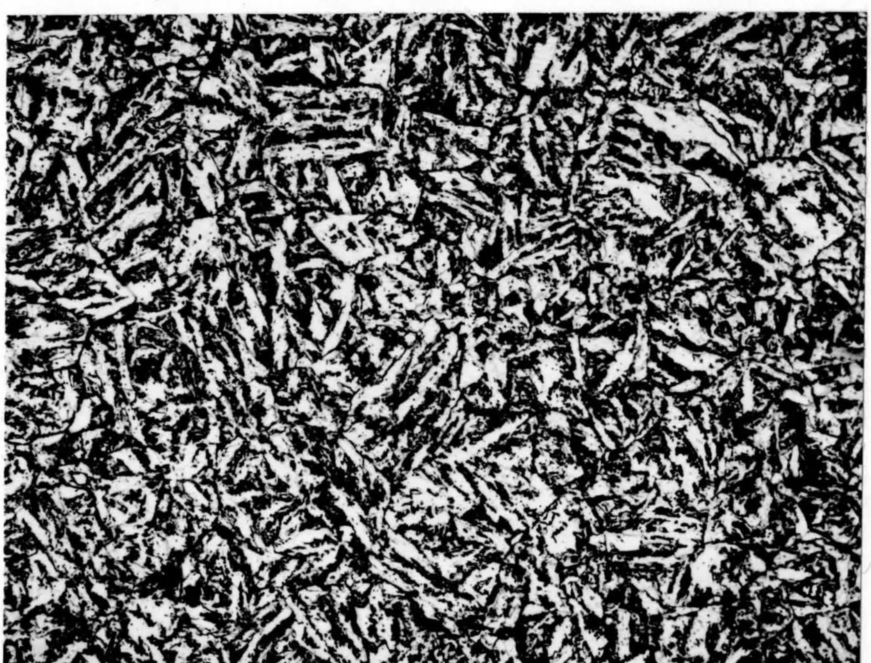

Fig. 15 -- Photomicrograph of Sample Normalized at 849°C for 2 Hours (500x)

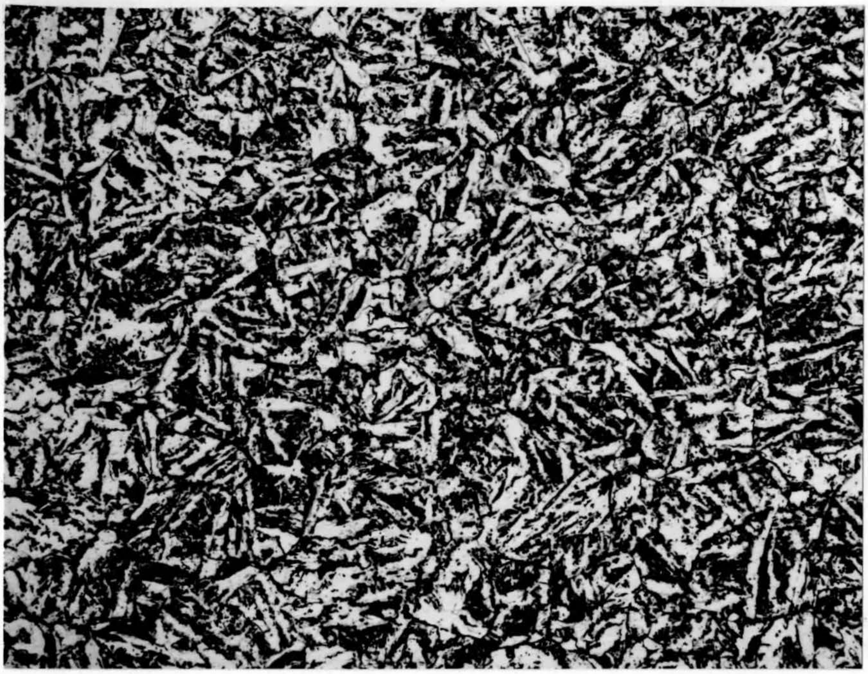

Fig. 16 -- Photomicrograph of Sample Normalized at 904°C for 5 Minutes (500x)

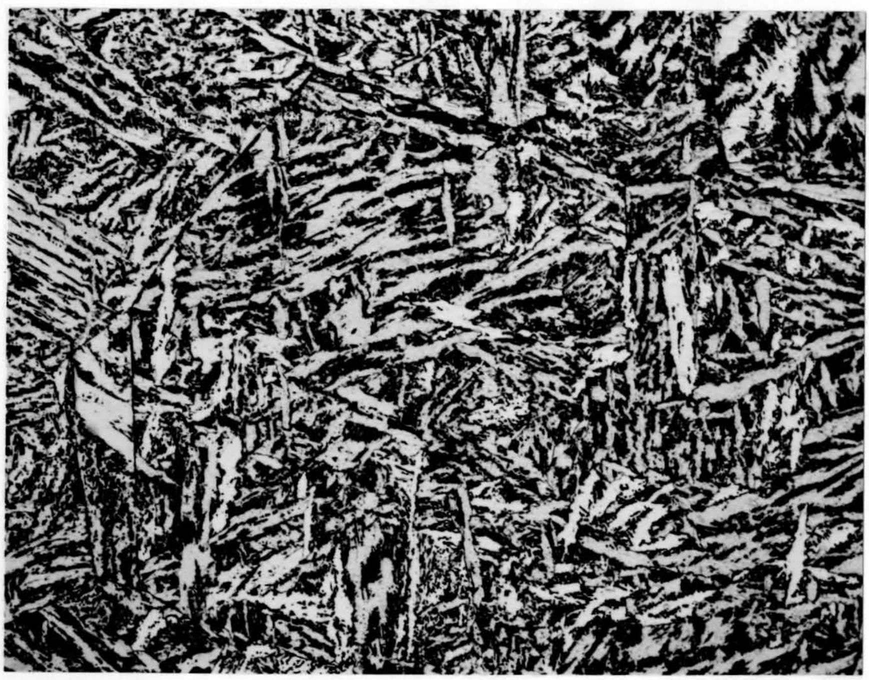

Fig. 17 -- Photomicrograph of Sample Normalized at 904°C for 2 Hours (500x)

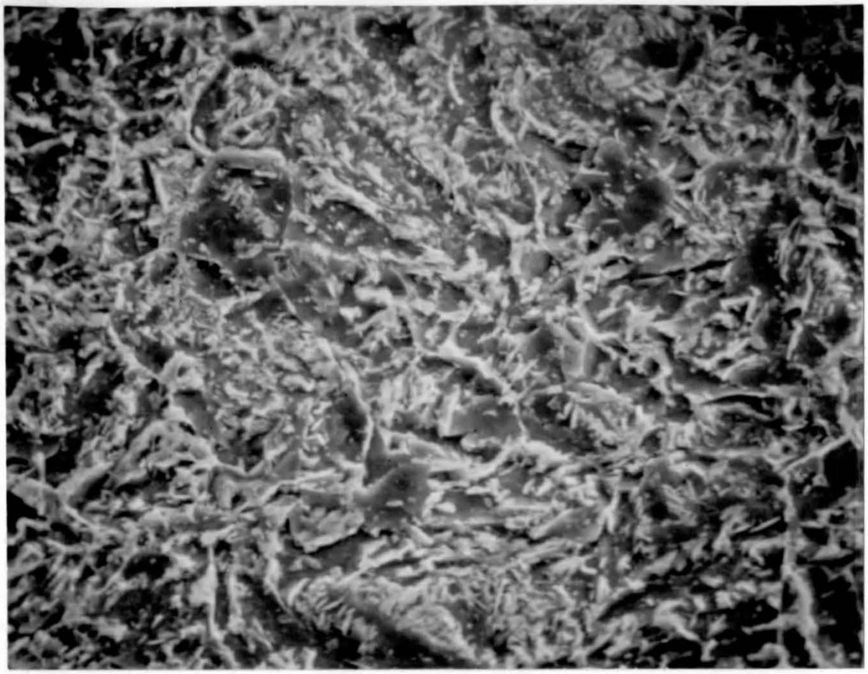

Fig. 18 -- SEM Photograph of Sample Normalized at 793°C for 5 Minutes (2000x)

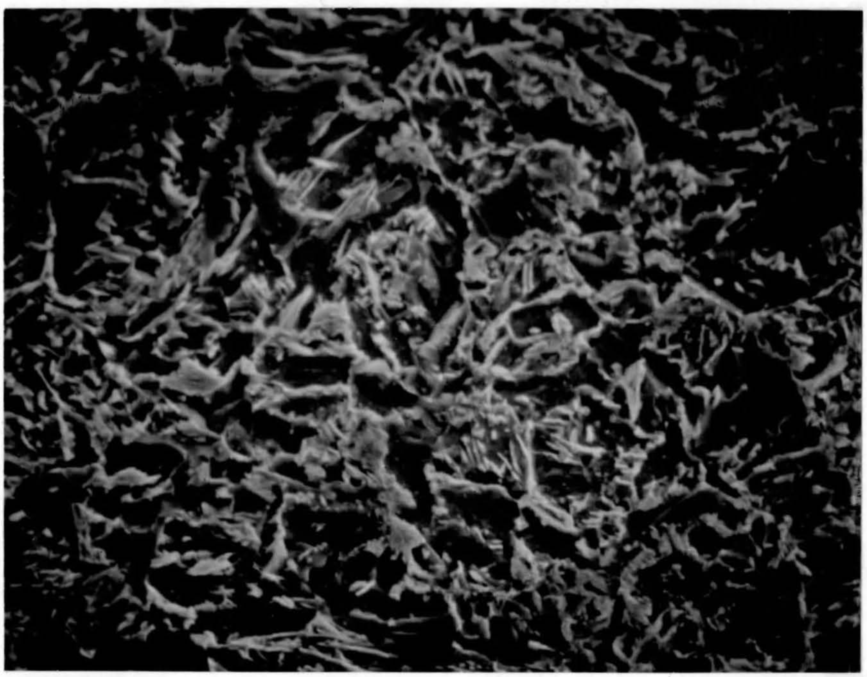

Fig. 19 -- SEM Photograph of Sample Normalized at 793°C for 2 Hours (2000x)

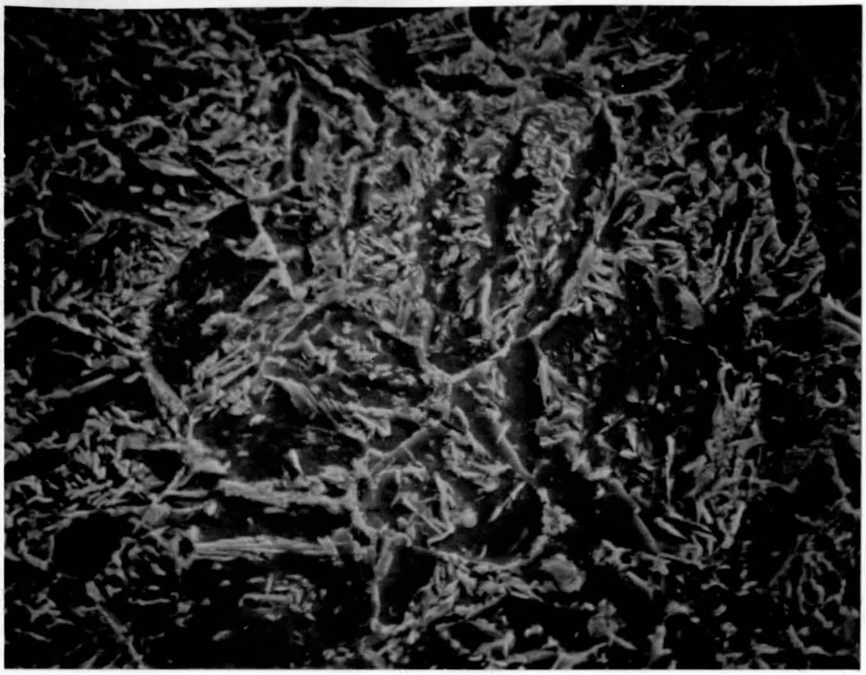

Fig. 20 -- SEM Photograph of Sample Normalized at 849°C for 5 Minutes (2000x)

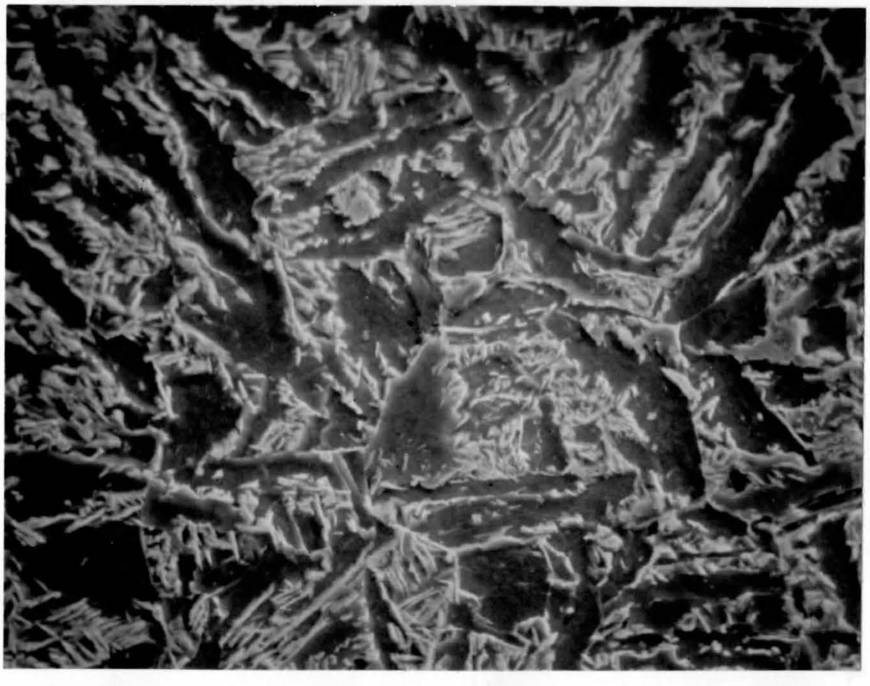

Fig. 21 -- SEM Photograph of Sample Normalized at 849°C for 2 Hours (2000x)

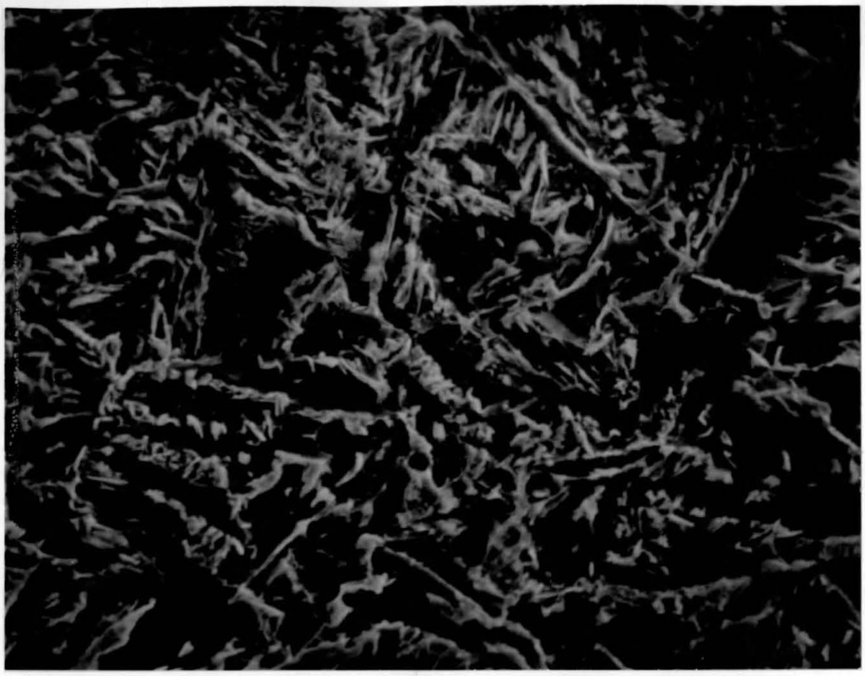

Fig. 22 -- SEM Photograph of Sample Normalized at 904°C for 5 Minutes (2000x)

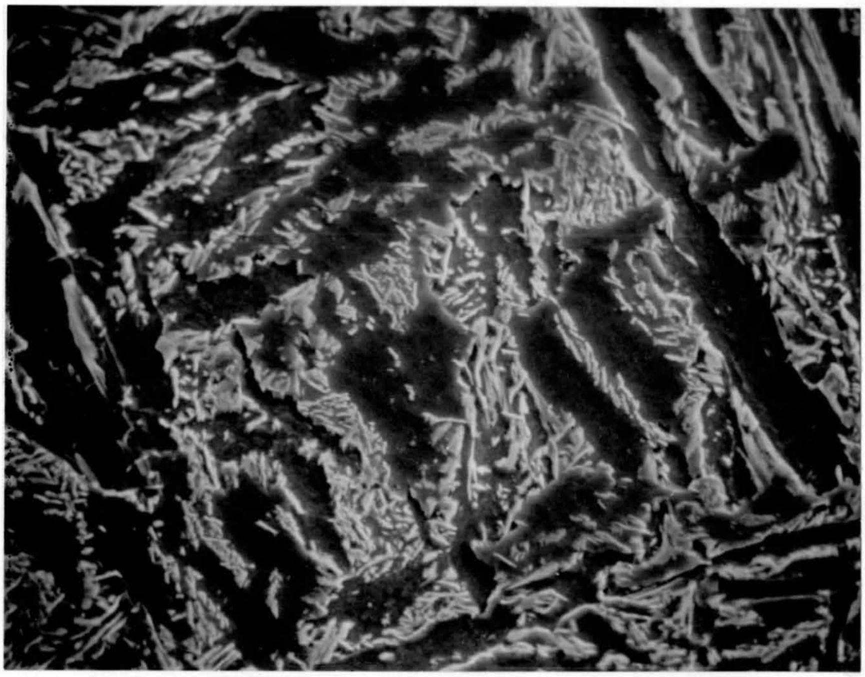

Fig. 23 -- SEM Photograph of Sample Normalized at 904°C for 2 hours (2000x)

TABLE I

Normalizing Cycles

Normalizing Temperature	Times At Normalizing Temperature
793°C	5 min., 20 min., 1 hr., 2 hrs.
849°C	5 min., 20 min., 1 hr., 2 hrs.
904°C	5 min., 20 min., 1 hr., 2 hrs.

TABLE II

Tests Cut From Each Section

1. Three Longitudinal Charpy Notched Impact Specimens.
2. Two Longitudinal Tensile Specimens.
3. Twelve Rotating Beam Longitudinal Fatigue Samples.
4. Transverse Section for Light Microscopy.
5. Transverse Section for Scanning Electron Microscopy.

APPENDIX

CHARPY IMPACT VALUES

NORMALIZED AT 793°C

TABLE III

Time	Test Temp	ENERGY Ft-lbs	ENERGY J	AVERAGE Ft-lbs	AVERAGE J	LAT. EXP. Mils	LAT. EXP.	AVERAGE Mils	AVERAGE
2 hrs.	-32°C	20.5	28.0			8.5	215		
		20.0	27.0	20.2	27.3	9.0	230	8.5	216.7
		20.0	27.0			8.0	205		
1 hr.	-32°C	20.0	27.0			14.5	370		
		19.0	26.0	19.3	26.3	8.0	205	10.0	255.0
		19.0	26.0			7.5	190		
20 min.	-32°C	19.5	26.5			8.5	215		
		19.0	26.0	19.2	26.2	7.5	190	8.0	203.3
		19.0	26.0			8.0	205		
5 min.	-32°C	19.0	26.0			7.5	190		
		19.0	26.0	19.2	26.2	8.5	215	8.2	206.7
		19.5	26.5			8.5	215		

CHARPY IMPACT VALUES

NORMALIZED AT 849°C

TABLE IV

Time	Test Temp	ENERGY Ft-lbs	ENERGY J	AVERAGE Ft-lbs	AVERAGE J	LAT. EXP. Mils	LAT. EXP.	AVERAGE Mils	AVERAGE
2 hrs.	-32°C	13.5	18.5			8.5	215		
		17.0	23.0	14.0	19.0	9.0	230	7.3	186.7
		11.5	15.5			4.5	115		
1 hr.	-32°C	19.5	26.5			8.5	215		
		15.5	21.0	17.5	23.7	7.5	190	7.3	185.0
		17.5	23.5			6.0	150		
20 min.	-32°C	17.5	23.5			8.5	215		
		18.0	24.5	17.7	23.8	7.5	190	7.5	188.3
		17.5	23.5			6.5	160		
5 min.	-32°C	19.5	26.5			7.5	190		
		19.0	26.0	18.7	25.3	9.0	230	7.5	190.0
		17.5	23.5			6.0	150		

CHARPY IMPACT VALUES

NORMALIZED AT 904°C

TABLE V

Time	Test Temp	ENERGY Ft-lbs	ENERGY J	AVERAGE Ft-lbs	AVERAGE J	LAT. EXP. Mils	LAT. EXP.	AVERAGE Mils	AVERAGE
2 hrs.	-32°C	10.5	14.0			4.0	100		
		12.0	16.0	11.5	15.3	3.5	90	4.0	101.7
		12.0	16.0			4.5	115		
1 hr.	-32°C	15.5	21.0			6.0	150		
		12.5	17.0	13.2	17.8	4.0	100	4.8	121.7
		11.5	15.5			4.5	115		
20 min.	-32°C	16.5	22.5			7.0	180		
		11.5	15.5	14.3	19.5	3.5	90	7.3	186.7
		15.0	20.5			11.5	290		
5 min.	-32°C	16.5	22.5			6.5	165		
		17.0	23.0	14.7	19.8	7.5	190	5.8	148.3
		10.5	14.0			3.5	90		

TENSILE PROPERTIES

TABLE VI

Normalizing Temp.	Time	2% Y.S. ksi	2% Y.S. MPa	U.T.S. ksi	U.T.S. MPa	% El.	BHN 3000Kg
793°C	2 hrs.	88.0	607	114.4	789	27.5	236
		88.2	608	114.9	792	25.5	236
	1 hr.	86.4	596	113.2	780	26.0	242
		87.0	600	114.3	788	26.5	246
	20 min.	88.1	607	115.6	797	25.0	242
		87.5	603	115.3	795	25.5	241
	5 min.	89.7	618	117.0	807	28.5	242
		89.0	614	118.6	818	26.5	248
849°C	2 hrs.	82.2	567	111.4	768	25.5	235
		80.5	555	110.3	760	27.0	234
	1 hr.	83.5	576	114.5	789	24.5	239
		82.2	567	111.7	770	23.0	236
	20 min.	84.2	581	112.7	777	25.5	242
		85.7	591	114.7	791	28.5	242
	5 min.	88.8	612	117.3	809	26.5	241
		87.7	605	115.5	796	25.0	239
904°C	2 hrs.	75.8	523	106.8	736	20.0	229
		76.6	528	108.7	750	20.0	229
	1 hr.	80.2	553	109.7	756	25.5	235
		79.3	547	109.5	755	23.5	239
	20 min.	79.8	550	111.6	769	24.5	236
		79.8	550	112.2	774	24.5	242
	5 min.	81.4	561	112.2	774	26.5	239
		78.9	544	111.9	772	25.0	241

FATIGUE TEST DATA

TABLE VII

Samples Normalized at 793°C

Time at Temp.	Stress - MPa	Cycles To Failure
5 min.	414.0	12,620*
	431.0	679
	448.0	576
	465.0	223
20 min.	396.0	29,265*
	414.0	2,023
	431.0	792
	448.0	822
	465.0	285
	483.0	188
	500.0	112
	517.0	99
1 hr.	379.0	10,651*
	396.0	10,827*
	414.0	952
	448.0	625
	465.0	155
	483.0	96
	500.0	82
2 hrs.	379.0	10,334*
	396.0	16,542*
	414.0	1,976
	448.0	1,371
	465.0	342
	483.0	111
	517.0	78
	551.0	45

* Test Discontinued - No Failure

FATIGUE TEST DATA

TABLE VIII

Samples Normalized at 849°C

Time at Temp.	Stress - MPa	Cycles To Failure
5 min.	379.0	12,009*
	396.0	4,381
	414.0	1,298
	431.0	350
	448.0	176
	465.0	185
	483.0	143
	500.0	108
20 min.	379.0	16,805*
	396.0	1,115
	414.0	681
	431.0	198
	448.0	196
1 hr.	362.0	10,308*
	396.0	1,085
	414.0	819
	431.0	643
	448.0	544
	465.0	168
2 hrs.	379.0	21,011*
	396.0	3,337
	414.0	538
	431.0	264
	448.0	264

* Test Discontinued - No Failure

FATIGUE TEST DATA

TABLE IX

Samples Normalized at 904°C

Time at Temp.	Stress - MPa	Cycles To Failure
5 min.	379.0	10,137*
	396.0	1,866
	414.0	860
	431.0	439
	465.0	119
20 min.	345.0	22,980*
	362.0	2,724
	379.0	1,621
	396.0	595
	414.0	749
	431.0	250
1 hr.	379.0	11,755*
	396.0	1,292
	414.0	556
	431.0	210
2 hrs.	327.0	10,132*
	345.0	3,152
	379.0	798
	414.0	130
	431.0	184
	448.0	228

* Test Discontinued - No Failure

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