ELEVENTH PROGRESS REPORT

TO

MATERIALS LABORATORY, WRIGHT AIR DEVELOPMENT CENTER

DEPARTMENT OF THE AIR FORCE

ON

FOUR LOW-ALLOY STEELS FOR ROTOR DISKS OF GAS TURBINES IN JET ENGINES

R. L. Jones
A. I. Rush
J. W. Freeman

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SUMMARY

This report presents the progress made in an investigation of the high temperature properties of low-alloy steels for use in jet engines. The period covered by the report was from July 1, 1953 to September 30, 1953.

Nearly complete data are submitted for survey tests of the influence of type of structure on properties at temperatures ranging from 700° to 1200°F for three steels. The steels are 4340, "17-22A"S and H-40 steels. The structures being considered are those obtained by isothermal transformation of 4340 and "17-22A"S at three temperatures in the pearlitic region and three in the bainitic region. In addition, normalized and oil-quenched specimens are included.

The data to date tend to show that as the test temperature is increased, maximum strength is associated with increasing temperature of transformation. Thus for 4340 steel, maximum strength shifted from lower bainite to upper bainite and the pearlites as the test temperature was increased from 700° to 1100°F. A similar, but less clear cut, trend was shown for the "17-22A"S and H-40 steels. The high strength of normalized steels is dependent on bainite formation. Apparently considerable variation in the strength of normalized steel is possible, depending on the type of bainites formed. The relatively high strength of the normalized specimens over the entire range of temperatures is probably due either to range of bainitic structures or to an advantage from continuous cooling transformation in the bainitic region.

Certain apparently anomalous relationships between structure and properties, particularly for "17-22A"S, need further clarification.

INTRODUCTION

This report covers the work done during the period between July 1, 1953 and September 30, 1953 on an investigation of the metallurgical factors involved in the use of heat-treatable low-alloy steels at high temperatures in aircraft propulsion systems. Contract Number: AF 33 (038)-13496 (Expenditure Order Number: 605-227 SR-7) and Supplemental Agreement Number: S4 (53-534) (Expenditure Order Number: R 615-13 SR-3a) authorize the work.

The investigation first evaluated the high temperature properties of four low-alloy ferritic steels in the form of rotor wheels for jet-engine gas turbines. A concurrent, limited investigation was started to determine the realtionships between types of structure, as controlled by heat treatment, and properties of the alloys. The properties of such steels at elevated temperatures vary with the types of structure formed by heat treatment as do the ordinary room temperature properties. The relationships between structures and properties at high temperatures are, however, not known. For this reason, that phase of the work was extended and is the subject of this progress report.

Nearly "pure structures" are being made by isothermal transformation of three ferritic steels: 4340, "17-22A"S and H-40. The properties of these steels after transformation under controlled conditions are being surveyed at temperatures ranging from 700° to 1200°F by limited creep and rupture tests. The initial surveys are nearly complete for this report. Immediate work for the future will involve completion of the isothermal studies and extension to include various rates of continuous cooling transformation. The final objective is to establish the metallurgical principle for producing as nearly optimum properties at elevated temperatures as possible in such alloys under production conditions.

TEST MATERIALS

The chemical composition of the alloys being studied was reported by the manufacturers as follows:

Steel	Heat	C	Mn	Si	Cr	Ni	Mo	V	W
4340	19053	.40	.70	.30	.78	1.75	.26	--	--
"17-22A"S	24797	.30	.63	.60	1.25	.25	.52	.25	--
"17-22A"S	10420	.29	.61	.67	1.30	.18	.47	.26	--
H-40	K-2509	.29	.48	.26	3.05	.49	.49	.85	.55

In extending the study of structures and properties, it was necessary to obtain additional bar stock. Additional stock of 4340 steel was obtained from the same heat as originally used. It was, however, necessary to take additional stock from another heat of "17-22A"S steel. The original supply of H-40 bar stock was sufficient for the purposes of the additional work.

RESULTS

The structures obtained by the heat treatments are outlined in Tables I, II and III. It will be noted that isothermal transformations were carried out at three temperatures in the pearlitic region and at three temperatures in the bainitic region for 4340 and "17-22A"S steels. One temperature of transformation was used for each region for H-40 steel, due to limited transformation characteristics of this higher alloyed steel. The temperatures and times of transformation were based on time-temperature-transformation diagrams previously reported. In addition, the structures obtained by the usual oil quenching and normalizing operations have been carried along.

It is important to recognize, as is outlined in the tables, that the actual structures deviated from the idealized structures in some cases. Simple names referring to the idealized structures have been used in referring to treatments and structures in the text as a matter of convenience. It should be further recognized that the idealized names do not necessarily describe the same structure in all steels. The names more accurately reflect the position of the transformation temperature in relation to the time-temperature-transformation diagram than the actual microstructures.

Under many conditions of transformation, the time for complete transformation was very long. Furthermore, the transformation rate often became so slow as to virtually stop before complete transformation. In such cases, the treatment conditions were selected to produce a predominance of the aim structure and to subsequently quench out the remaining austenite to martensite.

In those cases where the initial hardness exceeded 320 Brinell, tempering was used to reduce the hardness to 280-320 Brinell. Tempering curves have been previously reported.

Typical microstructures of the as-transformed structures are shown in Figures 1 through 20. The average percentage of each type of structure, based on a number of observations, has been included in Tables I, II and III. The tempered structures are not shown at this time because tempering tends to obscure the actual structure obtained by transformation. As previously mentioned, however, the structures harder than 320 Brinell were tempered before testing.

Survey of Properties of Structures at Elevated Temperatures

In setting up the original program for evaluating structures, it was decided to proceed on the following general basis:

1. Evaluate properties of structures over the range of temperatures over which creep could be a factor in performance. The lower limit was set at 700°F and the upper limit at 1100°F for 4340, and 1200°F for "17-22A"S and H-40 steels.

2. As the temperature is increased, the stresses at which yielding occurs shift from below those at which rupture occurs by creep in reasonable times to being well above the rupture strengths. For this reason, creep is the major factor of interest at 700°F. Any stresses causing rupture in less than 1000 hours would be well above the yield strength and yield characteristics would limit service stresses to those below which rupture would occur. Attempts were made to find a single stress which would evaluate the structures on the basis of the time required to reach one-per cent total deformation.

At 900°F, the intent was to also evaluate structures on the basis of total deformation, using a single stress.

At 1000°F, testing was limited to 4340 steel. Both creep and rupture properties were considered of interest at this temperature. It was considered, however, that two different stress levels would be required to evaluate both properties satisfactorily. The same reasoning was used for "17-22A"S and H-40 at 1100°F.

Testing at 1200°F was limited to "17-22A"S and H-40 steels. At this relatively high temperature, rupture properties for a time period of 100 hours were considered to be of most interest.

3. In some cases, the initial stress chosen was not well suited and repeat testing at another stress became necessary. This also arose in some cases from the choice of stress in the early part of the work where only the stress for one-per cent deformation was considered in the evaluations. As discussed later, the range in strength of the structures in some cases was too wide for evaluation by a single stress and recourse to variable stresses based on a percentage of the yield strength will be used for evaluation.

Survey of Relationships between Structure and Strength for 4340 Steel

The data obtained during the period covered by this report are given in Table IV. All of the data obtained to date have been summarized in the form of bar graphs in Figures 21, 22 and 23 to show the general trends of the data.

1. Properties of 4340 at 700°F: Minimum creep rates and the time required to reach one-per cent total deformation summarized in Figures 21 and 22 indicate that maximum strength was associated with the normalized structure and with structures formed at temperatures just above the martensite reaction temperature. There may have been some added contribution from continuous cooling transformation as judged by the high strength of the normalized stock. The higher the transformation temperature, the lower the strength. Actually, the pearlites are not being well evaluated by the stress used because their ultimate strength was so low, due to low hardness, that fracture occurred shortly after applying the load.

Tempered martensite obtained by oil quenching did not have as good creep resistance as the bainites or normalized material. This was an unexpected finding in that it had heretofore been expected that tempered martensite would compare more favorably at a temperature as low as 700°F.

2. Properties of 4340 at 900°F: Rupture of all the samples occurred in 4.5 to 1417 hours under 55,000 psi (see Figures 21, 22 and 23). Increasing the temperature of testing from 700° to 900°F apparently raised the optimum temperature of transformation to that of middle bainite. Lower bainite and the normalized material were even weaker than the upper bainitic sample. As expected, tempered martensite was comparatively weak. Again, the pearlites compared unfavorably due, at least in part, to low hardness and the relatively high testing stress.

The low elongations of the high strength middle and upper bainites in comparison to the other structures should be noted.

3. Properties of 4340 at 1000°F: Initial tests were carried out at 13,000 psi with the results summarized in Figures 21 and 22. The optimum strength again shifted to a higher temperature of transformation, upper bainite, with increasing test temperature. Upper and middle pearlite compared more favorably than at the lower temperatures. Lower pearlite was, however, the weakest structure tested. Tempered martensite fromoil quenching and lower bainite were quite weak.

Because 1000°F is a relatively high testing temperature for 4340 steel, relatively short time - high stress properties are of sufficient interest to warrant further study. For this reason, the structures are being tested at 31,000 psi for rupture strengths. Two such test results are included in Figure 23. While the data are limited, it will be noted that the upper bainite sample was stronger than the middle bainite, as in the lower stress tests. Figure 23 also includes the results from the one structure, lower pearlite, which fractured under 13,000 psi.

4. Properties of 4340 at 1100°F: Under a stress of 4500 psi, upper pearlite and upper bainite had the best creep strength (Figures 21 and 22). Middle bainite, middle pearlite and probably the normalized material were next strongest. Again lower pearlite was the weakest. There were some discrepancies between minimum creep rate and total deformation in these rankings. There was also some variation in stress used for the structures. This arose from the attempts during initial work to determine as nearly as possible the stress for one-per cent total deformation in 1000 hours.

At 1100°F, higher stress - shorter time properties are again of sufficient interest to warrant rupture tests and such tests are in progress at 18,000 psi. The tests for upper and middle bainite, Figure 23, are included. It will be noted that the difference in rupture strengths was similar to the case for the lower stress creep tests.

Survey of the Relationships between Structures and Strength for "17-22A"S Steel

Table IV gives the data obtained during the period covered by this report. All of the data obtained to date are summarized to show trends by the bar graphs of Figures 24, 25 and 26.

1. Properties of "17-22A"S at 700°F: The initial sorting stress, 115,000 psi, proved to be rather high inasmuch as all structures fracture in less than 300 hours, except middle bainite. Middle bainite (97% fine acicular bainite) was discontinued without fracturing at 1827

hours. It was therefore much stronger than any of the other structures on the basis of all three criteria--minimum creep rate, time to reach one-per cent total deformation, and rupture time. (See Figures 24, 25 and 26.) The next strongest structure was the tempered martensite obtained by oil quenching and tempering. Surprisingly, it was closely followed by middle pearlite. All of the fractured samples had good dutility.

The tests at 115,000 psi did not prove to be very useful in evaluating the structures at 700°F. The stress was too high in most cases, as was evidenced by rupture of most of the specimens. Secondly, there appeared to be a wide variation in strength. At 700°F yield strengths govern the maximum stress which can be used. For these reasons, it is planned to test at a lower stress, using a percentage of the yield strength of each structure as a sorting stress. These tests will also serve as a check on the very high strength shown by middle bainite in the initial tests.

2. Properties of "17-22A"S at 900°F: Middle bainite also had the highest strength at 900°F. (See Figures 24, 25 and 26.) The normalized material was next strongest. Lower bainite, middle pearlite and lower pearlite were the next strongest structures. It is probably important to note that the upper bainite and the tempered martensite of the oil-quenched structure were very weak, even in comparison to the middle and lower pearlites.

3. Properties of "17-22A"S at 1100°F: There was a surprisingly small spread in minimum creep rates, time for one-per cent total deformation or rupture time for all the structures under 19,000 psi. (See Figures 24, 25 and 26.) The normalized structure was somewhat the strongest. The individual rankings of the other structures tended to vary, depending on the criterion used. Some of the tests were initially run at

20,000 psi where the objective was to obtain fracture in about 1000 hours.

All structures had rather low elongation to fracture, except upper and lower pearlite.

4. Properties of "17-22A"S at 1200°F: Although the test is still incomplete, it is evident that upper pearlite will have the best strength at 1200°F under 7500 psi. Middle pearlite and the normalized structure follow in strength. (See Figures 24, 25 and 26.) Upper bainite, which ranked highest at 700° and 900°F, was about the weakest at 1200°F. All structures had considerably higher elongation than at 1100°F.

Survey of the Relationships between Structures and Properties for H-40 Steel

The data obtained during the period covered by this report are given in Table VI. The general trends of all data obtained to date are summarized by Figures 27, 28 and 29.

The data for H-40 steel are summarized in Figures 27, 28 and 29. It will be noted that the pearlitic structure was very weak at 900° and 1100°F, but was slightly the strongest at 1200°F. The sample transformed in the bainitic region was the strongest at 700° and 900°F and probably at 1100°F. A difference in stress at 1100°F makes the comparison uncertain. The tempered martensites (normalized and oil quenched) showed little difference at any of the temperatures, as might be expected. Probably they will be about as good as the bainitic sample at 1100°F.

All fractured specimens showed good elongation.

Correlation of Structures of Forged Rotor Wheels and Properties

At the time the report on the properties of wheels was submitted, attempts were in progress to correlate the properties of the wheels with their microstructures. This has proven to be very difficult. First, the tempered structures of the wheels are difficult to identify with certainty. Secondly, the information available from isothermal transformation to relate structure to properties has been rather incomplete. It is also turning out that structures formed by continuous cooling, as was the case for the wheels, are difficult to break down in terms of the isothermally formed structures.

It has been decided to issue a factual report summarizing the structures of the wheels. Insofar as possible, the structures will be related to properties. However, a good correlation will be dependent on the completion of the study of the continuously cooled structures now in progress.

DISCUSSION

The initial surveys of representative structures formed by isothermal transformation are nearing completion. While the data are sparse, certain trends are becoming evident.

1. There is a definite trend for maximum strength of 4340 steel to be associated with increasing temperature of transformation as the test temperature is increased. A similar trend is present for "17-22A"S steel, although less definite than for 4340 steel. H-40 steel

reacted in the same way, as judged by the shift in relative strengths of the "pearlitic" range and tempered martensites. In all three cases, bainites tended to have the highest strength, although for 4340 and "17-22A"S there was considerable variation, dependent on the temperature of transformation within the bainitic region.

2. For 4340 steel there was a definite progression of maximum strength with increasing temperature from 700° to 1100°F. At 700°F, transformation just above the Ms temperature was strongest. The Cr-Mo-V steels ("17-22A"S and H-40), however, apparently varied somewhat in transformation conditions for maximum strength at 700°, 900° and 1100°F. At the highest temperatures (1100° or 1200°F) in every case pearlitic range transformation tended to give highest strength.

This correlation between temperatures of transformation and properties does take into account the relatively high strength of the normalized structures. It is assumed for the present, at least, that normalizing of 4340 and "17-22A"S produces transformation over a range of temperatures in the bainitic region. Thus, the normalized structures tend to include the most favorable temperatures of transformation and have high strength over a considerable range of test temperatures. There also seems to be reason to believe that there was an advantage for continuous cooling transformation during normalizing at some test conditions.

It is not certain, but probable, that secondary hardening effects introduced by vanadium influence the strength characteristics of the "17-22A"S and H-40 steel. This probably is related to the apparent non-uniform relationships between types of structures and strength in comparison to the regular progression for 4340 steel.

3. The differences in strength between structures tended to diminish with increasing testing temperature.

4. Because normalizing or liquid quenching are almost universally used for practical heat treating, the indications of the data for these treatments are important. Heretofore it has been thought that tempered martensite would be at least equal to other structures at relatively low temperatures. However, intermediate transformation products have shown better properties for all three steels at the lower temperatures.

For 4340 and "17-22A"S steel, tempered martensite did fall off very rapidly with increasing temperature. However, it did retain its strength very well for H-40 steel up to 1200°F.

Normalized structures have generally been noted for their relatively high strength at elevated temperatures. In general, normalizing did tend to give relatively high strengths. It seems evident, however, that the strength after normalizing will be dependent on the cooling rates which control the temperatures of transformation and the resulting structures. In other words, the normalized specimens tested have strengths characteristic of transformation of one-inch bar stock on air cooling. Other section sizes would cool at different rates and transform differently as a consequence. This should modify the relative position of "normalized" structures in the rankings shown.

5. It should be noted that while pearlites tend to become strong in relation to the other structures at 1100° and 1200°F, "upper" pearlite seems always to be the strongest. Lower pearlite was very weak in most of the tests.

6. There was some variation in hardness between the structures and between the same structures tested at different temperatures. The following tabulation gives the hardness data obtained on the individual specimens of 4340 steel before testing.

Test Temp (°F)	Stress (psi)	Upper Pearlite	Middle Pearlite	Lower Pearlite	Upper Bainite	Middle Bainite	Lower Bainite	Normalized	Oil Quenched
700	90,000	--	199	--	324	309	277	300	304
900	55,000	217	231	260	325	313	277	300	306
1000	13,000	219	229	270	322	307	294	301	306
	31,000	--	--	--	327	295	--	--	--
1100	4,500	212	233	275	319	302	301	311	309
	18,000	--	--	--	233	293	--	--	--

Reference to the creep-rupture data shows that:

(a) Lower bainite had superior strength at 700°F in spite of lower hardness. The test temperature had to be increased before the higher hardness middle and upper bainites became superior. This is contrary to the expected trends of higher hardness accompanying higher strength, the lower the test temperature.

(b) In view of the differences in strength, it is unlikely that lower bainite with an equivalent hardness would have equaled the strength of middle and upper bainite at the higher test temperatures.

(c) Upper pearlite, which was much softer than lower pearlite was consistently stronger.

The individual variations in hardness, therefore, seem unlikely to be responsible for general trends in strength developed previously for the data.

The low strength of the lower pearlite seems difficult to understand in view of the hardness. It appears as if the fine carbide structure has inherently low strength. An alternative possibility is that the prolonged time at 1050°F for transformation destroyed some structural condition controlling strength that is not reflected in hardness.

As the work continues, more attention will be given to the development of fundamental explanations of the results.

7. The hardness values of the individual specimens of "17-22A"S steel are summarized in the following tabulation:

Test Temp (°F)	Stress (psi)	Upper Pearlite	Middle Pearlite	Lower Pearlite	Upper Bainite	Middle Bainite	Lower Bainite	Normalized	Oil Quenched
700	115,000	--	267	263	284	309	275	302	278
900	70,000	196	266	266	289	307	283	303	278
1100	19,000	309	285	313	327	310	302	311	306
1200	7,500	237	376	293	320	310	273	318	313

The variations in hardness are considerably greater than seemed reasonable. Checking into the reasons for the tendency for high hardness of the samples run at 1100°F disclosed that in changing heats of stock, a difference in response to heat treatment was found. The microstructures of the new heat stock (Heat 10420) were originally checked for isothermal transformation characteristics and the two heats found identical for practical purposes. However, it is now known that the two heats vary in as-transformed hardness and tempering characteristics. Heat 10420 tends to give lower hardness on transformation, particularly in the pearlitic region. Secondly, it tempered more easily than Heat 24797. It has now been determined that tempering conditions should have been changed as follows to obtain 300 Brinell hardness:

	Heat Number 24797		Heat Number 10420	
	Temp (°F)	Time (hrs)	Temp (°F)	Time (hrs)
Lower Pearlite	1200	12	1200	6
Upper Bainite	1200	16	1200	12
Lower Bainite	1200	12	1200	6
Oil Quenched	1300	1	1300	1/2

Future tests will be carried out using the adjusted tempering to keep the hardness values near 300 Brinell.

The analyses apparently show no significant difference between the two heats. However the original heat (Heat 24797) had slightly higher C, Mo and lower V. All of these would tend to give high hardenability. The as-quenched hardness of the oil-quenched specimens from this heat are on the high side of the range to be expected for the analysis. Heat 10420, however, quenched out to the lower side of the range. Thus, there is a real difference in hardenability. Secondly, the low hardness of the pearlites from Heat 10420 indicates a substantial reduction in secondary hardening characteristics. Secondary hardening appears to be responsible for high hardness of pearlitic structures in "17-22A"S steel.

The influence of these variations in hardness and response to heat treatment on the trends for the relations between structure and properties previously discussed is difficult to clarify. First of all, it depends on which heat is accepted as representative of the alloy. The following comments are offerred:

(a) The comparatively high strength of the pearlites at 1100°F may be due in part to high hardness and extensive secondary hardening. This, however, cannot explain their relatively good properties at 1200°F. It seems certain, however, that if the high hardness had been obtained in the specimens tested at 700° and 900°F, they would have compared more favorably than they did.

(b) There are numerous cases where hardness alone cannot explain the variations in strength. It certainly cannot account for the high strength of middle bainite at 700°F or the difference between the oil quenched and normalized samples at 700°F. The same thing is probably true at 900°F for the middle bainite and the normalized materials, although admittedly they both are somewhat harder than other structures. The variations in properties at 1100°F (other than for the pearlites) and at 1200°F do not seem consistent with hardness.

(c) It now appears that secondary hardening characteristics are important to strength of "17-22A"S. As yet it is uncertain whether the variation of strength with temperature of transformation is due to heat to heat variations or is related to the effect of the temperature of transformation on secondary hardening. Check tests will be required to clear this us.

8. Thus far, no major variation in hardness has been observed for the H-40 specimens. The variations in strength with transformation conditions, therefore, are free from influence from hardness, other than the low hardening of the sample transformed in the pearlitic region as previously discussed.

FUTURE WORK

1. Complete the testing of isothermally transformed specimens as previously outlined in the report.

2. Conduct such check tests as may be necessary to clear up hardness and heat to heat variation effects.

3. Start the study of continuous cooling transformation structures and properties.

TABLE II

Type Structures, Heat Treatments and Actual Structures of 1.25 Cr-Mo-Si-V ("17-22A"S) Steel

(All "17-22A"S bar stock austenitized at 1750°F for 1 hour.)

Aim Structure	Transformation Conditions		Approximate Structure Obtained	B H N	Tempering		B H N
	Temp-°F	Time-hrs			Temp-°F	Time-hrs	
Upper Pearlite	1300	1-1/2	45% medium pearlite + 55% ferrite	196/237	None	--	196/237
Middle Pearlite	1225	1-1/2	40% medium fine pearlite + 60% ferrite	266/285	None	--	266/285
Lower Pearlite	1150	10	40% fine pearlite + 60% ferrite	375	1200	12	263/313
Upper Bainite	900	2	60% upper bainite + 40% martensite	465	1200	16	284/327
Middle Bainite	800	1/2	97% fine acicular bainite + 3% martensite	360	1200	4	307/310
Lower Bainite	700	1/12	100% lower bainite	365	1200	12	273/302
Normalized	Air Cooled from 1750		15% martensite + 85% coarse bainites	355	1200	10	302/313
Oil Quenched	Oil Quenched from 1750		100% martensite	525	1300	1	272/310

TABLE III

Type Structures, Heat Treatments and Actual Structures for 3 Cr-Mo-W-V (H-40) Steel

(All H-40 bar stock austenitized at 1950°F for 1 hour.)

Aim Structure	Transformation Conditions		Approximate Structure Obtained	B H N	Tempering		B H N
	Temp-°F	Time-hrs			Temp-°F	Time-hrs	
Pearlite	1300	24	fine carbide precipitate	190/200	None	--	190/200
Bainite	750	10	100% bainite	480	1300	1	293/313
Normalized	Air Cooled from 1950		20% martensite + 80% bainites	435	1200	18	310/320
Oil Quenched	Oil Quenched from 1950		100% martensite	523	1200	12	290/323

TABLE IV

Rupture, Total Deformation and Creep Data at 700°, 900°, 1000° and 1100°F for 4340 Steel

Aim Structure	BHN	Temperature (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2")	Reduction of Area (%)	Deformation on Loading (in./in.)	Time to Reach Specified Total Deformations 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hour)
Middle Pearlite 85% fine pearlite and fine carbide-ferrite aggregate + 15% ferrite	199	700	90,000	10.7	23	57	--	--	--	--	--	--
Middle Pearlite 85% fine pearlite and fine carbide-ferrite aggregate + 15 % ferrite	231	900	55,000	9.7	28	56	--	a	a	a	<1	--
Upper Bainite 70% upper bainite + 30% martensite	325	900	55,000	1215	6	6.4	0.00265	a	a	6	48	0.00163
Upper Bainite 70% upper bainite + 30% martensite	327	1000	31,000	389	10	7	0.00185	a	<1	13	75	--
Middle Bainite 100% medium acicular bainite	295	1000	31,000	261	5.9	5.6	0.00190	a	<1	18	85	--
Middle Pearlite 85% fine pearlite and fine carbide-ferrite aggregate + 15% ferrite	229	1000	13,000	1539(d)	--	--	0.00053	10	52	515	1175	0.00060
Upper Pearlite 65% medium pearlite + 35% ferrite	212	1100	4,500	1146(d)	--	--	0.00053	52	235	893	1900(b)	0.00046
Middle Pearlite 85% fine pearlite and fine carbide-ferrite aggregate + 15% ferrite	233	1100	4,500	1148(d)	--	--	0.00024	25	93	315	643	0.00139
Middle Bainite 100% medium acicular bainite	293	1100	18,000	80	11	8	0.00080	--	--	--	--	--
Upper Bainite 70% upper bainite + 30% martensite	323	1100	18,000	106	14.3	10	0.00130	--	--	--	--	--

(a) Specimen reached this deformation on loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen, elongation % in 1-inch.
(d) Test discontinued at this time.

TABLE V

Rupture, Total Deformation and Creep Data at 700°, 900°, 1100° and 1200°F for 1.25 Cr-Mo-Si-V ("17-22A"S) Steel

Aim Structure	BHN	Temperature (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2")	Reduction of Area (%)	Deformation on Loading (in./in.)	Time to Reach Specified Total Deformations				Minimum Creep Rate (%/hour)
								0.1%	0.2%	0.5%	1.0%	
Lower Pearlite 40% fine pearlite + 60% ferrite	263	700	115,000	g	19(c)	61	--	--	--	--	--	--
Middle Bainite 100% fine acicular bainite	309	700	115,000	1827(d)	--	--	0.0061	a	a	a	45	0.00029
Upper Pearlite 45% medium pearlite + 55% ferrite	196	900	70,000	112	29(c)	60	--	--	--	--	--	--
Middle Pearlite 40% medium fine pearlite + 60% ferrite	266	900	70,000	1484	13(c)	25	0.00570	a	a	a	24	0.0023
Lower Pearlite 40% fine pearlite + 60% ferrite	266	900	70,000	1205(d)	--	--	0.00406	a	a	2	53	0.00223
Middle Bainite 100% fine acicular bainite	307	900	70,000	1648(d)	--	--	0.00323	a	a	65	2500(b)	0.00014
Middle Bainite 100% fine acicular bainite	310	1100	19,000	815(f)	4(c)	3	0.0010	a	30	222	575	0.0015
Normalized 15% martensite + 85% coarse bainite	309	1100	41,000	111.5	2.5	3.1	--	--	--	--	--	--
Upper Pearlite 45% medium pearlite + 55% ferrite	237	1200	7,500	910(h)			0.00030	40	182	590		0.00066
Lower Pearlite 40% fine pearlite + 60% ferrite	293	1200	7,500	349	17	(e)	0.00040	8	20	67	120	0.00656

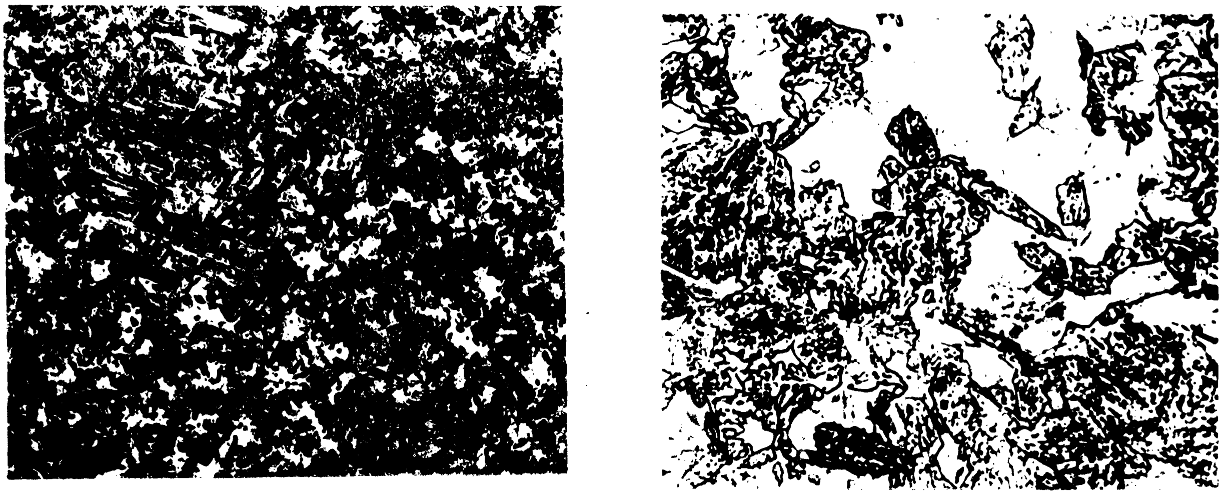
(a) Specimen reached this deformation on loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen, elongation % in 1-inch.
(d) Test discontinued at this time.
(e) Very badly scaled.
(f) Broke in shoulder.
(g) Broke on loading.
(h) Test in progress.

TABLE VI

Rupture, Total Deformation and Creep Data at 700°, 900°, 1100° and 1200°F for 3 Cr-Mo-W-V (H-40) Steel

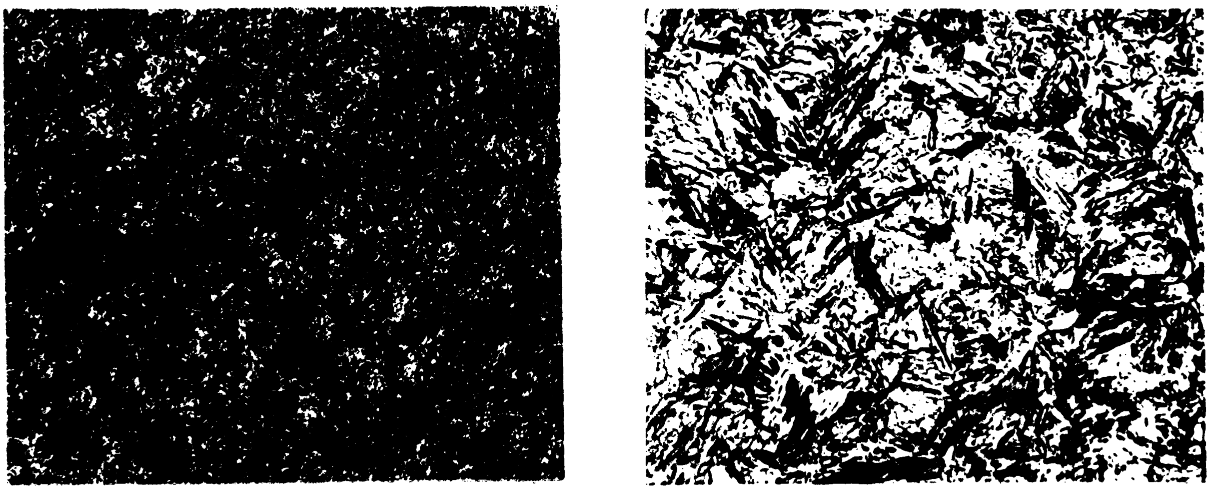
Aim Structure	BHN	Temperature (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2")	Reduction of Area (%)	Deformation on Loading (in./in.)	Time to Reach Specified Total Deformations 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hour)
Normalized 70% bainite + 30% martensite	--	700	90,000	1292(d)	--	--	0.00424	a	a	13	1770(b)	0.00011
Oil Quenched 98% martensite + 2% ferrite	290	700	90,000	1514(d)	--	--	0.00410	a	a	16	1900(b)	0.00016
Pearlite fine carbide precipitate	193	700	90,000	24	22.0(c)	61.0	--	--	--	--	--	--
Bainite 60% martensite + 40% bainite and acicular ferrite	293	700	90,000	1170(d)	--	--	0.00329	a	a	1040	>2000(b)	0.00005
Normalized 70% bainite + 30% martensite	--	900	65,000	1052	18.0(c)	36.0	0.00316	a	a	10	85	0.00418
Oil Quenched 98% martensite + 2% ferrite	290	900	65,000	917	31.0(c)	68.0	0.00360	a	a	1	50	0.00485
Pearlite fine carbide precipitate	198	900	65,000	3.3	22.0(c)	68.0	--	--	--	--	--	--
Bainite 60% martensite + 40% bainite and acicular ferrite	309	900	65,000	1193(d)	--	--	0.00330	a	a	20	296	0.00061
Normalized 70% bainite + 30% martensite	316	1100	31,000	720(e)	--	--	0.00146	a	7	274	677	0.00105
Oil Quenched 98% martensite + 2% ferrite	321	1100	30,000	865	20.0	26.0	0.00150	a	2	94	279	0.00237
Pearlite fine carbide precipitate	190	1100	30,000	23	49.0	82.0	--	--	--	--	--	--
Bainite 60% martensite + 40% bainite and acicular ferrite	313	1100	35,000	405	12.0(c)	33.0	0.00140	a	~0.2	13	110	0.00585
Normalized 70% bainite + 30% martensite	310	1100	40,000	193	5	13.6	--	--	--	--	--	--
Normalized 70% bainite + 30% martensite	--	1200	25,000	100	17	45	--	--	--	--	--	--
Oil Quenched 98% martensite + 2% ferrite	--	1200	25,000	62	45	74	--	--	--	--	--	--
Pearlite Fine carbide precipitate	200	1200	25,000	142	23	58	--	--	--	--	--	--
Bainite 60% martensite + 40% bainite and acicular ferrite	293	1200	25,000	86	27(c)	52	--	--	--	--	--	--

(a) Specimen reached this deformation on loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen, elongation % in 1-inch.
(d) Test discontinued at this time.
(e) Broke in threads.



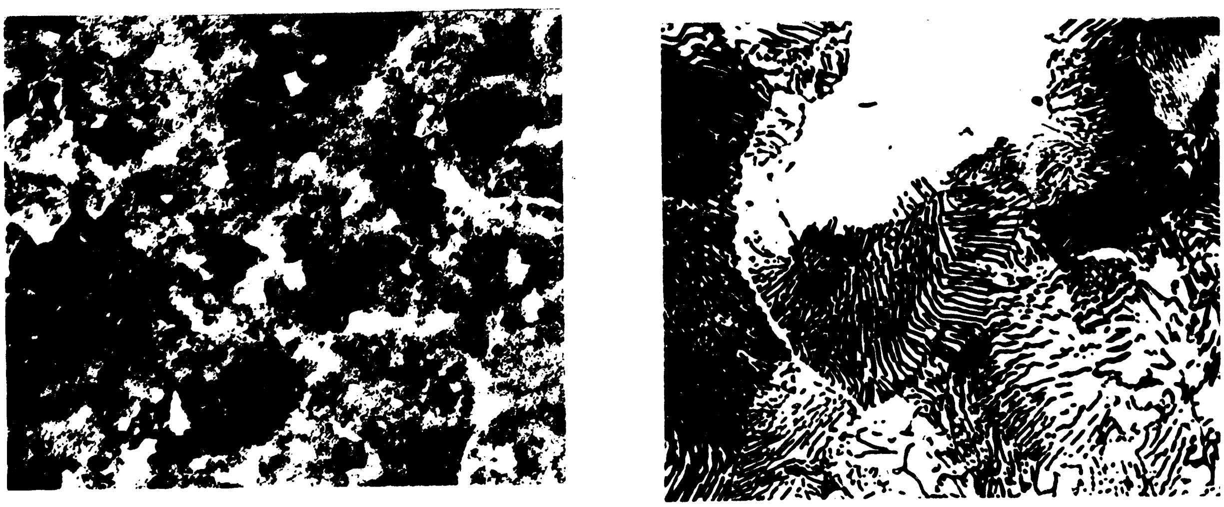
X100D X1000D

Figure 1. - Microstructure of Normalized 4340 Steel (Air Cooled after 1 hour at 1750°F).



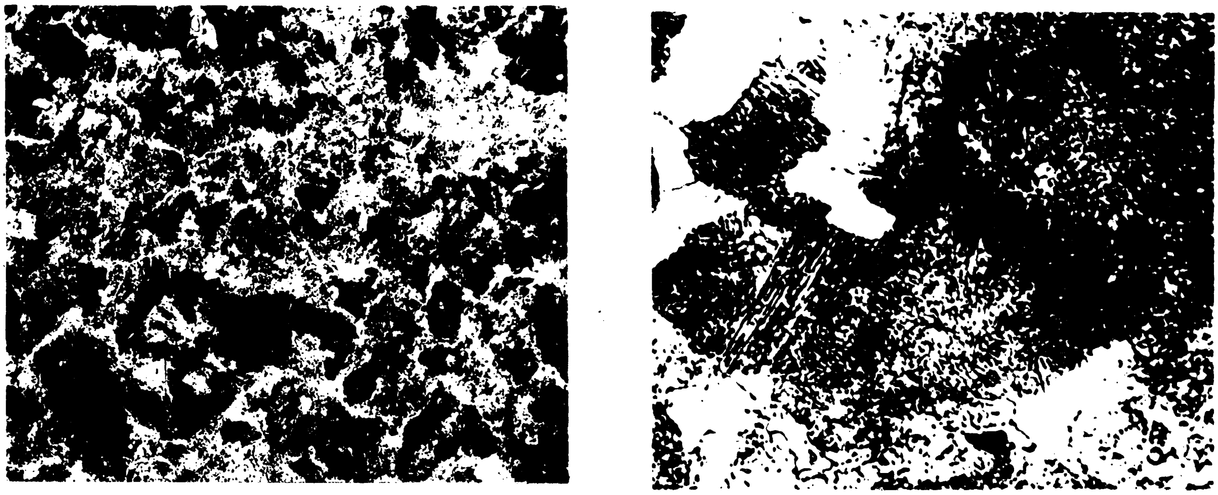
X100D X1000D

Figure 2. - Microstructure of Oil-Quenched 4340 Steel (Oil Quenched after 1 hour at 1750°F).



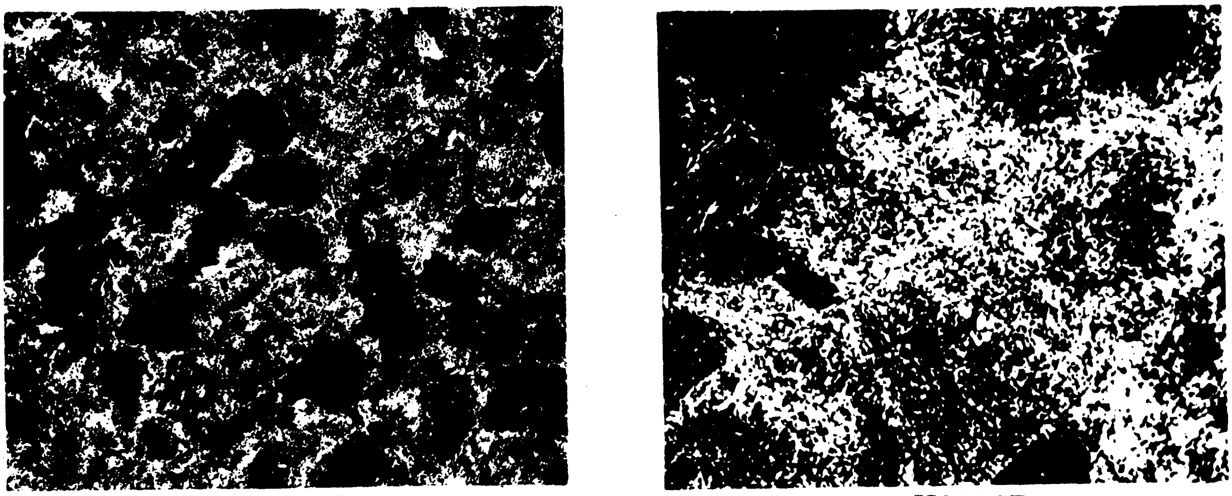
X100D X1000D

Figure 3. - Microstructure of "Upper Pearlite" Obtained in 4340 Steel by Isothermal Transformation at 1240°F for 10 hours after Austenitizing for 1 hour at 1750°F.



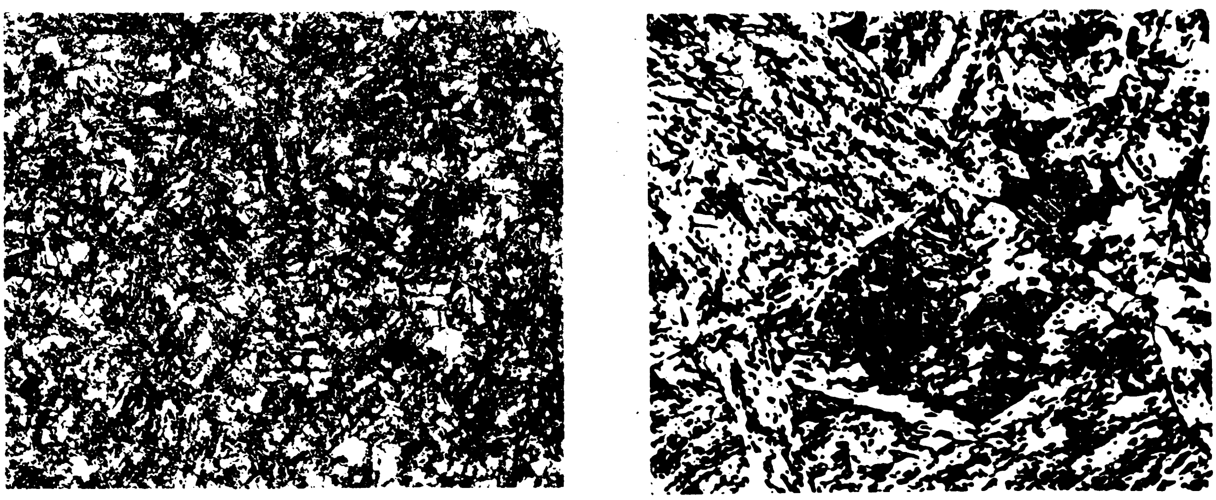
X100D X1000D

Figure 4. - Microstructure of "Middle Pearlite" Obtained in 4340 Steel by Isothermal Transformation at 1150°F for 14 hours after Austenitizing for 1 hour at 1750°F.



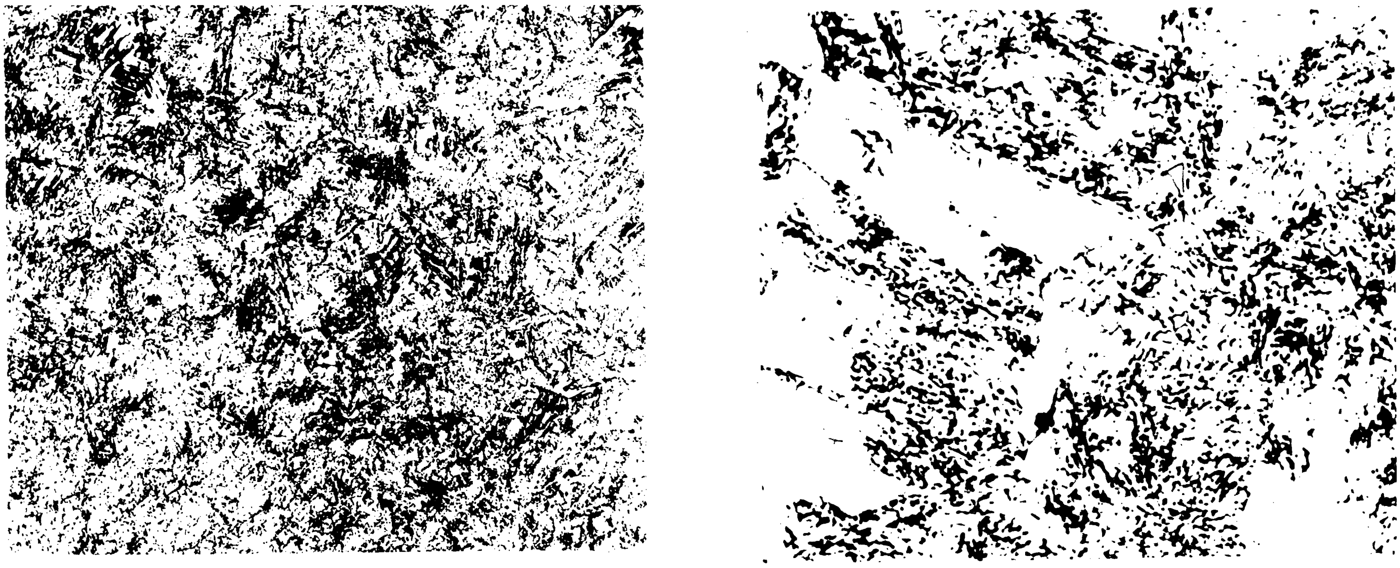
X100D X1000D

Figure 5. - Microstructure of "Lower Pearlite" Obtained in 4340 Steel by Isothermal Transformation at 1050°F for 111 hours after Austenitizing 1 hour at 1750°F. .



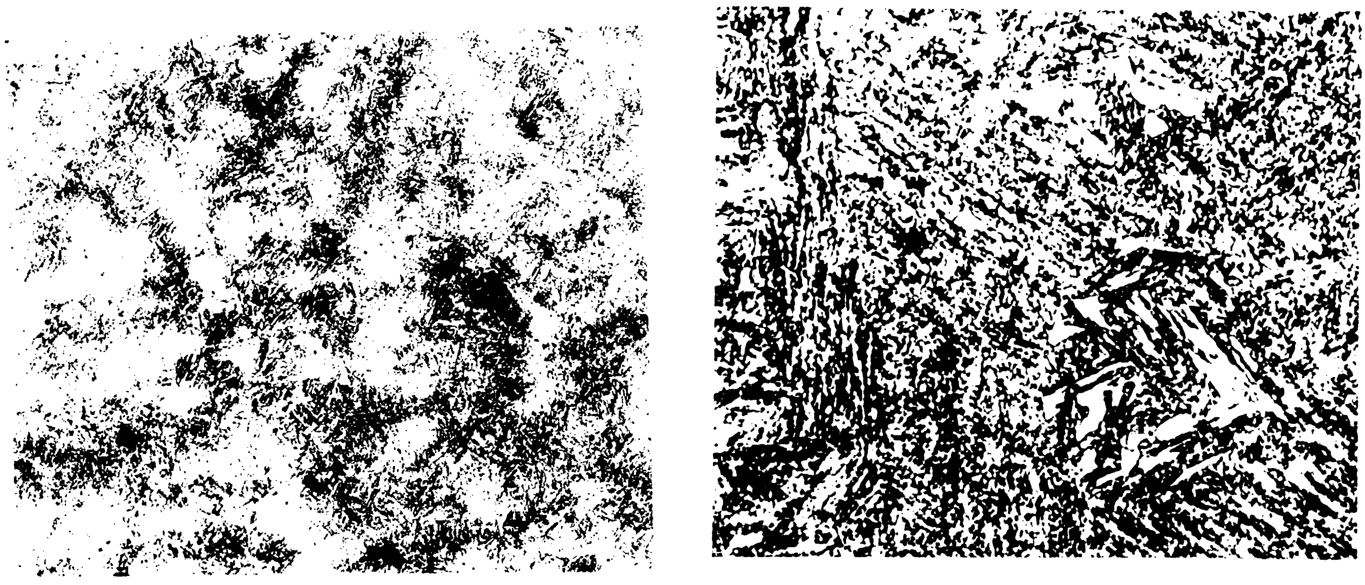
X100D X1000D

Figure 6. - Microstructure of "Upper Bainite" Obtained in 4340 Steel by Isothermal Transformation at 850°F for 28 hours after Austenitizing for 1 hour at 1750°F.



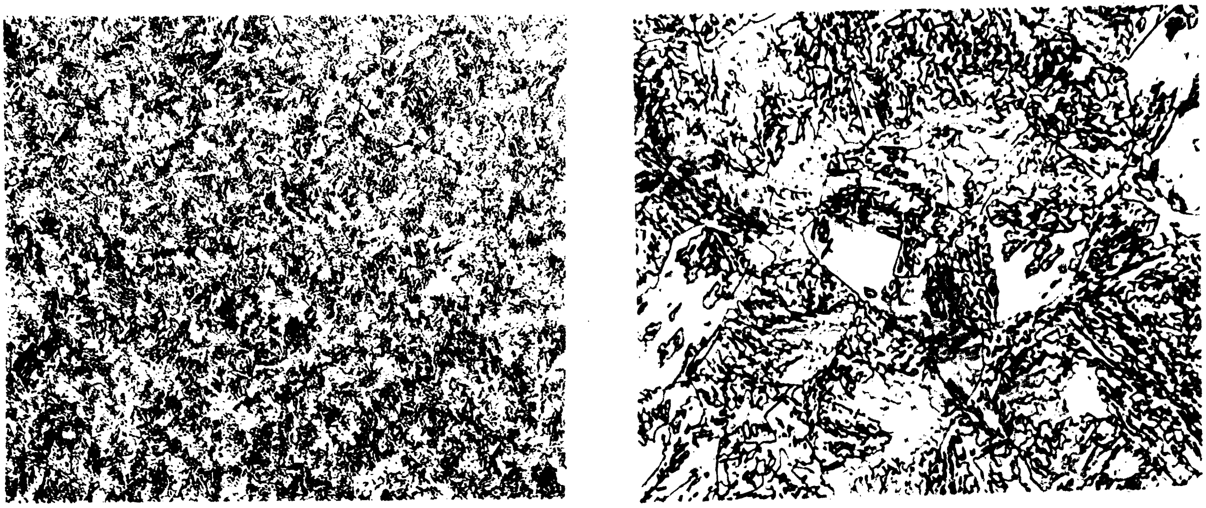
X100D X1000D

Figure 7. - Microstructure of "Middle Bainite" Obtained in 4340 Steel by Isothermal Transformation at 750°F for 24 hours after Austenitizing for 1 hour at 1750°F.



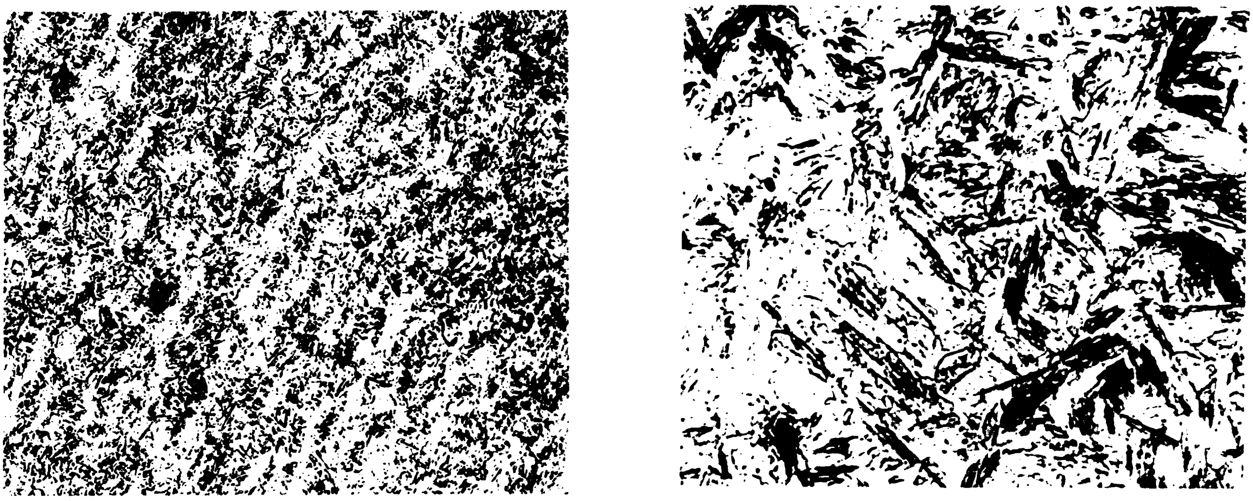
X100D X1000D

Figure 8. - Microstructure of "Lower Bainite" Obtained in 4340 Steel by Isothermal Transformation at 650°F for 1-1/2 hours after Austenitizing for 1 hour at 1750°F.



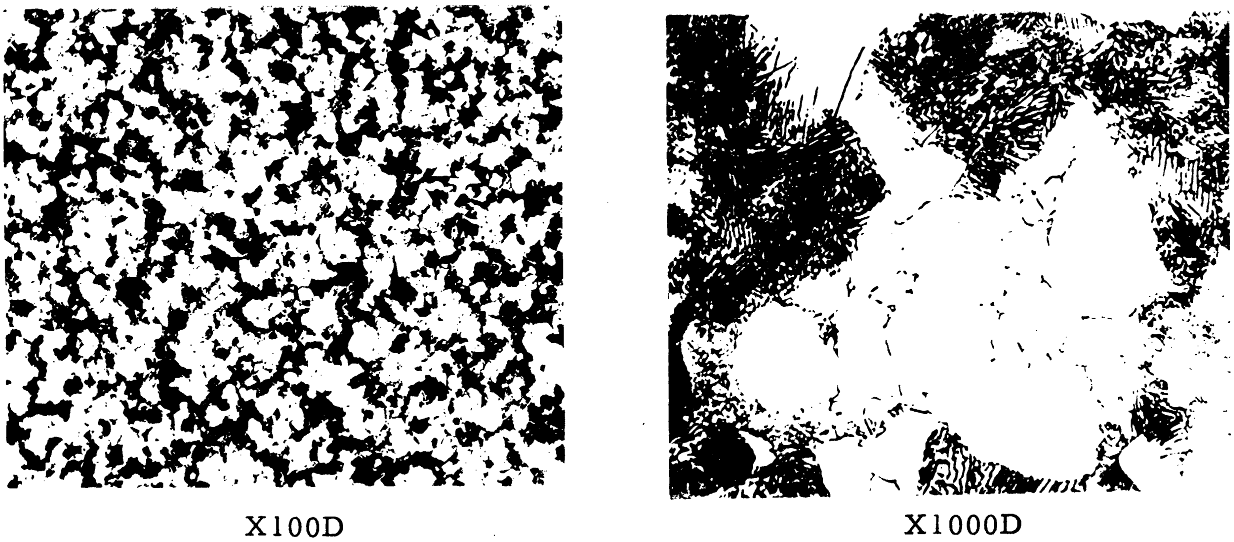
X100D X1000D

Figure 9. - Microstructure of Normalized "17-22A"S Steel (Austenitized at 1750°F for 1 hour and Air Cooled).



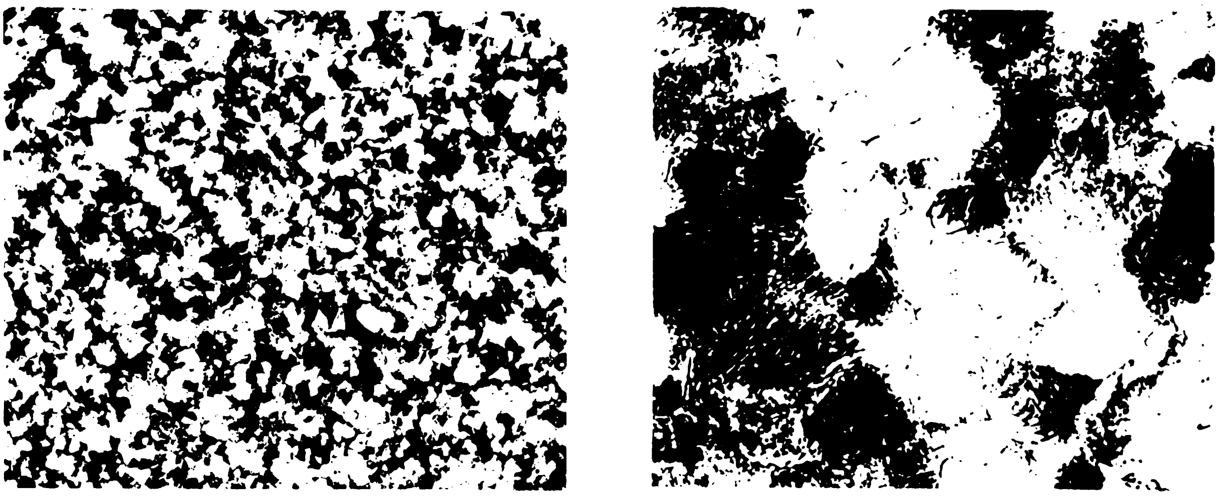
X100D X1000D

Figure 10. - Microstructure of Oil-Quenched "17-22A"S Steel (Oil Quenched after 1 hour at 1750°F).



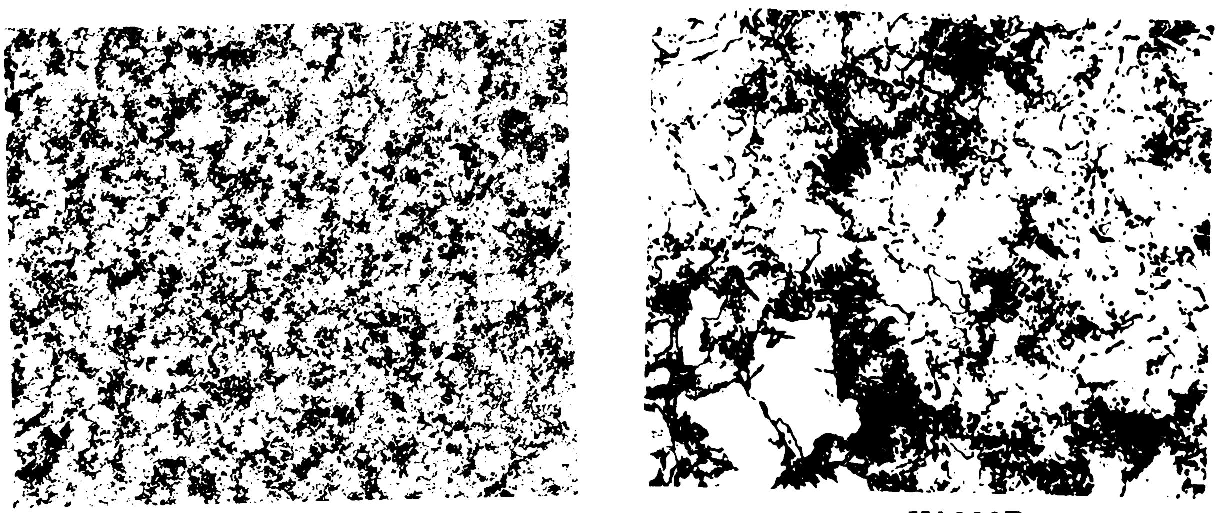
X100D X1000D

Figure 11. - Microstructure of "Upper Pearlite" Obtained in "17-22A"S Steel by Isothermal Transformation at 1300°F for 1-1/2 hours after Austenitization for 1 hour at 1750°F.



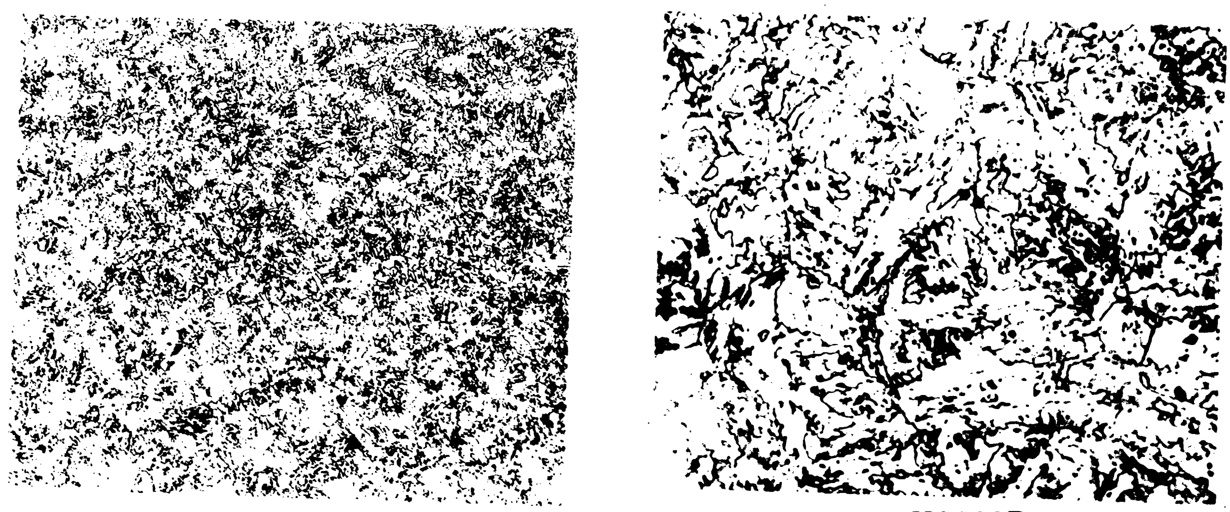
X100D X1000D

Figure 12. - Microstructure of "Middle Pearlite" Obtained in "17-22A"S Steel by Isothermal Transformation at 1225°F for 1-1/2 hours after Austenitization for 1 hour at 1750°F.



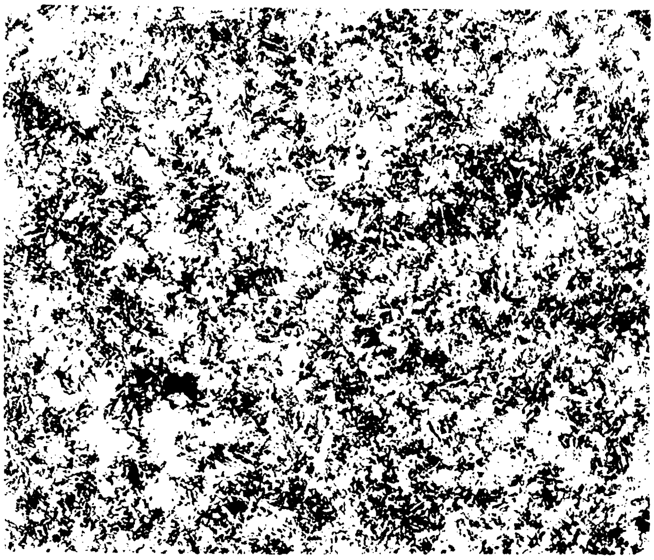
X100D X1000D

Figure 13. - Microstructure of "Lower Pearlite" Obtained in "17-22A"S Steel by Isothermal Transformation at 1150°F for 10 hours after Austenitization for 1 hour at 1750°F.

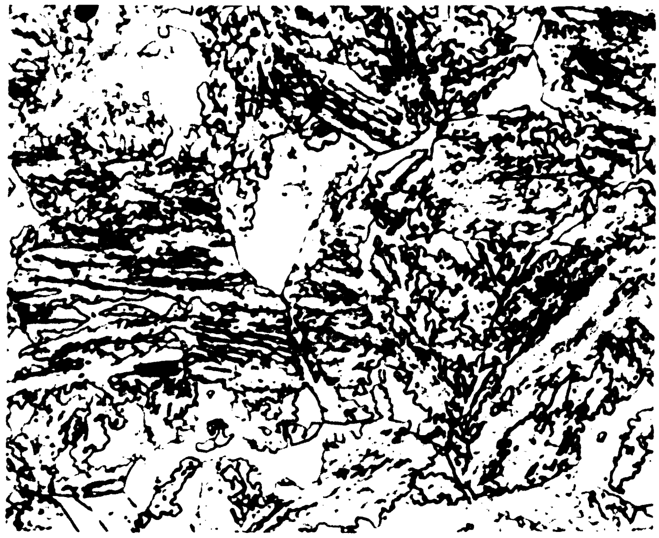


X100D X1000D

Figure 14. - Microstructure of "Upper Bainite" Obtained in "17-22A"S Steel by Isothermal Transformation at 900°F for 2 hours after Austenitization for 1 hour at 1750°F.

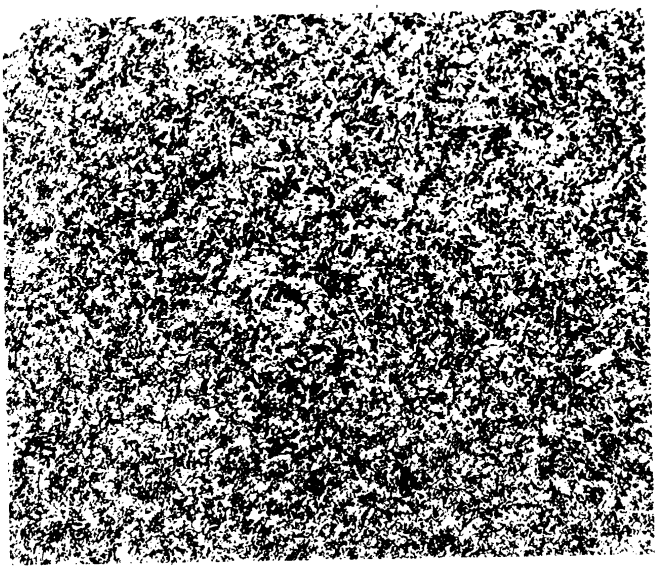


X100D

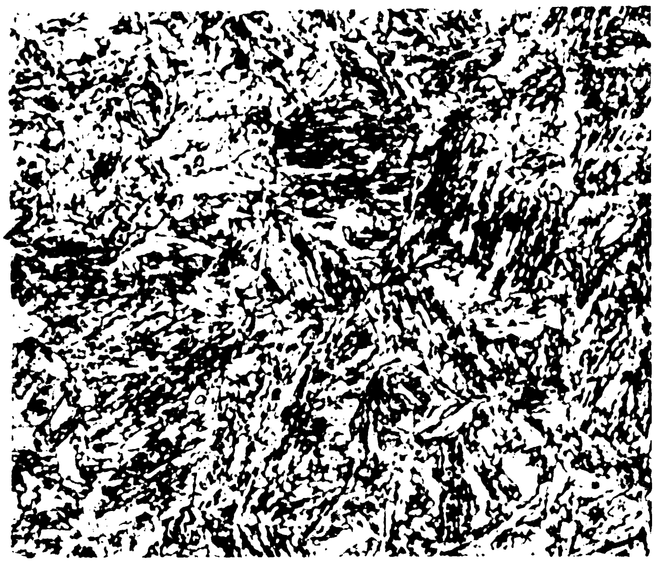


X1000D

Figure 15. - Microstructure of "Middle Bainite" Obtained in "17-22A"S Steel by Isothermal Transformation at 800°F for 1/2 hour after Austenitization for 1 hour at 1750°F.



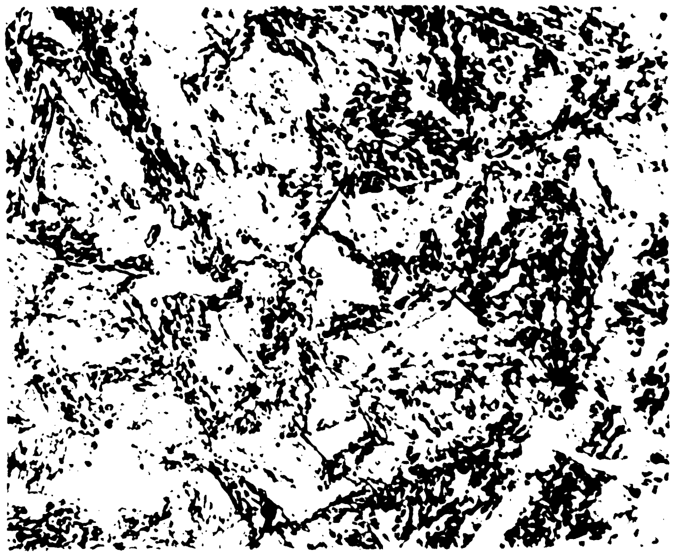
X100D



X1000D

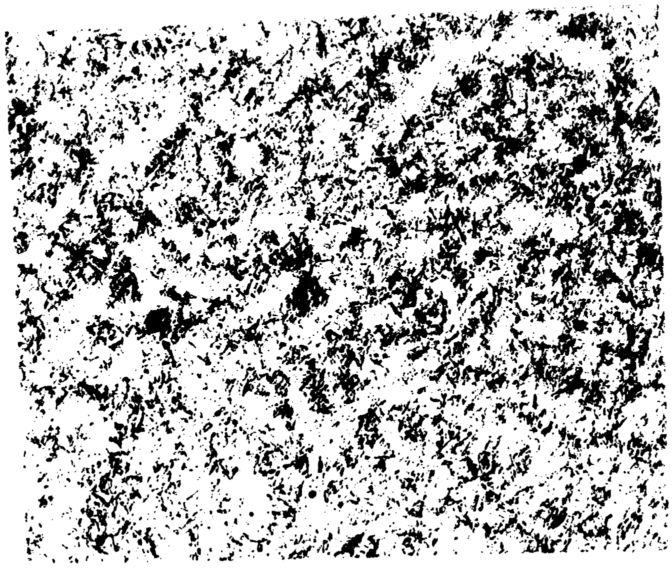
Figure 16. - Microstructure of "Lower Bainite" Obtained in "17-22A"S Steel by Isothermal Transformation at 700°F for 1/12 hour after Austenitization for 1 hour at 1750°F.

X100D



X1000D

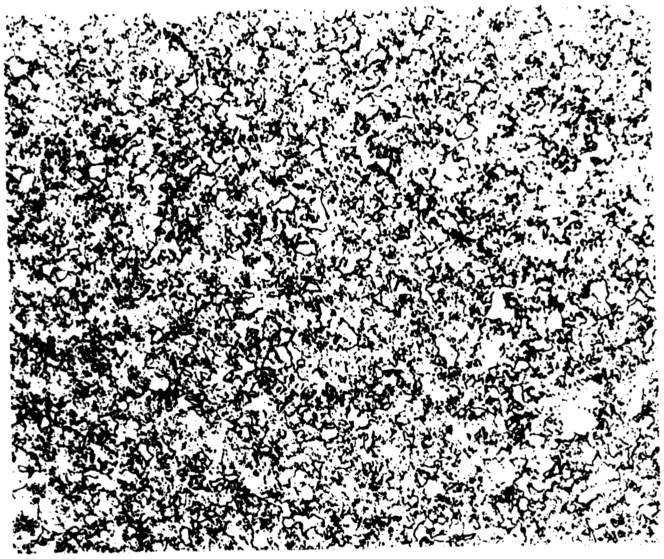
Figure 17. - Microstructure of Normalized H-40 Steel (Austenitized 1 hour at 1950°F and Air Cooled).



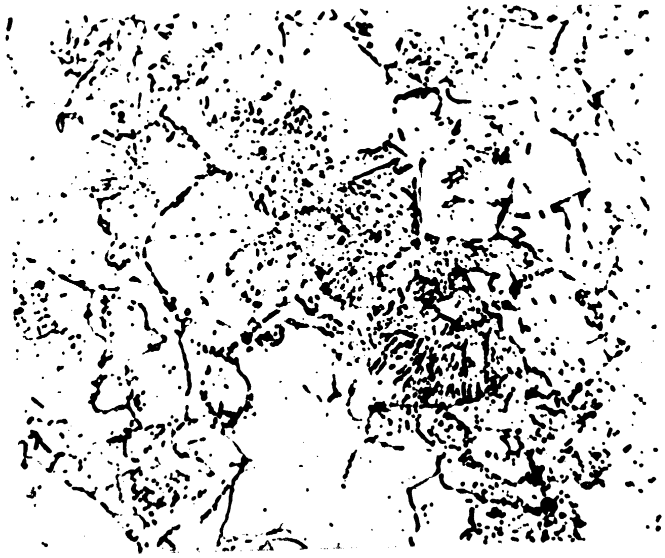
X100D

X1000D

Figure 18. - Microstructure of Oil-Quenched H-40 Steel (Austenitized 1 hour at 1950°F and Oil Quenched).

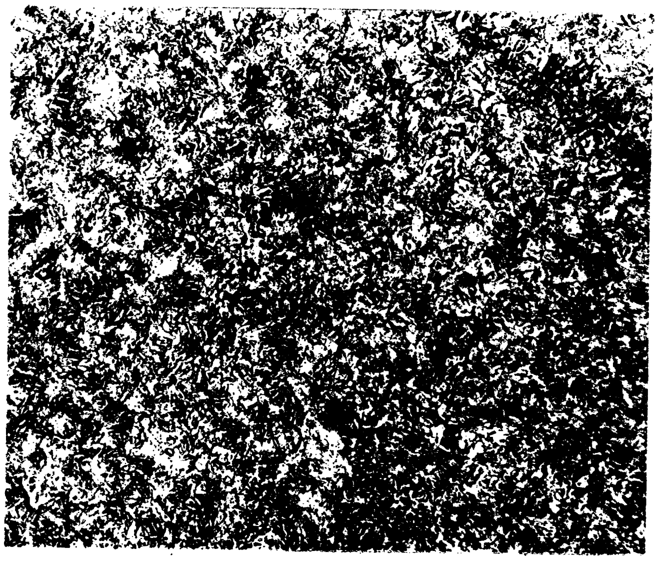


X100D

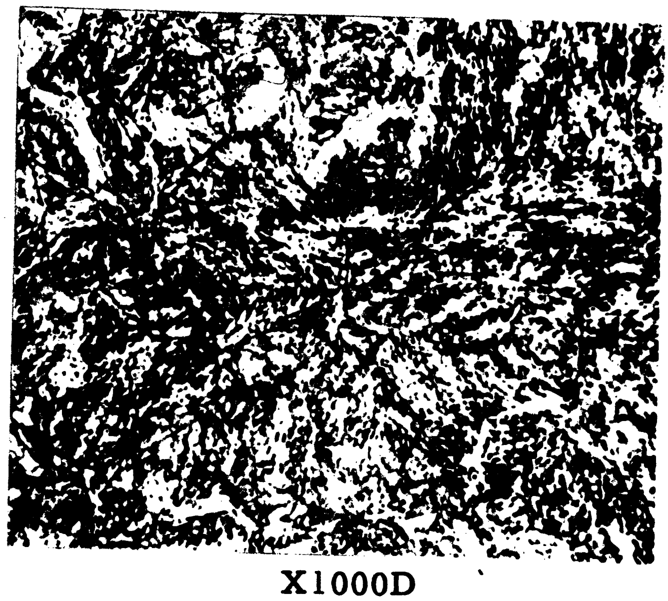


X1000D

Figure 19. - Microstructure of "Pearlite" Obtained in H-40 Steel by Isothermal Transformation at 1300°F for 24 hours after Austenitization for 1 hour at 1950°F.



X100D



X1000D

Figure 20. - Microstructure of "Bainite" Obtained in H-40 Steel by Isothermal Transformation at 750°F for 10 hours after Austenitization for 1 hour at 1950°F.

TABLE I

Type Structures, Heat Treatments and Actual Structures for 4340 Steel

(All 4340 bar stock austenitized at 1750°F for 1 hour.)

Aim Structure	Transformation Conditions		Approximate Structure Obtained	B H N	Tempering		B H N
	Temp-°F	Time-hrs			Temp-°F	Time-hrs	
Upper Pearlite	1240	10	80% medium pearlite + 20% ferrite	212/221	None	--	212/221
Middle Pearlite	1150	14	95% fine pearlite and fine carbide-ferrite aggregate + 5% ferrite	197/223	None	--	197/233
Lower Pearlite	1050	111	99% very fine carbide-ferrite aggregate + 1% ferrite	255/275	None	--	255/275
Upper Bainite	850	28	70% upper bainite + 30% martensite	319/327	None	--	319/327
Middle Bainite	750	24	100% medium acicular bainite	293/313	None	--	293/313
Lower Bainite	650	1-1/2	100% lower bainite	430	1100	1-1/4	277/301
Normalized	Air cooled from 1750		35% martensite + 65% bainites	385	1100	1	300/311
Oil Quenched	Oil Quenched from 1750		100% martensite	585	1100	10	304/309

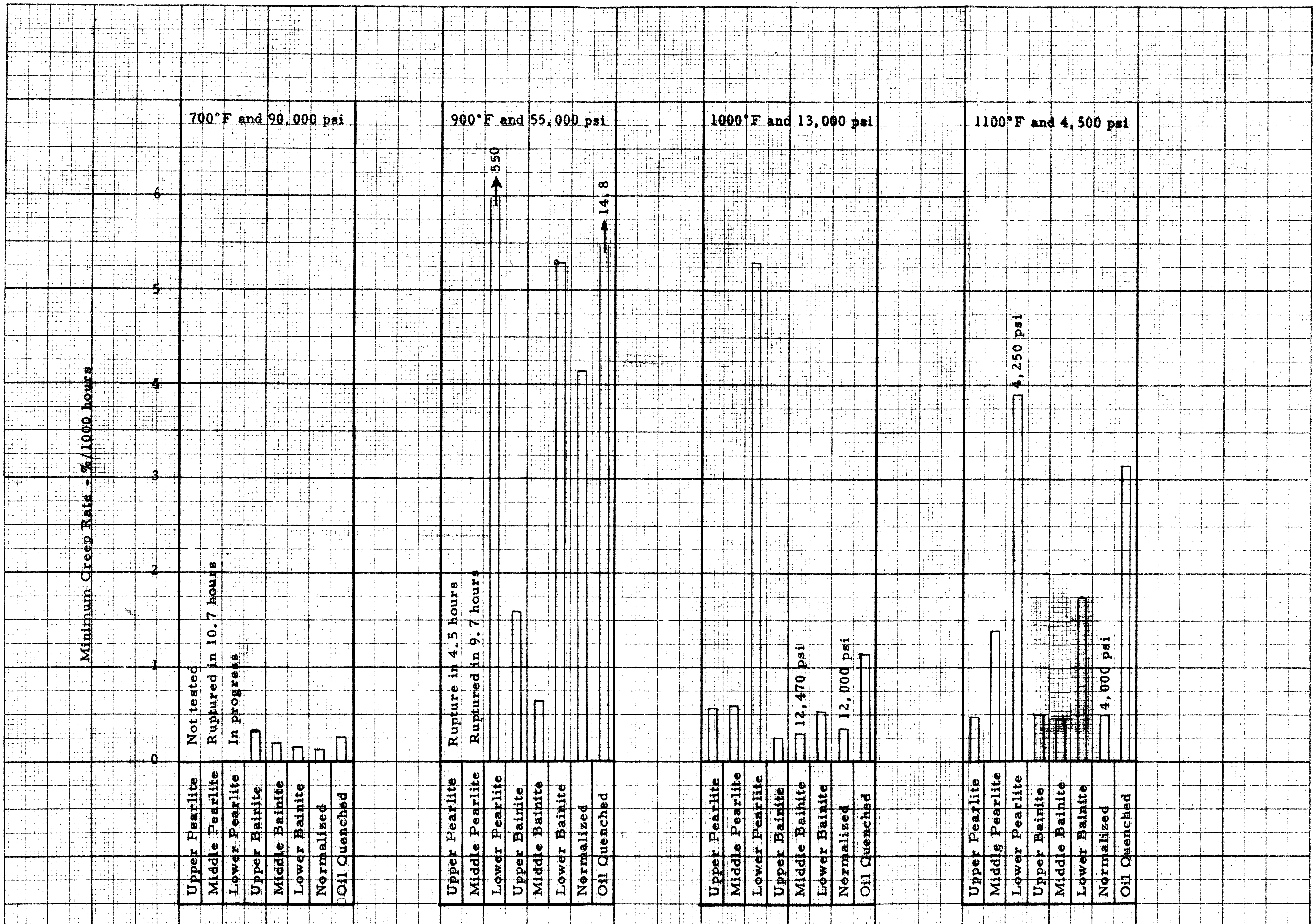


Figure 21. - Comparison of Minimum Creep Rate at 700°, 900°, 1000° and 1100°F and Indicated Stresses for the Structures Obtained in 4340 Steel.

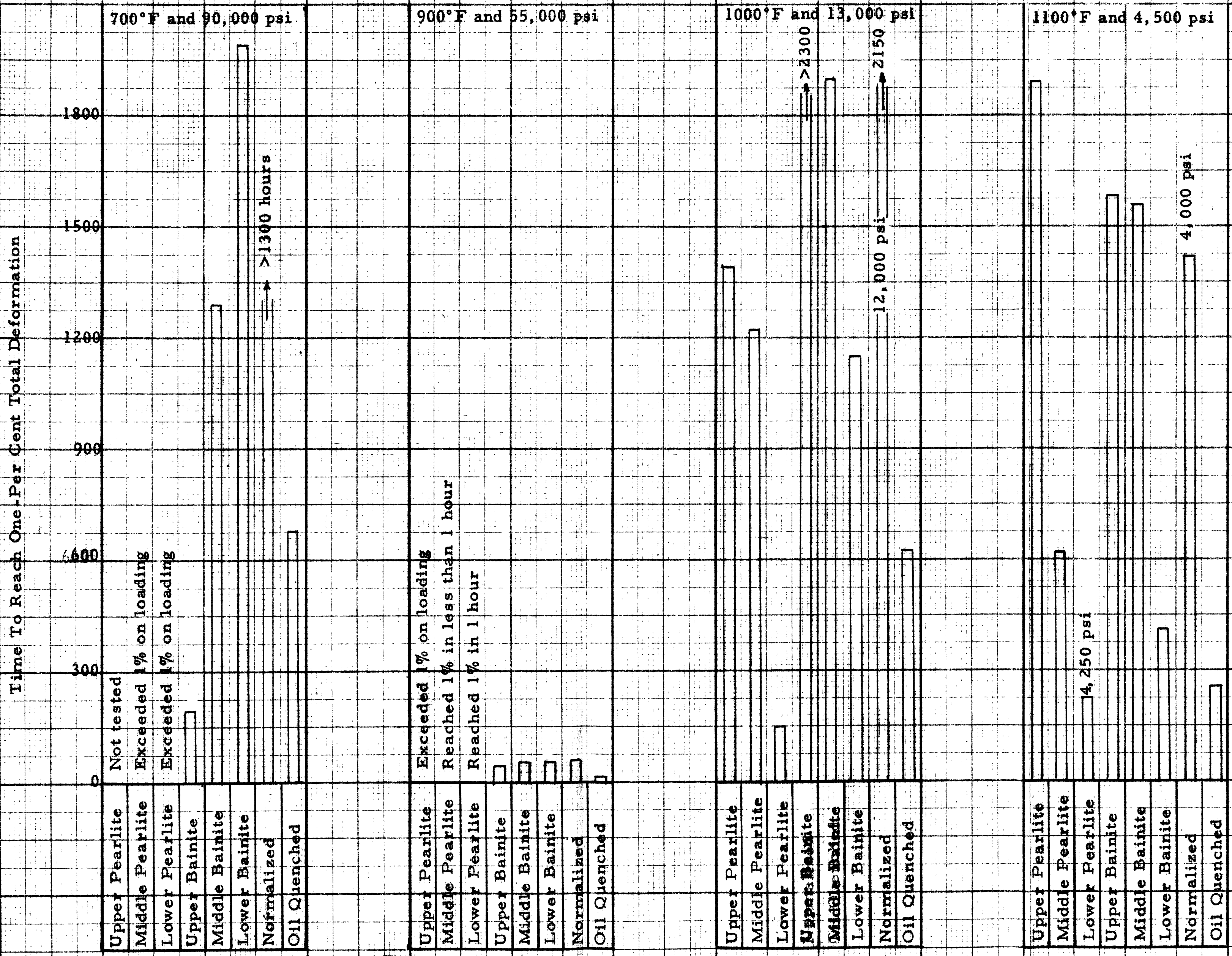


Figure 22. - Comparison of Time to Reach One-Per Cent Total Deformation at 700°, 900°, 1000° and 1100°F and Indicated Stresses for the Structure Obtained in 4340 Steel.

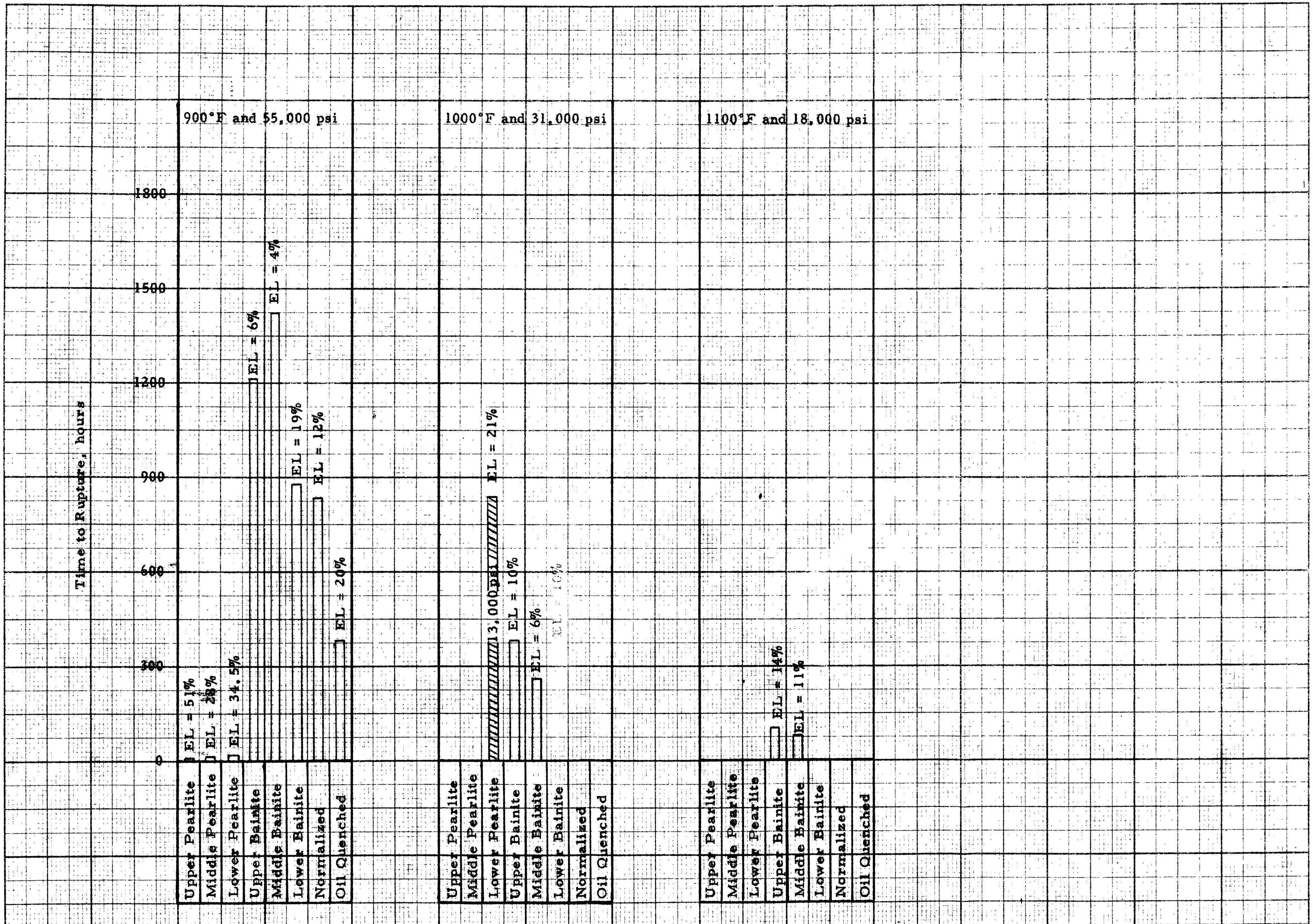


Figure 23. - Comparison of Time to Rupture at 900°, 1000° and 1100°F and Indicated Stresses for the Structures Obtained in 4340 Steel.

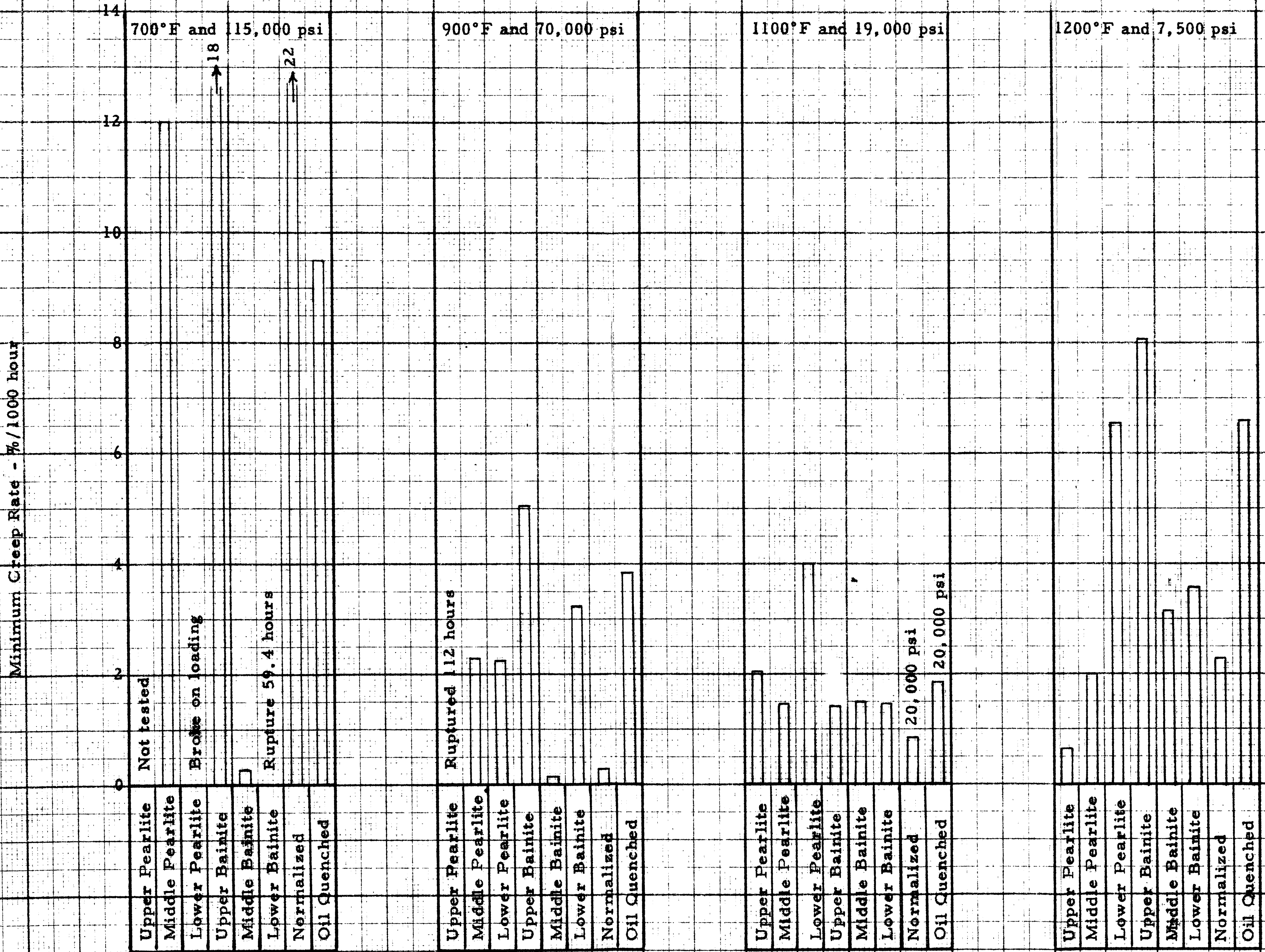


Figure 24. - Comparison of Minimum Creep Rate at 700°, 900°, 1100° and 1200°F and Indicated Stresses for the Structures Obtained in "17-22A"S Steel.

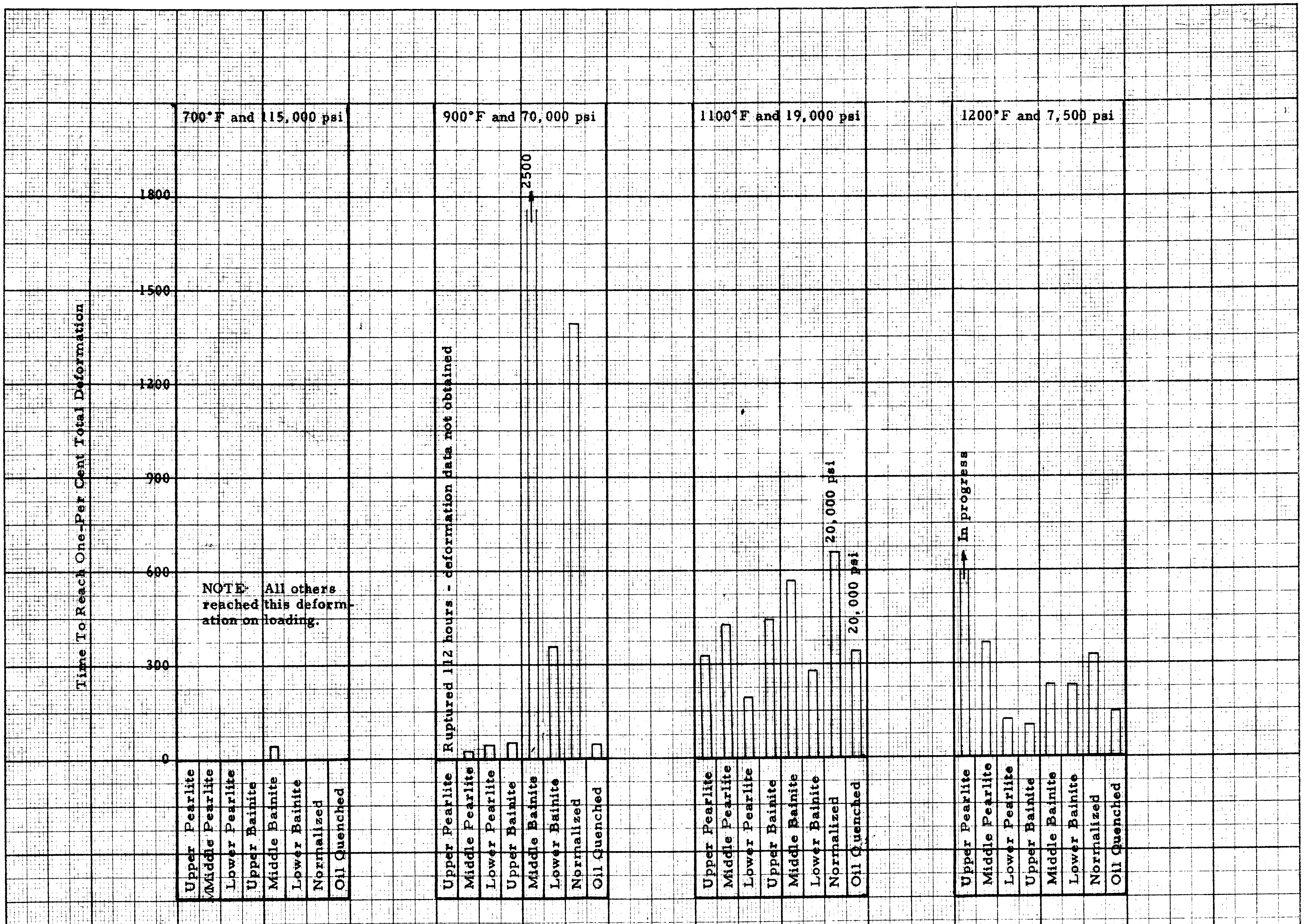


Figure 25. - Comparison of Time to Reach One-Per Cent Total Deformation at 700°, 900°, 1100° and 1200°F and Indicated Stresses for the Structures Obtained in "17-22A"S Steel.

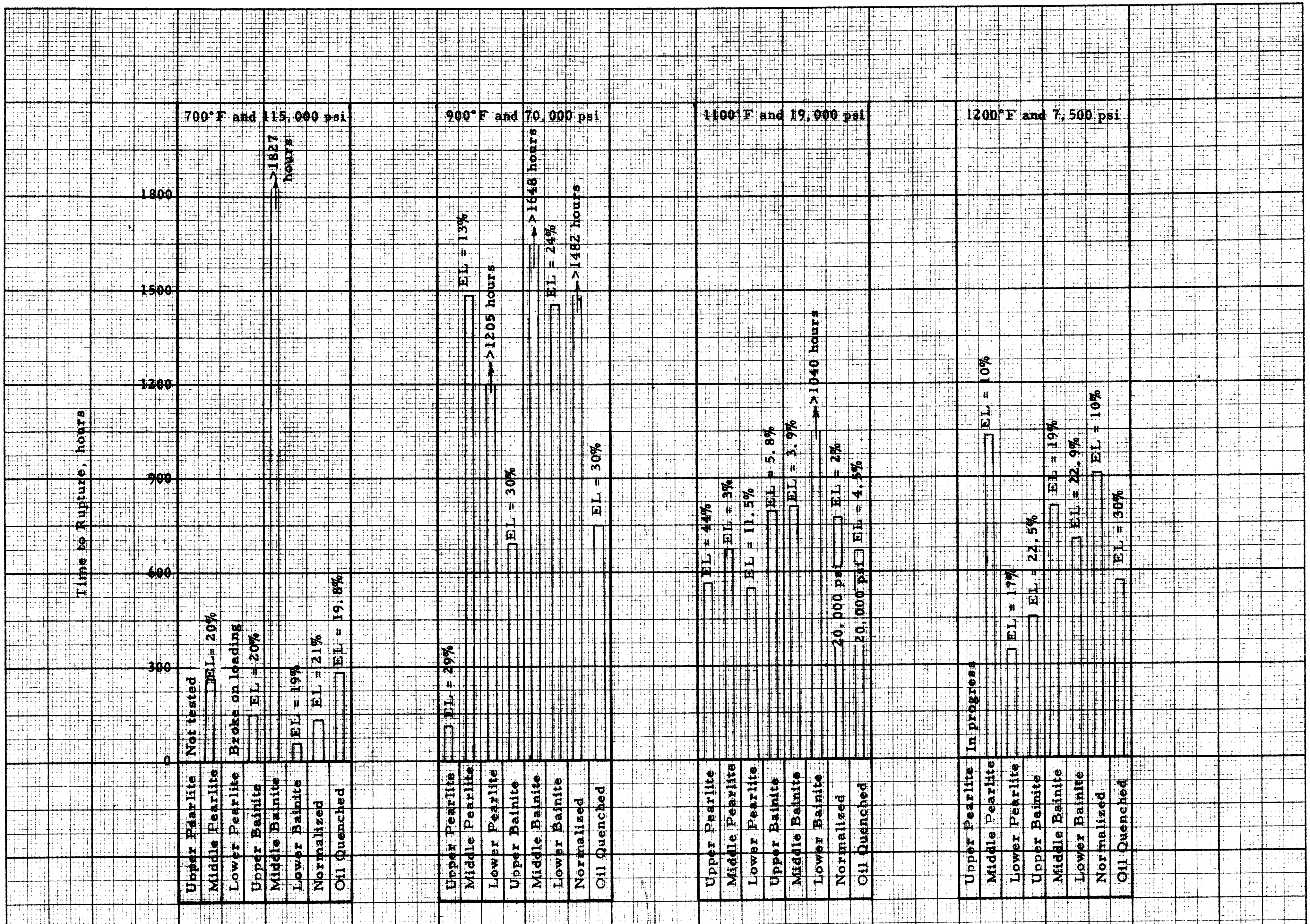


Figure 24 - Comparison of Time to Rupture at 700°, 900°, 1100° and 1200°F and Indicated Stresses for the Structures Obtained in "17-22A"S Steel.

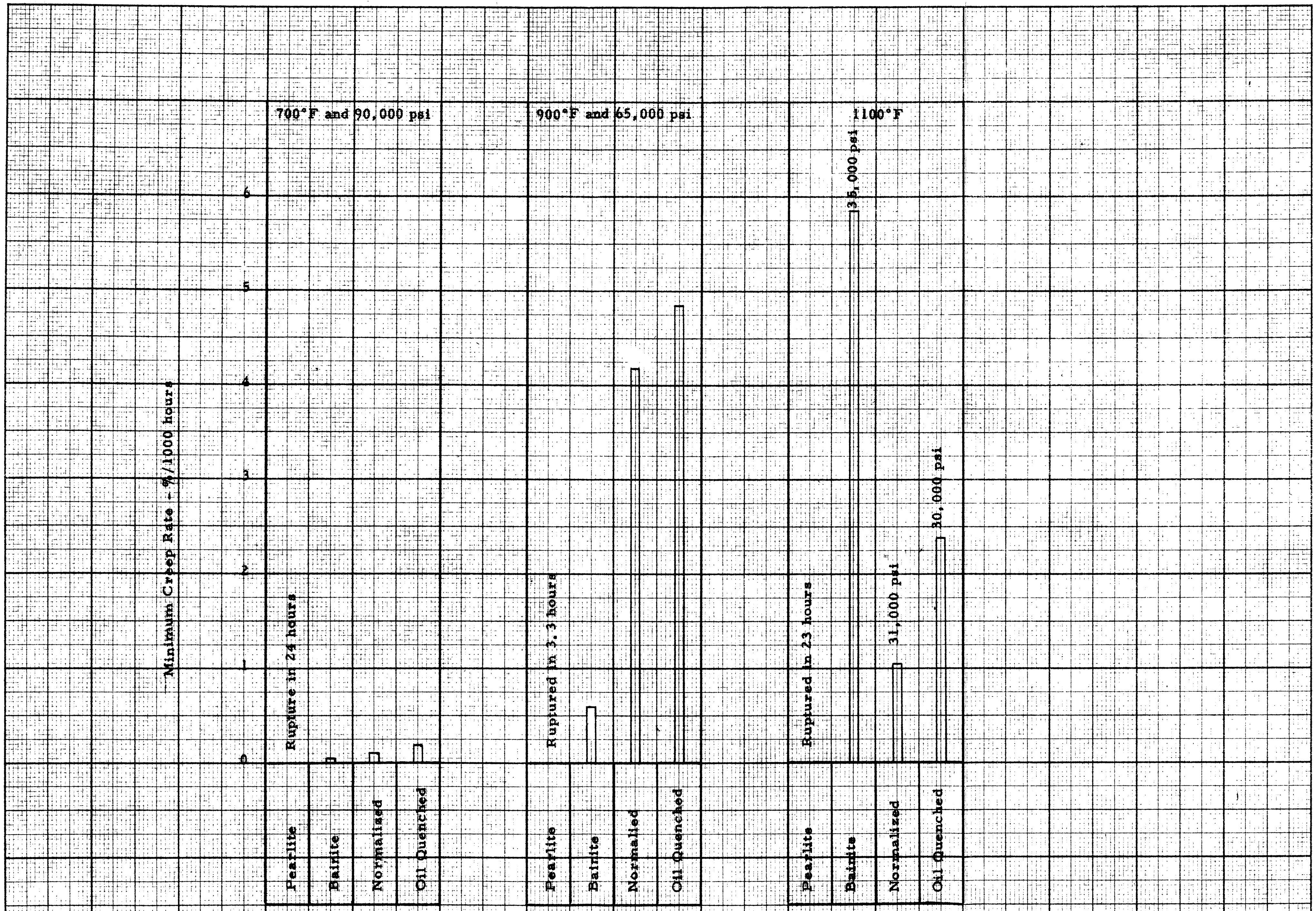


Figure 27. - Comparison of Minimum Creep Rate at 700°, 900° and 1100°F for the Structures Obtained in H-40 Steel.

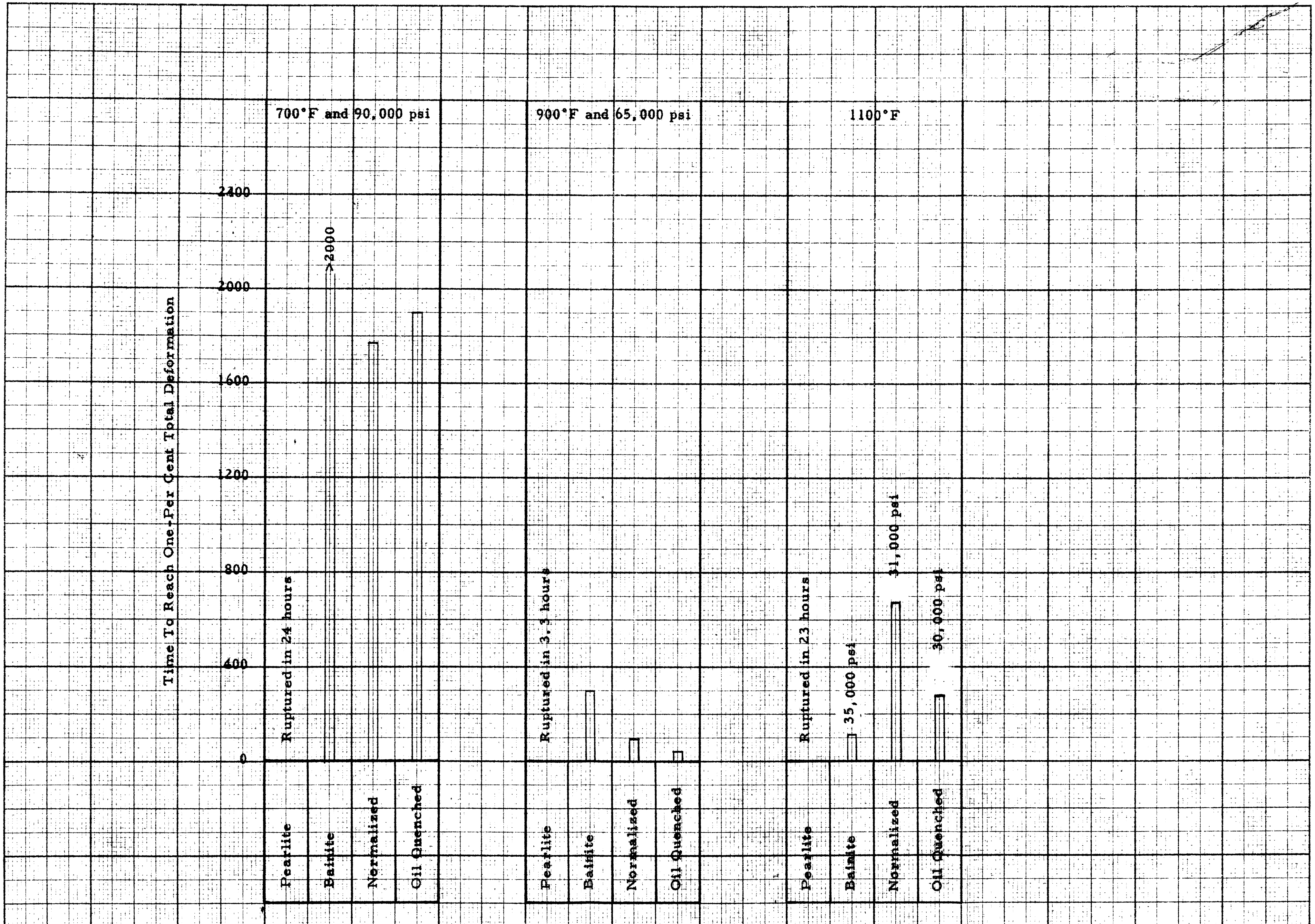


Figure 23. - Comparison of Time to Reach One-Per Cent Total Deformation at 700°, 900° and 1100°F and Indicated Stresses for the Structures Obtained in H-40 Steel.

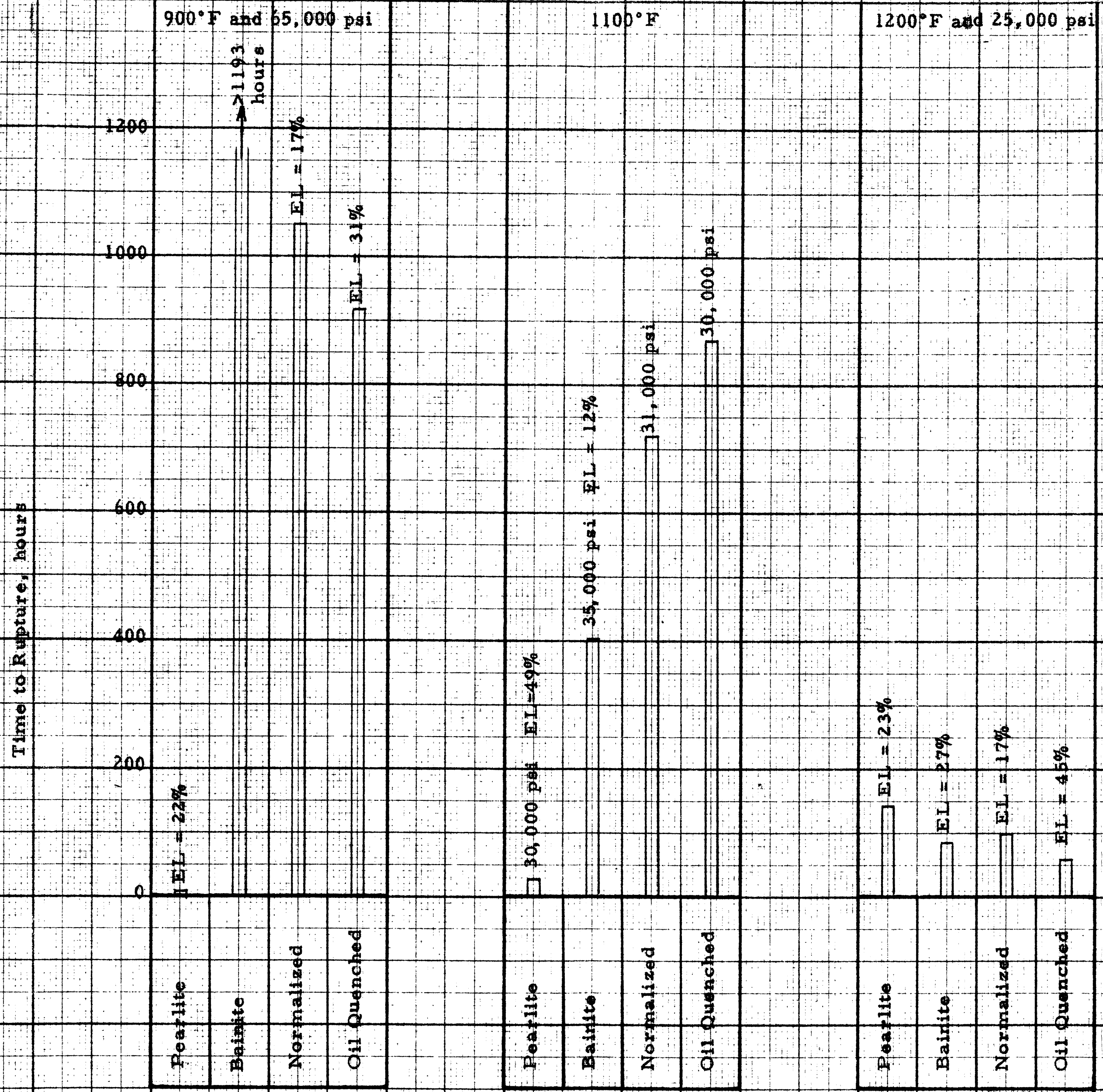


Figure 29. - Comparison of Time to Rupture at 900°, 1100° and 1200°F and Indicated Stresses for the Structures Obtained in H-40 Steel.