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RESEARCH MEMORANDUM

ENGINE PERFORMANCE OF OVERTEMPERATURE HEAT-TREATED S-816 BUCKETS

By R. A. Signorelli, F. B. Garrett, and J. W. Weeton

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Cleveland, Ohio

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ENGINE PERFORMANCE OF OVERTEMPERATURE HEAT-TREATED S-816 BUCKETS

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SUMMARY

An investigation was conducted to study the effect of short-time overtemperature heat treatments at temperatures between 1550° and 2350° F on the turbojet engine performance of S-816 buckets. Overtemperature heat-treated and standard Air Force stock buckets were run in a J33-9 turbojet engine for cycles comprising 15 minutes at rated speed and 5 minutes at idle speed. The results indicated that none of the overtemperature heat treatments adversely affected bucket life. Differences in the as-overtemperatured microstructures and in bucket creep rate suggested that stress-rupture strength was changed by the overtemperature heat treatment. Bucket life was not reduced, because factors other than stress rupture influenced failure.

INTRODUCTION

Turbojet engines are frequently overtemperatured, or overheated during service operation. Overtemperaturing may occur under either of two basically different conditions: during starting (hot starts) or during flight. Bucket stresses are low during hot starts because engine speed is low. Any metallurgical change occurring in a bucket under hot-start conditions could therefore be largely attributed to temperature effects. However, during overtemperature in flight, stresses are high because of high engine speed; creep and strain-aging also affect the buckets.

Severe overtemperature conditions during service operation of aircraft cause warpage, cracking, and even melting of buckets. In most cases, bucket exposure to overtemperature is not revealed by inspection of buckets during overhauls, and usually is not recorded by pilots. Cracked or warped nozzle vanes sometimes indicate overtemperature operation of the engine. Where overtemperature is suspected to have occurred, it has been the practice to study the microstructure of representative buckets. Metallographic studies have been conducted by the U. S. Air Force and by bucket manufacturers for some time. Spheroidization and solution of carbides, particularly grain-boundary carbides, are the chief microstructural evidences of overtemperature.

[redacted]

The detection of turbine buckets in danger of imminent failure has been a basic problem. The effects of overtemperature operation make the problem more acute, because a few minutes at overtemperature may drastically reduce bucket life. There are, however, no quantitative data on the effect of overtemperature operation on bucket life.

This investigation is one of several being conducted at the Lewis laboratory to obtain a better understanding of the overtemperature problem. It was conducted to determine the effects of short-time overtemperature heat treatments upon engine performance of S-816 buckets. 3937

Buckets taken at random from standard Air Force stock were given a 15-minute overtemperature heat treatment at various temperatures between 1550° and 2350° F. This temperature range extends from a low over-aging temperature to a eutectic melting temperature. All buckets used were new, and the effects of the treatments are considered the result of temperature alone.

The buckets were run in a J33-9 turbojet engine operated over cycles of 15 minutes at rated speed and 5 minutes at idle speed with a bucket temperature of 1500° F.

MATERIALS

Standard Air Force stock J33-9 buckets of forged S-816 (AMS 5765A) were used. The nominal chemical composition of S-816 is as follows:

Element	C	Co	Cr	Ni	Mo	W	Cb	Fe	Mn
Weight, percent	0.4	43.7 (bal)	20	20	4	4	4	2.8	1.0

The Air Force stock buckets included as a standard for comparison were installed in the engine as they came from stock; others were first given the overtemperature heat treatment.

PROCEDURE

Heat Treatment

All buckets used had been given the following heat treatment during manufacture: solution treatment, 1 hour at 2150° F, followed by a water quench; aging treatment, 16 hours at 1400° F, followed by air cooling. (See AMS 5765A.) The overtemperature heat treatments were performed at the Lewis laboratory. Seven groups of six buckets each, were heat-treated for 15 minutes in an argon atmosphere at a temperature of 1550°, 1700°, 1800°, 1900°, 2000°, 2150°, or 2350° F, and air-cooled.

This temperature range extends from 50° above the normal operating temperature of the bucket to a temperature at which incipient eutectic melting is possible for alloy S-816. Overtemperatured buckets were inspected for surface defects using post-emulsifying Zyglo and were found to be sound.

Engine Operation

The seven groups of overtemperatured buckets and a group of standard buckets were run in a J33-9 turbojet engine. The operating cycles consisted of 15 minutes at rated speed (11,750 rpm) and 5 minutes at idle speed. Bucket stress and temperature were controlled by engine speed and exhaust-nozzle opening, respectively, bucket temperature was measured with thermocouples installed in two buckets connected to a recording device through a slip-ring system. Details of bucket stress, bucket temperature, and engine operation are given in references 1 to 3.

The test was continued until there were enough bucket failures to establish the behavior pattern of each group. It was necessary to heat-treat and test additional buckets in two of the groups because failure by damage reduced the effective size of the original group. In the discussion of bucket life herein, only time at rated speed is considered.

Bucket Elongation Measurement

Two buckets of each group except the group heat-treated at 2350° F (group 7) were scribed near the trailing edge as shown in figure 1 and described in reference 4. Bucket elongation measurements were made at frequent intervals (after bucket failures or necessary shutdowns) using an optical extensometer.

Macroexamination of Failed Buckets

A bucket was considered to be failed and was removed from the engine test when complete fracture occurred or when cracks or severe necking made it apparent that complete fracture was imminent. Failed buckets were examined visually at low magnifications to determine, as nearly as possible, the manner in which failure occurred. The failures were classified (as in ref. 5) into the following categories:

(1) Stress rupture: Bucket failures occurred by cracking within the airfoil or by fracturing in an irregular, jagged, intercrystalline path. In addition to the main fracture, other similarly formed cracks sometimes occurred near the origin of the main fracture.

(2) Fatigue: Cracks progressed from nucleation points, usually at or near the leading or trailing edges, in straight paths, which frequently were smooth, often showed progression lines or concentric rings and appeared to be transcrystalline.

(3) Stress rupture plus fatigue: Bucket failures appeared to be caused by a combination of the two preceding mechanisms. The fracture surface of buckets in this group consisted of a small area having stress-rupture characteristics and a larger area having fatigue characteristics. 4027
A further criterion was that other cracks, which appeared to be stress-rupture cracks, were present in the area adjacent to the main crack or fracture edge.

(4) Damage: Buckets with severe nicks and dents in the airfoil that obviously initiated failure were not considered in the analysis of the failure types.

In all cases where complete fracture occurred buckets failed in tension because of the progressive reduction in load-carrying area, so that all showed a large area of rough fractured surface.

Metallurgical Studies

Microstructural, grain-size, and hardness studies were made of airfoil specimens cut from unrun buckets given the overtemperature heat treatment.

RESULTS

Engine Operating Results

<u>Engine results</u>. - The engine results are presented in figure 2 and table I. Buckets overtemperatured in the range of 1550° to 2150° F (groups 1 to 6) ran about as long as the standard S-816 group. Buckets overtemperatured at 2350° F (group 7) ran longer than the standard group. Mean life of the standard buckets, group 8, was 188 hours. Mean life of overtemperatured groups 1 to 6 ranged from 175 to 212 hours. Mean life of overtemperatured group 7 buckets was at least 336 hours; one bucket did not fail in 527 hours. The failures, excluding failure by damage, were classified by visual examination as follows: stress rupture, 9 percent; stress rupture plus fatigue, 56 percent; and fatigue, 35 percent.

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Elongation. - Elongation measurements for groups 1 to 6 and the standard group are shown in figure 3. Measurements were taken on two buckets of each group; data from the bucket with the greater elongation of each group was plotted. Only the values for zone 2 are plotted because this zone showed the greatest elongation. The final values measured ranged from 8 to 11 percent, a rather narrow spread of values. The narrow spread is in part due to the fact that the final measurements take no account of the total ultimate elongations just prior to fracture. The rates of elongation may be used to determine the relative stress-rupture damage resulting from the overtemperature treatments. The rate of elongation (creep) increased with increasing temperature for the temperatures ranging from 1550° to 2000° F (groups 1 to 5). The blades overtemperatured at 2150° F (group 6) had a creep rate slightly lower than that of the 1550° F group. All overtemperature heat-treated groups shown had elongation rates appreciably higher than that of the standard group.

Metallurgical Studies of Buckets

Microstructure. - Photomicrographs of standard and as-overtemperatured S-816 structures are shown in figures 4 to 13. These figures show the microstructures produced from the slight over-age at 1550° F to complete solution of grain-boundary precipitates at 2150° and at 2350° F. There is indication of slight spheroidization of grain-boundary precipitates with the 1550° F treatment. Agglomeration and spheroidization of the precipitates increased with increasing temperature from 1700° to 1900° F. At 2000° F, the precipitates began to dissolve. The 2150° and 2350° F treatments dissolved all precipitates except the massive, stable (Cb, Ta)C. There was evidence of eutectic melting in the specimens heat-treated at 2350° F, although it is not shown in the photomicrographs. The over-etched structures shown in figures 11 and 13 reveal the grain boundaries and grain size of the solution-treated structures that were not visible when the same specimens were etched normally (figs. 10 and 12).

Hardness and grain size. - The hardness and grain-size results are shown in table II. The overtemperature heat treatments from 1550° to 2000° F produced visible changes in the microstructure, but did not change hardness or grain size. Hardness was about Rockwell C-23 to C-25, and average ASTM grain size was 6 to 7. The heat treatments at 2150° and 2330° F reduced hardness to Rockwell B-96, and produced grains larger than ASTM 1.

Failure Mechanisms

If stress rupture were the only mechanism of failure, the buckets should run in the engine for 1000 hours. (The 1000-hr life is calculated from centrifugal-stress and temperature conditions in bucket airfoils and stress-rupture properties of the material.) A detailed description of the methods of calculation of expected life and analysis of failure mechanisms are presented in reference 4. The mean life of all groups of buckets in this investigation was considerably less than 1000 hours. This leads to the conclusion that something other than centrifugal stress acted to reduce bucket life. It has been shown in reference 6 that vibratory loads superimposed on a mean tensile load can appreciably reduce test life. Since fatigue characteristics were observed on the fracture surfaces of 91 percent of the buckets and performance of buckets in this investigation was much less than 1000 hours, the reduction in life may be at least partly attributed to fatigue. 3937

DISCUSSION OF RESULTS

Although the overtemperature heat treatments studied covered a wide range of temperatures, 1550° to 2350° F, none of the treatments affected bucket life adversely. In fact, the performance of buckets overtemperatured at 2350° F (group 7) was somewhat superior to that of the other groups.

It must not be concluded, however, that properties of the overtemperatured material were not affected. The higher creep rates of some of the groups of buckets would indicate that the stress-rupture strength of these groups was reduced. Investigations conducted by several manufacturers have shown that overtemperaturing specimens can reduce the stress-rupture strength of S-816. For example, figure 14 shows that overtemperaturing for 4 hours at temperatures between 1800° and 2000° F drastically reduces 1500° F stress-rupture strength (ref. 7). Unpublished data obtained at the Lewis laboratory corroborated some of this work; test specimens cut from buckets overtemperatured in service have shown decreased stress-rupture strengths. Still further evidence of damage to stress-rupture strength has been found at the Engineering Research Institute, University of Michigan, where cyclic treatments were studied.

The buckets of this investigation failed primarily by fatigue or by a combination of stress-rupture followed by fatigue as was previously described. The overtemperature heat treatments given would almost certainly reduce bucket life in an engine that fails buckets by stress-rupture alone.

The reasonable assumption has been made that for alloy S-816, reduction in creep resistance is evidence of reduction in stress-rupture strength (see fig. 3). The higher creep rates for blade groups overtemperatured between 1550° and 2000° F indicate that the damage increased with increasing temperature. The changes in microstructure correlate well with the changes in creep rates; the microstructures of figures 5 to 9 show increasing spheroidization or agglomeration of precipitates with increasing temperature. Depletion of solute atoms from the matrix by precipitation and agglomeration of precipitates would be expected to decrease creep resistance.

The 2150° and 2350° F treatments, however, are solution treatments rather than over-aging treatments, as indicated in figures 10 to 13. Precipitation of minor phases during engine operation probably strengthened the materials so treated and increased creep resistance. The elongation curves of figure 3 for the 2150° F treatment buckets are in agreement with this. Unfortunately, elongation data for the 2350° F treatment buckets were not obtained.

It may be speculated that the increased degree of solution treatment occurring at 2350° F not only increased creep strength of the material, as would be expected from reference 8, but also fatigue resistance. No improvement was noted in the performance of the buckets given the 2150° F "solution" overtemperature treatment; possibly because strength was not increased sufficiently. Scatter in lives of groups 1 to 6 obscured any differences in performance.

SUMMARY OF RESULTS

This investigation was conducted to study the effect of short-time overtemperature heat treatments at temperatures between 1550° and 2350° F on turbojet engine performance of S-816 buckets. The treatments were intended to simulate hot-start conditions. Buckets given the different overtemperature treatments were run in a J33-9 turbojet engine under cyclic conditions along with standard Air Force buckets.

The results obtained are as follows:

1. None of the overtemperature heat treatments, which covered the temperature range from 1550° to 2350° F, adversely affected bucket life. Mean life of bucket groups overtemperatured between 1550° and 2150° F ranged from 175 to 212 hours; mean life of buckets overtemperatured at 2350° F was above 336 hours. Air Force buckets selected from stock, run as a standard for comparison, had a mean life of 187 hours.

2. Drastic differences were found in the as-overtemperatured microstructures and in bucket creep rate during the engine test. These differences suggest that bucket stress-rupture properties were changed by the overtemperature treatments. Actual bucket life was not reduced, however, because factors other than stress-rupture influenced failure.

CONCLUDING REMARKS

The significance of the present investigation lies in the fact that overtemperature without stress appears to have reduced stress-rupture strength, but did not reduce bucket performance.

The mechanism of turbine-bucket failure in different engine types must be considered before overtemperature studies have general significance. This investigation was conducted in a high-stress engine, which has a greater tendency to fail buckets in stress-rupture than would a low-stress engine. In spite of this, 91 percent of bucket failures showed evidence of fatigue. 3937

It appears that additional studies of overtemperatured buckets should be made in engines that have even greater tendencies toward producing fatigue or thermal-stress failures in buckets.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 7, 1955

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TABLE I. - RESULTS OF ENGINE OPERATION

Group	Overtemperature heat treatment following standard heat treatment: 15 min at °F-	Failure time, hr	Failure type	Height above base, in.	Location of failure with respect to edges	Mean life, hr
1	1550	33.4	Damage	$1\frac{7}{8}$	Leading	
		99.5	Fatigue	$2\frac{7}{8}$	Leading	
		108.0	Damage	$1\frac{7}{8}$	Leading	
		161.9	Stress rupture plus fatigue	$2\frac{1}{4}$	Trailing	
		181.8	Stress rupture plus fatigue	$2\frac{7}{16}$	Leading	
		186.1	Stress rupture plus fatigue	$3\frac{1}{8}$	Leading	
		192.7	Stress rupture plus fatigue	$2\frac{3}{16}$	Trailing	
		214.6	Damage	$2\frac{1}{2}$	Leading	
		237.0	Damage	$2\frac{1}{2}$	Leading	
		254.6	Fatigue	$1\frac{9}{16}$	Trailing	181.8
2	1700	80.1	Fatigue	$2\frac{1}{8}$	Trailing	
		109.2	Stress rupture plus fatigue	$3\frac{1}{8}$	Leading	
		214.4	Damage	$2\frac{5}{16}$	Leading	
		217.5	Stress rupture plus fatigue	$2\frac{1}{8}$	Leading	
		217.5	Stress rupture plus fatigue	$2\frac{5}{8}$	Leading	
		297.5	Damage	$2\frac{1}{8}$	Leading	189.4
3	1800	86.2	Damage	$2\frac{3}{4}$	Leading	
		100.7	Fatigue	$1\frac{3}{4}$	Trailing	
		120.5	Damage	3	Leading	
		147.5	Stress rupture plus fatigue	$1\frac{5}{8}$	Trailing	
		199.9	Stress rupture plus fatigue	$2\frac{3}{8}$	Leading	
		251.5	Stress rupture plus fatigue	$2\frac{3}{4}$	Leading	174.9
4	1900	89.5	Stress rupture	$2\frac{1}{2}$	Trailing	
		133.6	Fatigue	$2\frac{13}{16}$	Leading	
		157.5	Stress rupture plus fatigue	$2\frac{13}{16}$	Leading	
		217.1	Stress rupture	$2\frac{3}{8}$	Trailing	
		172.5	Stress rupture plus fatigue	2	Leading	
		347.6	Damage	$1\frac{1}{8}$	Leading	186.3
5	2000	157.2	Fatigue	$2\frac{1}{8}$	Leading	
		187.9	Stress rupture plus fatigue	$2\frac{3}{4}$	Leading	
		196.3	Damage	$2\frac{15}{16}$	Leading	
		205.2	Stress rupture	$2\frac{1}{4}$	Leading	
		215.3	Stress rupture plus fatigue	$2\frac{3}{8}$	Leading	192.4

TABLE I. - Concluded. RESULTS OF ENGINE OPERATION

Group	Overtemperature heat treatment following standard heat treatment: 15 min at °F	Failure time, hr	Failure type	Height above base, in	Location of failure with respect to edges	Mean life, hr
6	2150	71.0	Damage	$3\frac{1}{2}$	Leading	
		80.3	Damage	$2\frac{7}{16}$	Leading	
		92.8	Damage	$2\frac{3}{4}$	Leading	
		158.7	Fatigue	$1\frac{3}{4}$	Trailing	
		160.3	Stress rupture plus fatigue	$1\frac{7}{8}$	Trailing	
		197.6	Damage	$3\frac{1}{4}$	Leading	
		197.8	Fatigue	$2\frac{3}{8}$	Trailing	
		208.1	Stress rupture plus fatigue	2	Trailing	
		214.6	Damage	$3\frac{3}{16}$	Leading	
		235.8	Stress rupture plus fatigue	$2\frac{3}{16}$	Leading	
		262.2	Damage	$2\frac{5}{8}$	Leading	
		270.9	Damage	$1\frac{5}{8}$	Leading	211.8
7	2350	61.0	Fatigue	$3\frac{1}{4}$	Trailing	
		351.9	Fatigue	$1\frac{1}{2}$	Trailing	
		403.2	Damage	$2\frac{7}{8}$	Leading	
		527.2	Not failed			335.8
Standard Air Force stock for comparison		30.1	Damage	$2\frac{5}{8}$	Trailing	
		49.8	Stress rupture	$2\frac{1}{2}$	Trailing	
		52.7	Fatigue	$3\frac{3}{16}$	Trailing	
		75.1	Fatigue	$1\frac{7}{8}$	Trailing	
		84.5	Fatigue	$3\frac{3}{16}$	Leading	
		85.3	Fatigue	$1\frac{3}{4}$	Trailing	
		132.8	Stress rupture plus fatigue	$2\frac{7}{16}$	Leading	
		151.3	Stress rupture plus fatigue	3	Leading	
		162.2	Stress rupture plus fatigue	$3\frac{1}{8}$	Leading	
		190.8	Stress rupture plus fatigue	3	Leading	
		208.8	Stress rupture plus fatigue	$2\frac{3}{4}$	Leading	
		221.8	Damage	$1\frac{1}{2}$	Leading	
		253.0	Damage	$2\frac{3}{16}$	Leading	
		258.6	Fatigue	$2\frac{3}{16}$	Trailing	
		264.5	Stress rupture plus fatigue	$2\frac{1}{2}$	Leading	
		298.6	Damage	$2\frac{5}{8}$	Leading	
		340.5	Stress rupture plus fatigue	$2\frac{15}{16}$	Leading	
		356.8	Damage	$2\frac{11}{16}$	Leading	187.5

TABLE II. - AS-HEAT-TREATED HARDNESS AND GRAIN SIZE

Bucket group	Rockwell hardness[a]			ASTM grain size		
	R_A	Converted		Smallest	Largest	Average
		R_C	R_B			
1	63	25	--	8	4	6
2	62	23	--	8	4	7
3	62	23	--	8	4	7
4	63	25	--	8	4	6
5	63	25	--	8	5	7
6	59	--	96	8	>1	4
7	59	--	96	7	>1	3
Standard	63	26	--	8	6	7

[a]Hardness is an average of five or more readings measured on Rockwell-A scale and converted.

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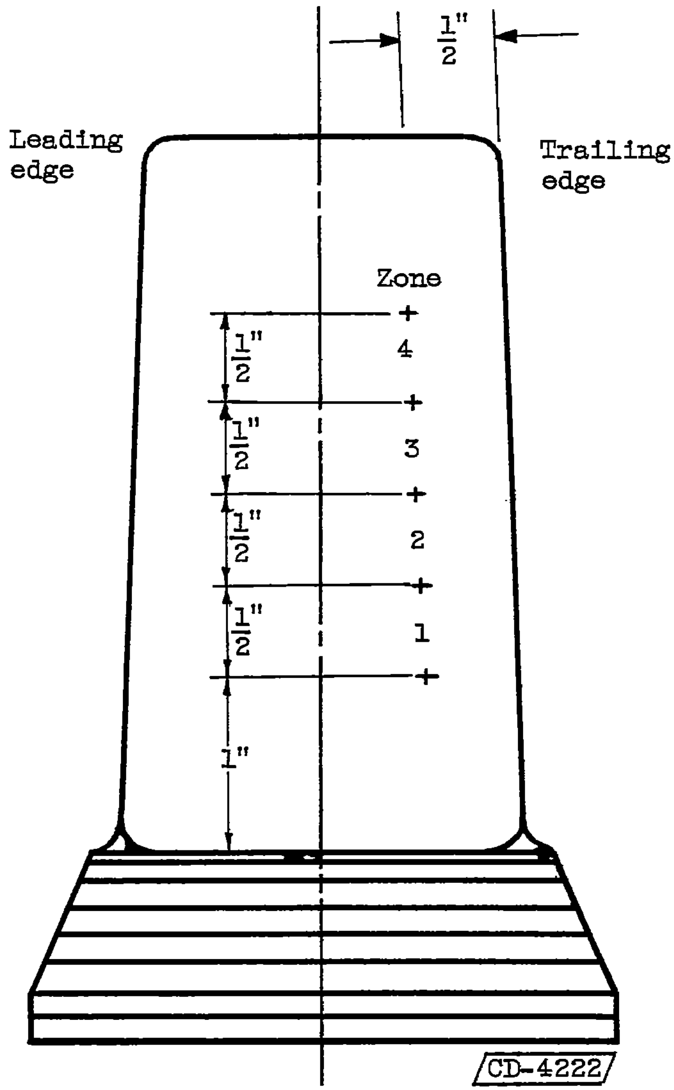


Figure 1. - Location of scribe marks on concave side of buckets for use in measuring elongation.

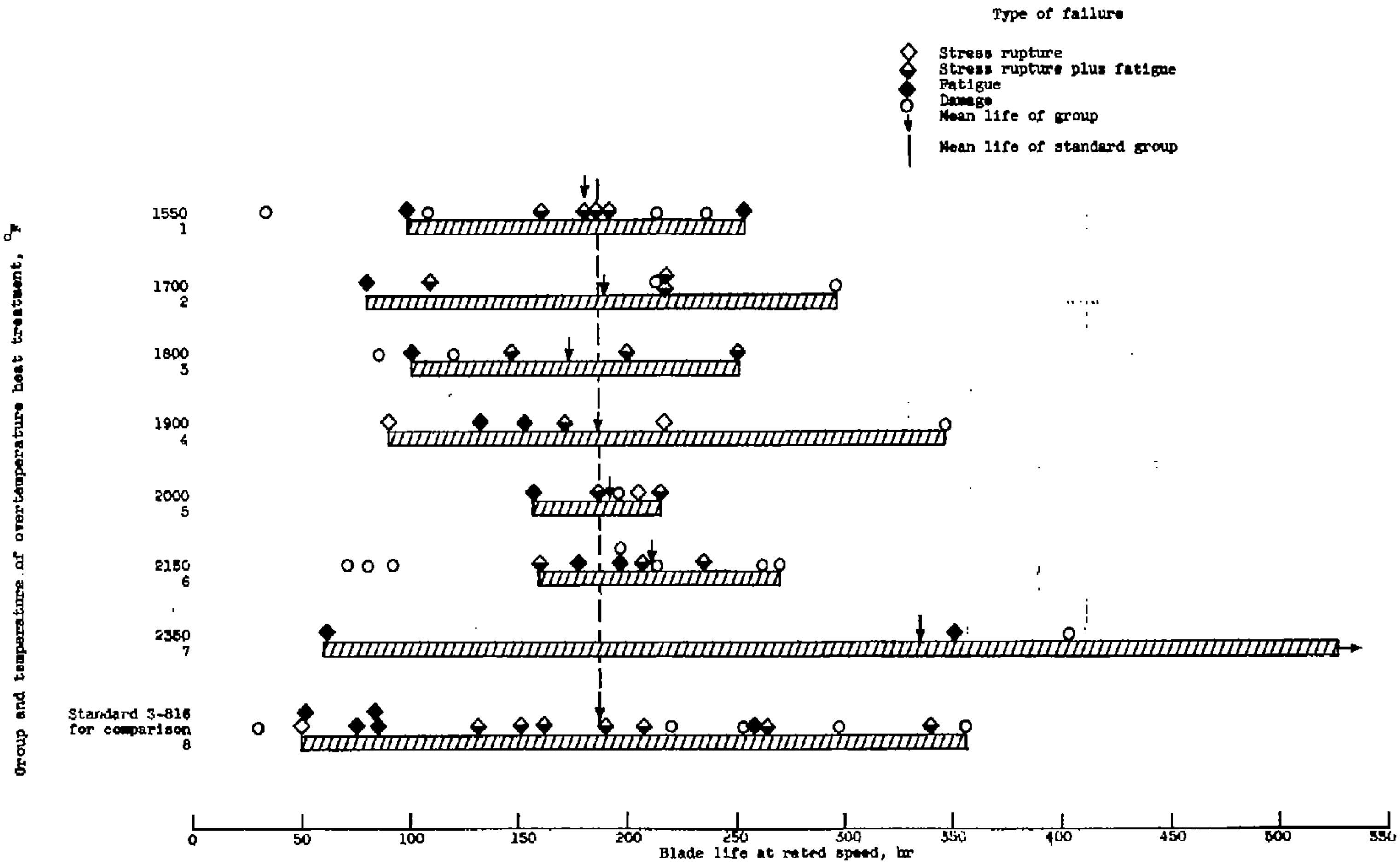


Figure 2. - Engine results.

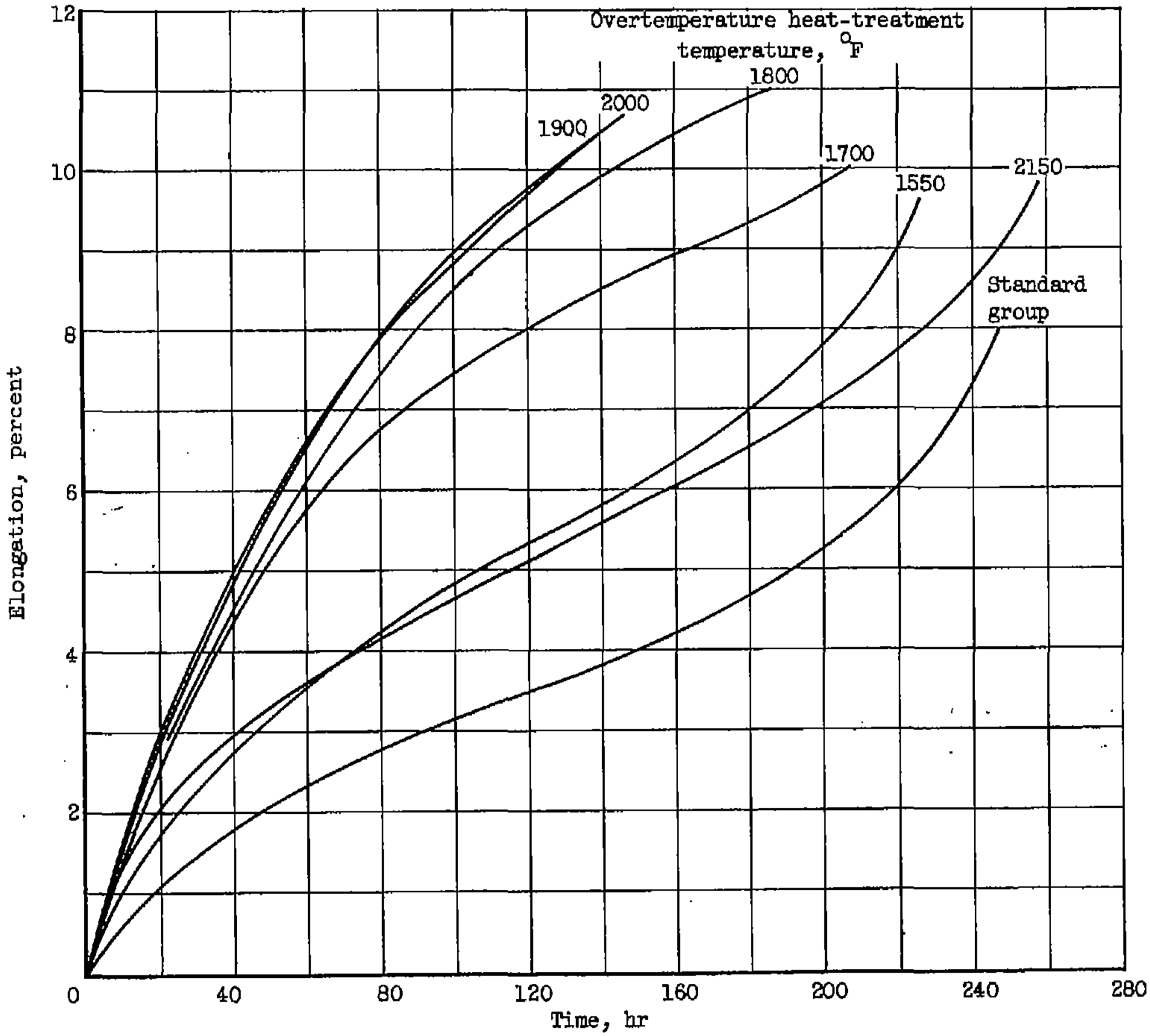
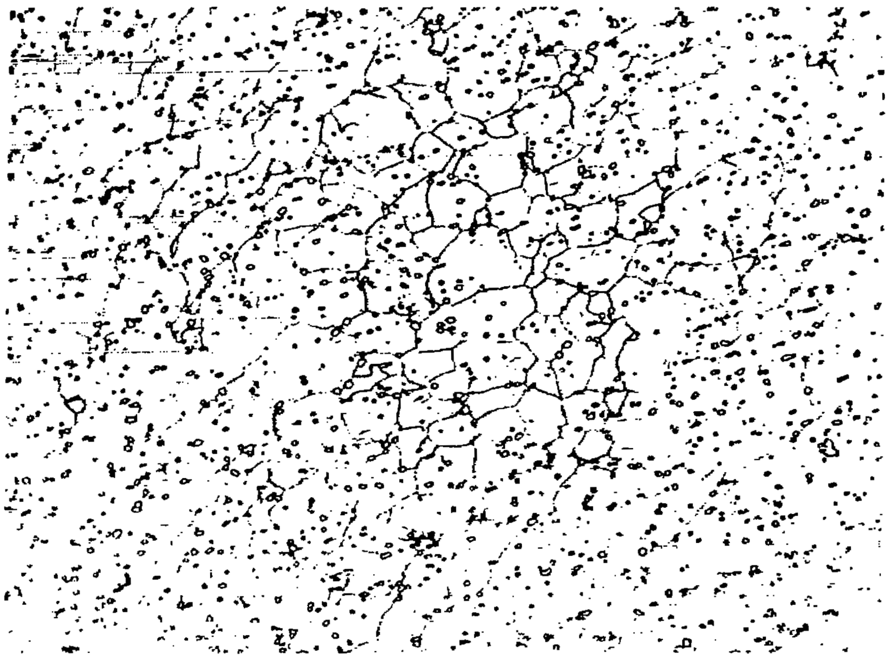


Figure 3. - Elongation of zone 2 during engine test.



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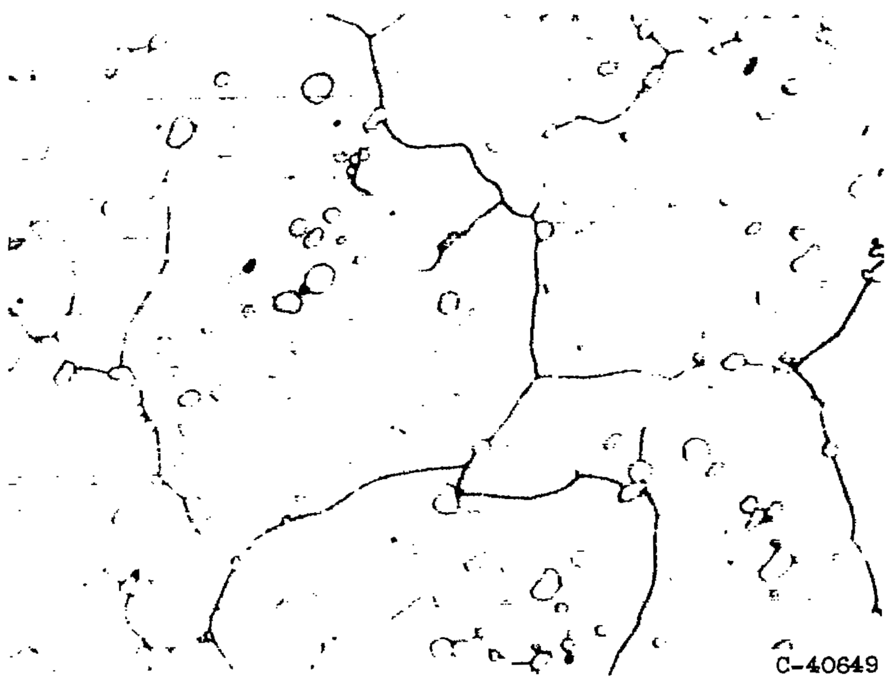
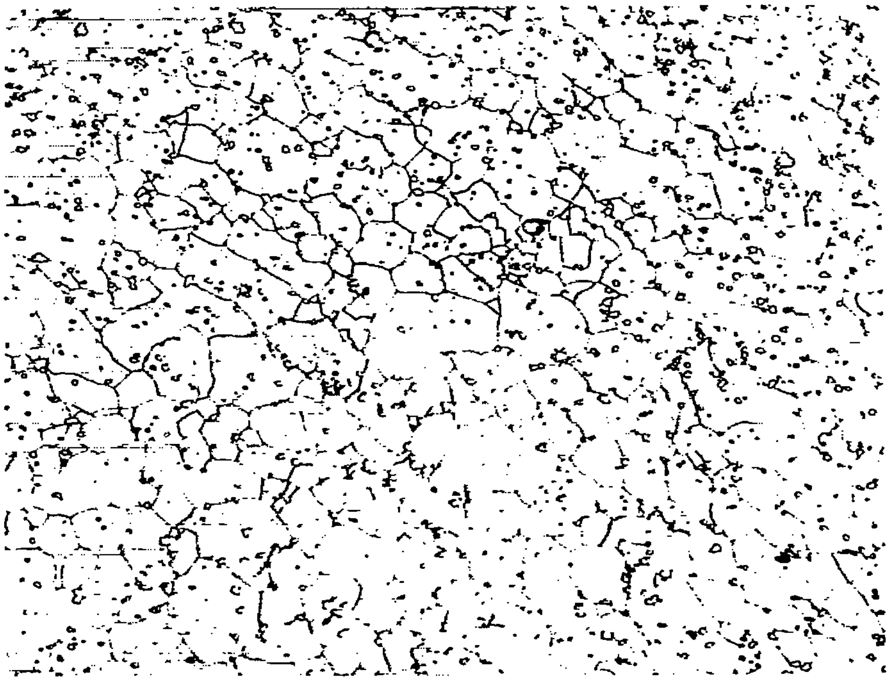


(b) X1000.

Figure 4. - Microstructure of S-816 after standard heat treatment. Etchant, 25 percent aqua regia plus 75 percent glycerol.



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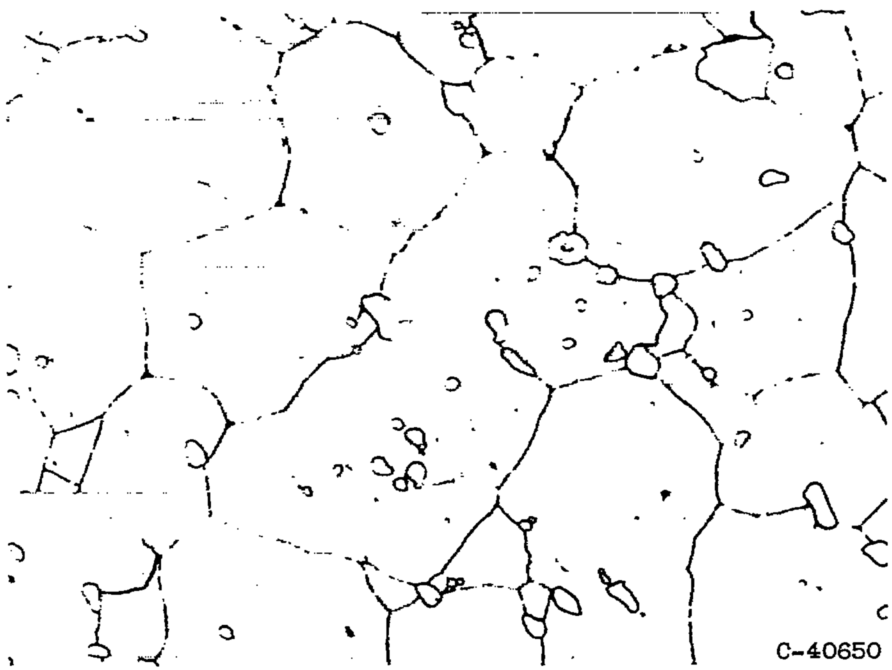
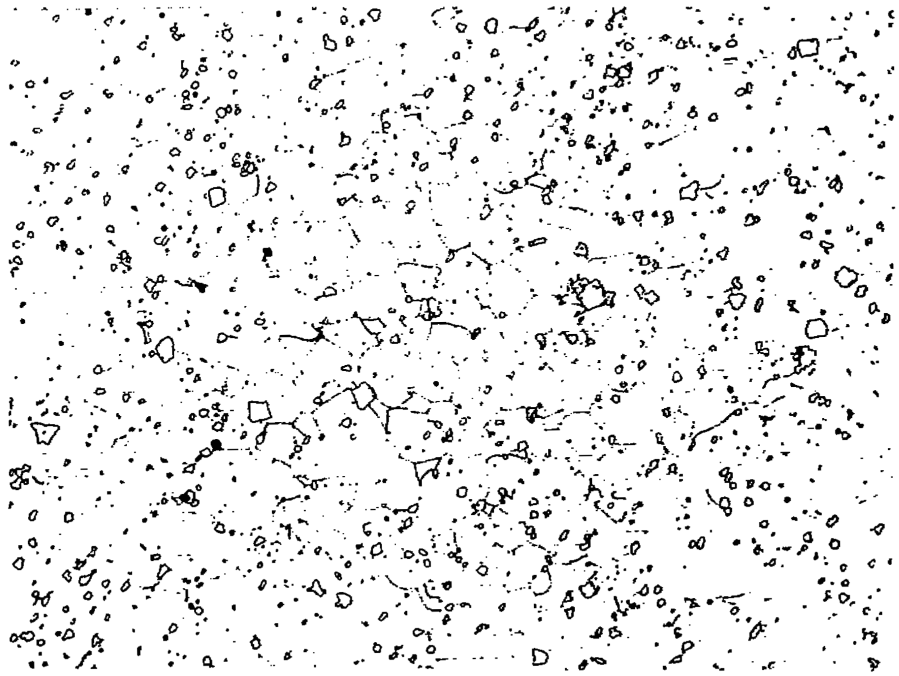


(b) X1000.

Figure 5. - Microstructure of S-816 after 15 minutes at 1550° F. Etchant, 25 percent aqua regia plus 75 percent glycerol.

[redacted]



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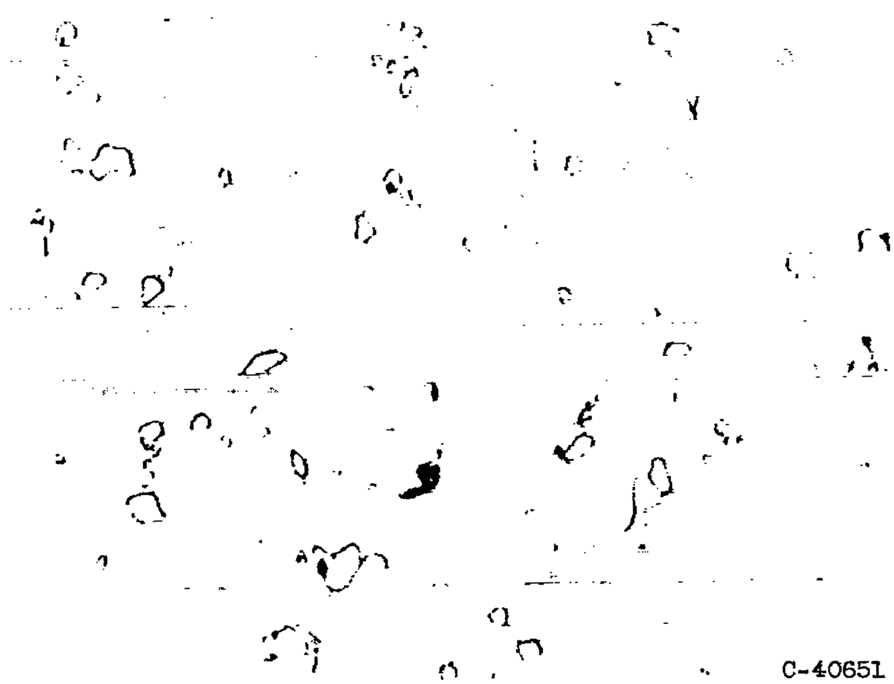
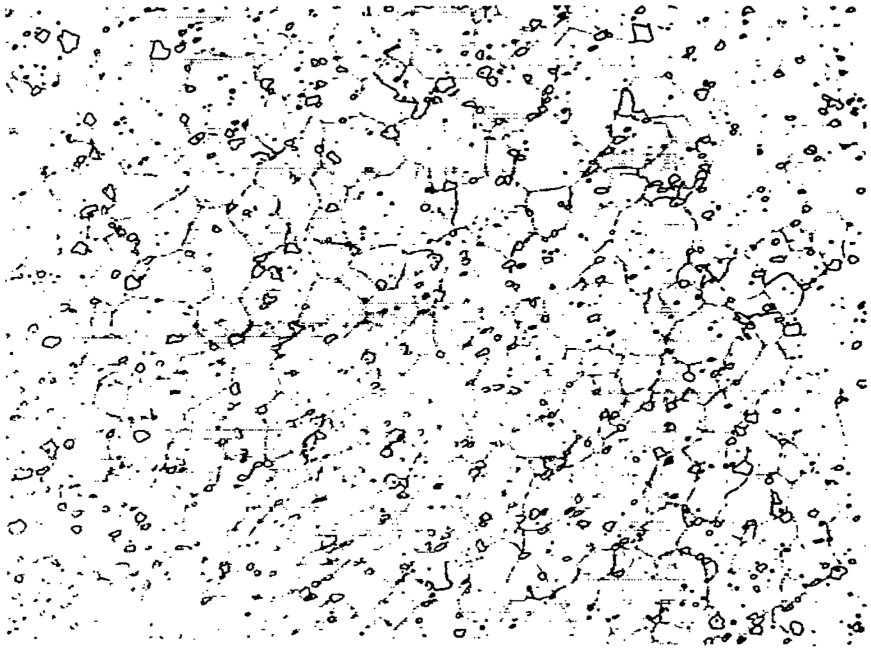


(b) X1000.

Figure 6. - Microstructure of S-816 after 15 minutes at 1700° F. Etchant, 25 percent aqua regia plus 75 percent glycerol.

[redacted]

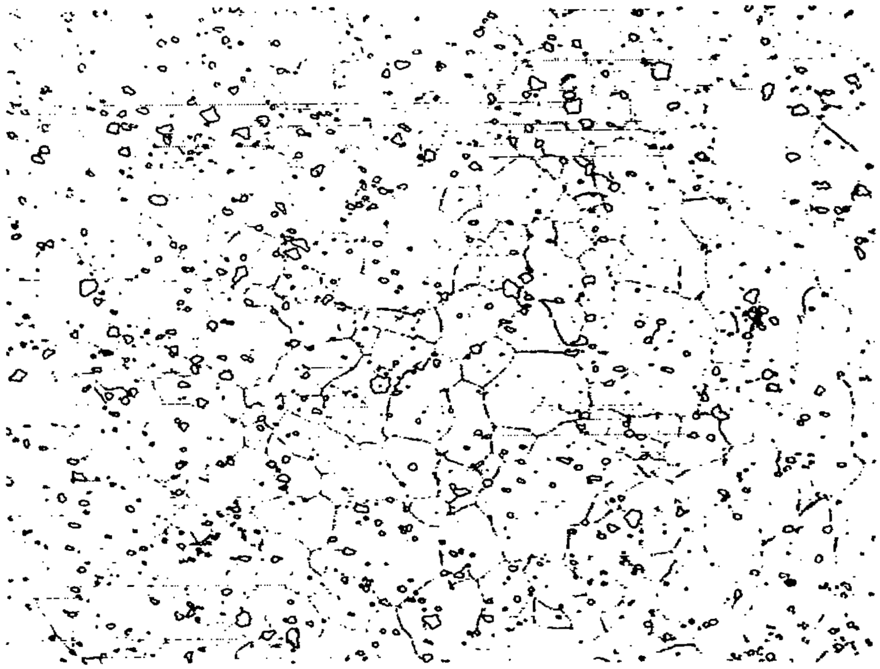


(a) X250.

(b) X1000.

Figure 7. - Microstructure of S-816 after 15 minutes at 1800° F. Etchant, 25 percent aqua regia plus 75 percent glycerol.

[redacted]



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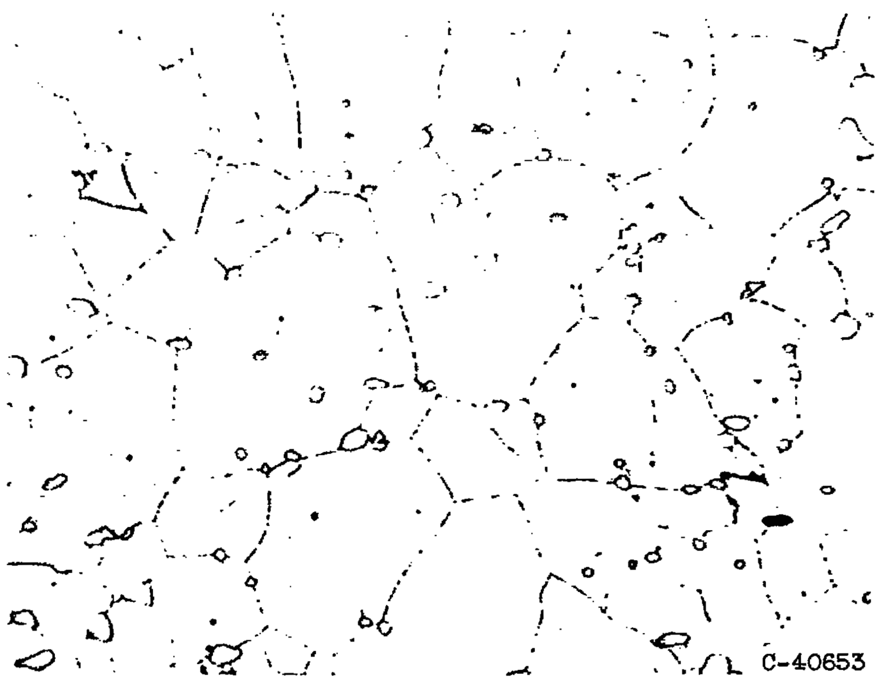

(b) X1000.

Figure 8. - Microstructure of S-816 after 15 minutes at 1900° F. Etchant, 25 percent aqua regia plus 75 percent glycerol.

[redacted]

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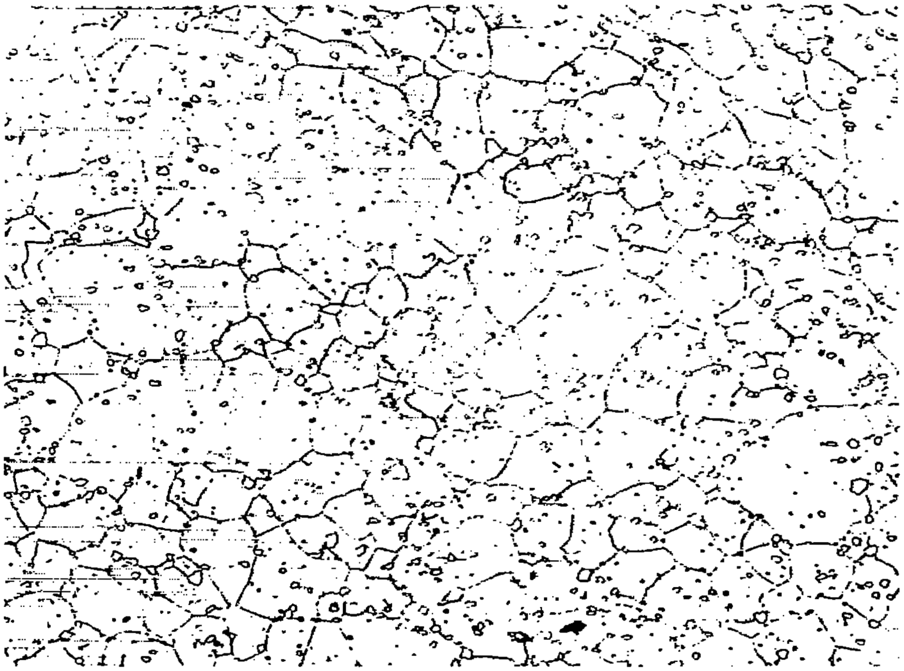
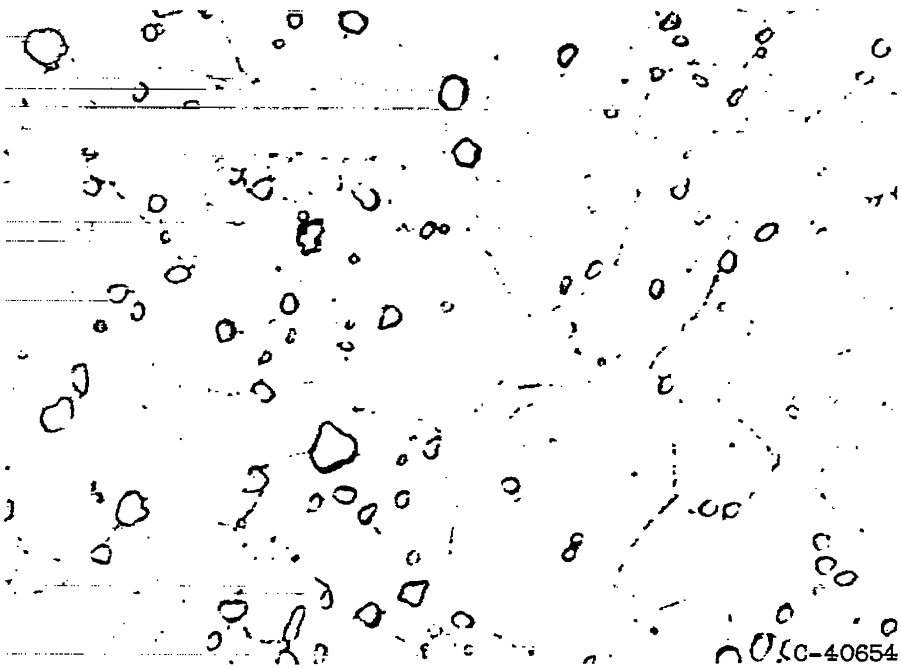


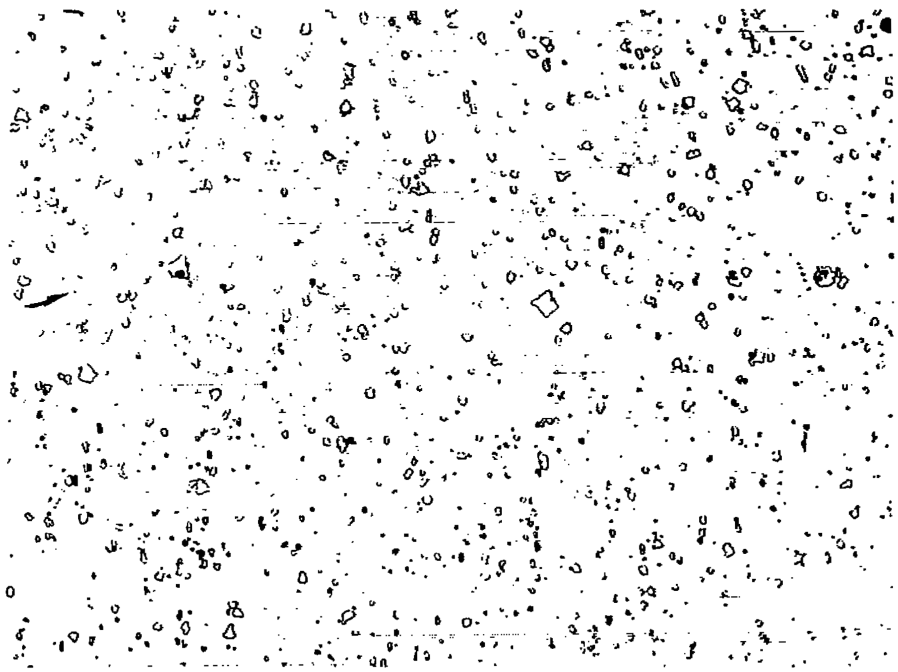
(a) X250.



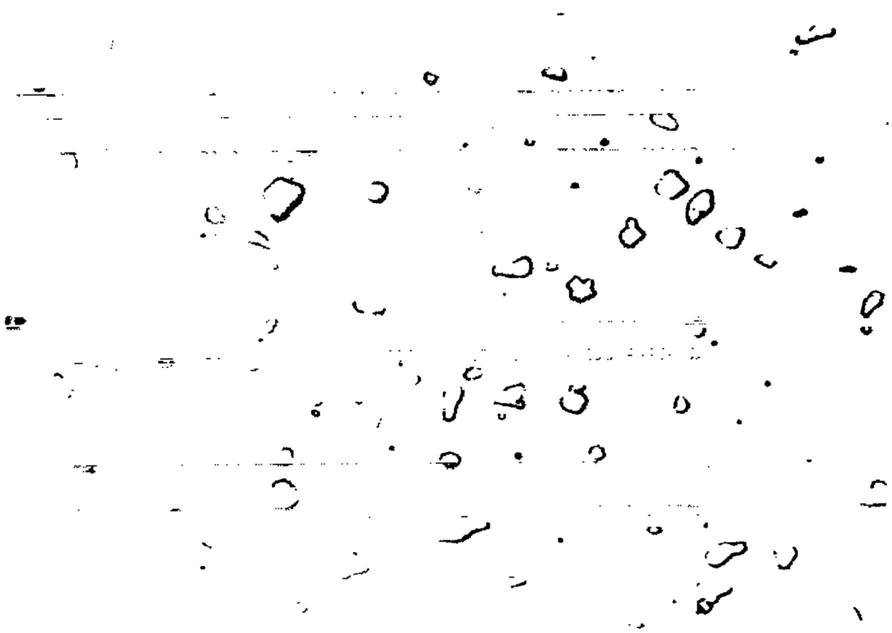
(b) X1000.

Figure 9. - Microstructure of S-816 after 15 minutes at 2000° F. Etchant, 25 percent aqua regia plus 75 percent glycerol.

3937



(a) X250.

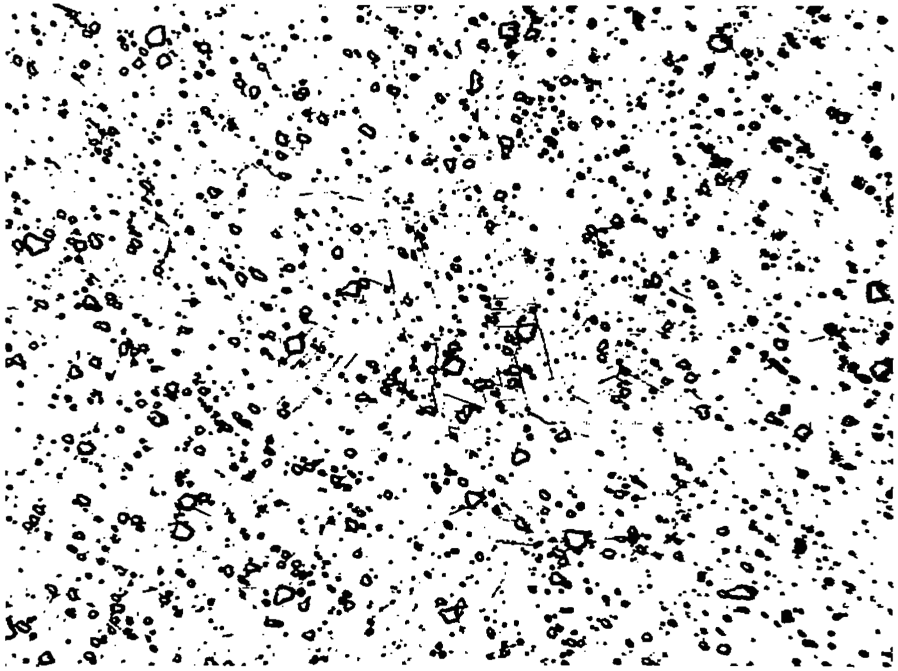


C-40655

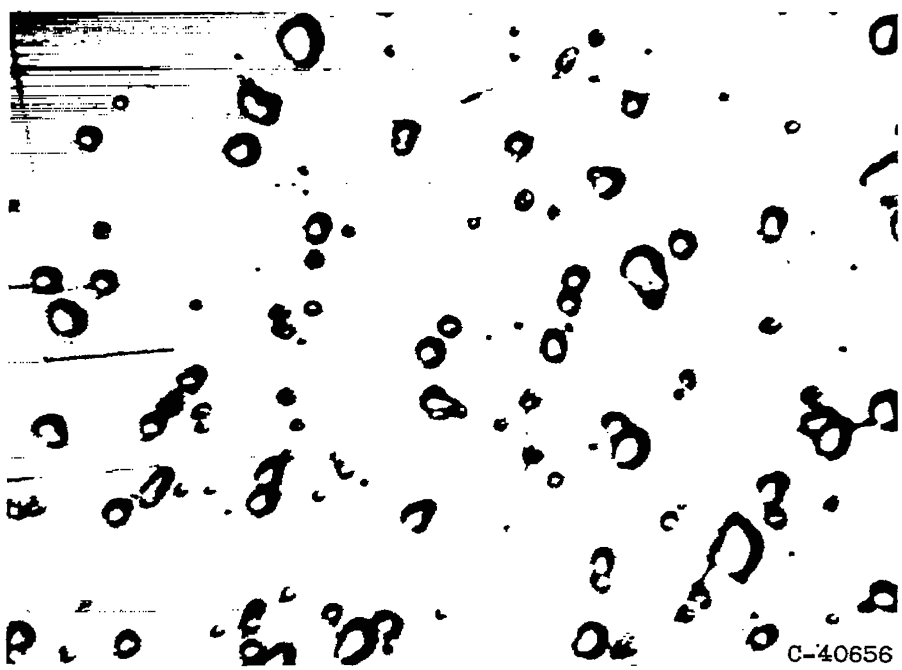
(b) X1000.

Figure 10. - Microstructure of S-816 after 15 minutes at 2150° F. Etchant, 25 percent aqua regia plus 75 percent glycerol.

3937



(a) X250.

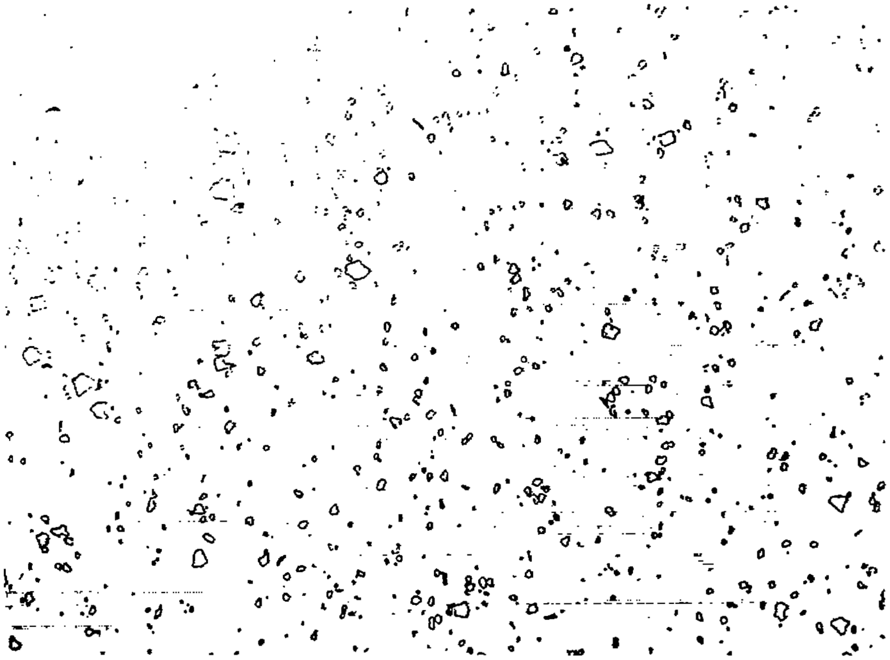


(b) X1000.

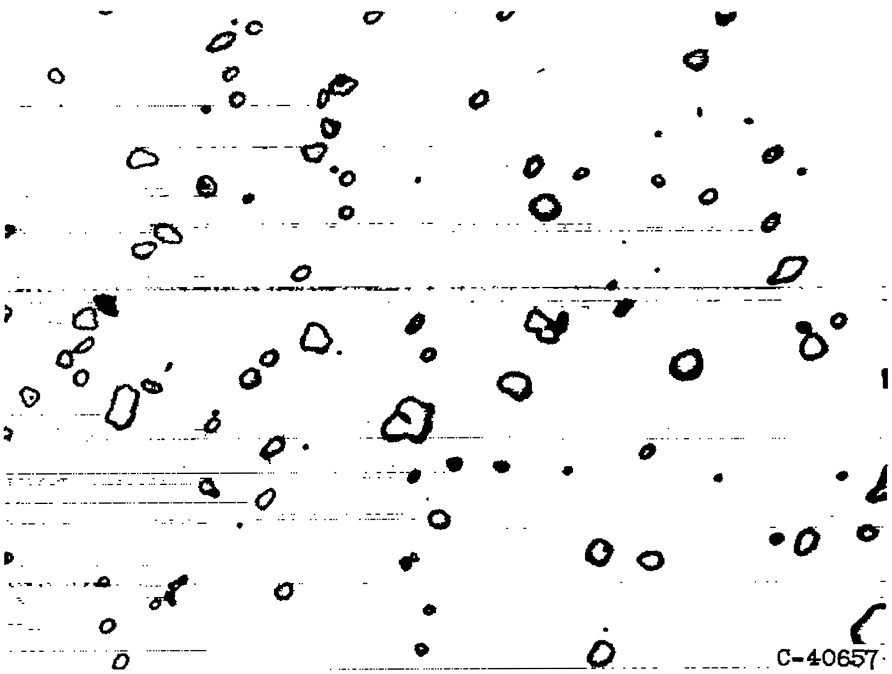
Figure 11. - Microstructure (over etched to emphasize grain boundaries) of S-816 after 15 minutes at 2150° F. Etchant, 10 percent hydrochloric acid.

[redacted]

3937



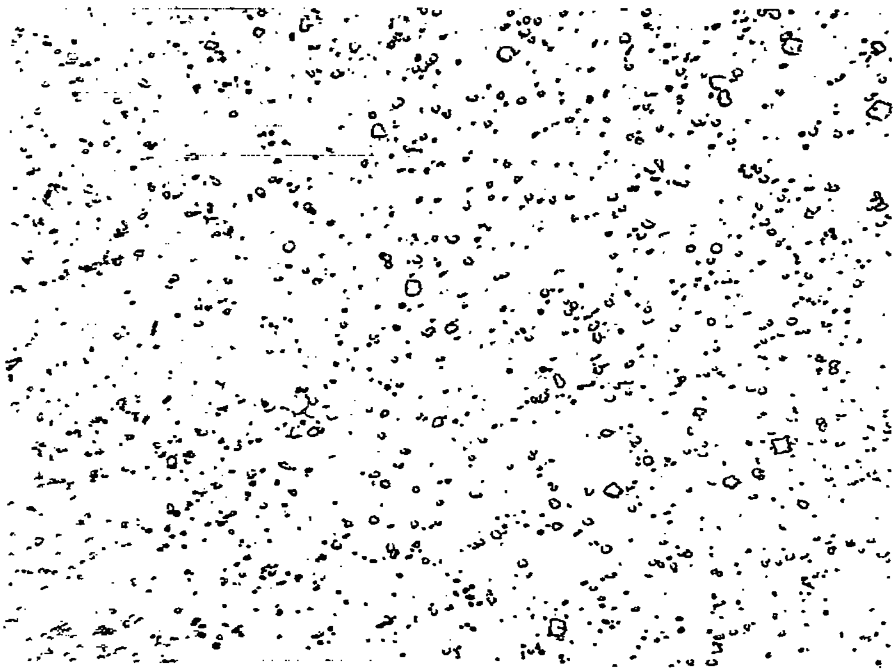
(a) X250.



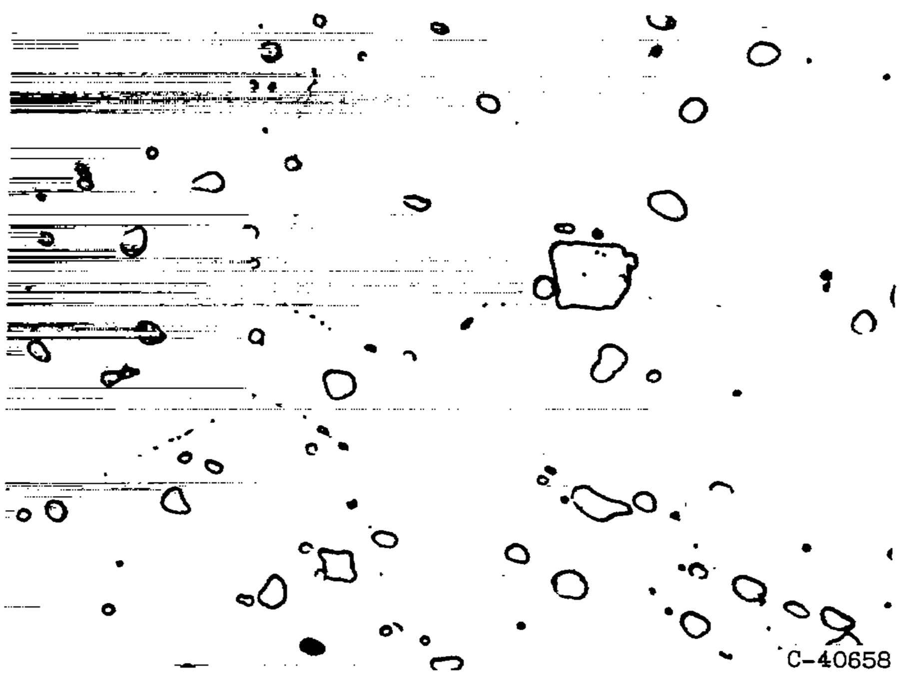
(b) X1000.

Figure 12. - Microstructure of S-816 after 15 minutes at 2350° F. Etchant, 25 percent aqua regia plus 75 percent glycerol.

[redacted]



(a) X250.



(b) X1000.

Figure 13. - Microstructure (over etched to emphasize grain boundaries) of S-816 after 15 minutes at 2350° F. Etchant, 10 percent hydrochloric acid.

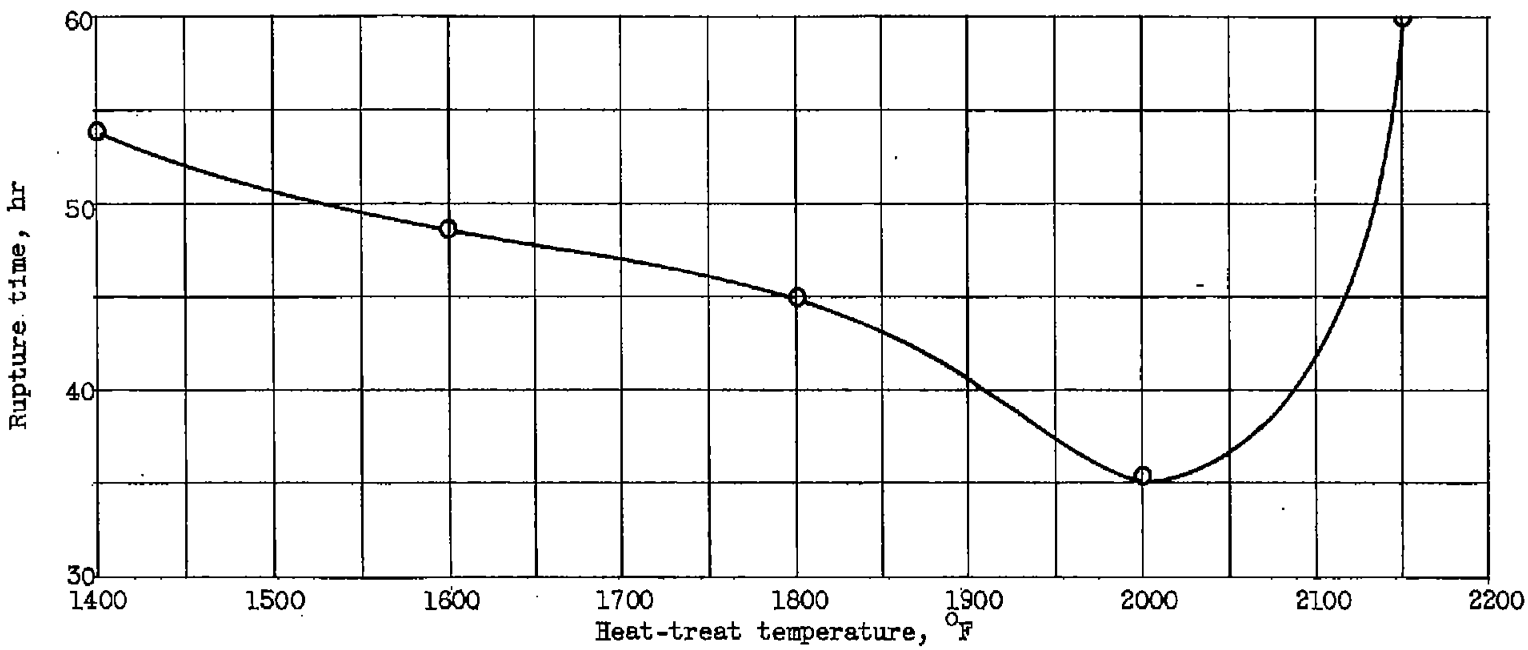


Figure 14. - Influence of heat-treat temperature on stress-rupture life of S-816 alloy at 25,000 psi and 1500° F. Heat treatment: 1 hour at 2150° F, water quench; 16 hours at 1400° F, air cool; 4 hours at temperatures shown. (Ref. 7)

[redacted]