NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2513

EFFECTS OF SOME SOLUTION TREATMENTS FOLLOWED BY AN AGING TREATMENT ON THE LIFE OF SMALL CAST GAS-TURBINE BLADES OF A COBALT-CHROMIUM-BASE ALLOY

II - EFFECT OF SELECTED COMBINATIONS OF SOAKING TIME, TEMPERATURE, AND COOLING RATE

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Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

An investigation was conducted to determine the effects of various heat treatments on the microstructure and the life of small cast turbine blades of Haynes Stellite alloy 21, a cobalt-chromium-base alloy. Six heat treatments, which involved combinations of the following conditions, were studied: soaking at 2100° or 2250° F for 1 or $1\frac{1}{2}$ hours followed by air cooling to room temperature or furnace cooling to 1800° F and air cooling to room temperature. These treatments were followed in each case by aging at 1500° F for 72 hours.

Twenty blades taken from each of the six heat-treated groups together with 22 as-cast blades were assembled in a small gas turbine, which was driven by hot gas. At the blade midspan, the temperature was 1500° F and the stress was 20,000 pounds per square inch.

A marked improvement in blade life could be associated with a lamellar microstructure produced by soaking at 2250° F for 1 or $1\frac{1}{2}$ hours followed by slow furnace cooling to 1800° F. The best performing group had a first failure time of 103.6 hours, a mean life of 150.8 hours, and a final failure time of 197.4 hours compared with 33.3, 78.0, and 114.1 hours, respectively, for the as-cast blade group.

INTRODUCTION

The time to overhaul of gas-turbine engines depends largely on blade life. Hence, improvement in blade life is desirable. The aging of Haynes Stellite alloy 21 (a cobalt-chromium-base alloy) blades for

48 hours at 1500° F has been found to improve mean life (reference 1). Solution treatment of this alloy at 2100°, 2250°, or 2350° F for 1/2 hour followed by either air or furnace cooling and a 48-hour age at 1500° F improved blade mean life without a significant change in uniformity as measured by the standard deviation (reference 2).

The research described herein was conducted at the NACA Lewis laboratory and is an extension of the investigation described in reference 2. The effect of increased soaking time at 2100° and 2250° F followed by either air or furnace cooling and by increased aging time at 1500° F upon mean life and uniformity of small cast gas-turbine blades of Haynes Stellite alloy 21 was studied in the present investigation. The blades were operated in a small gas turbine at a stress of approximately 20,000 pounds per square inch and a temperature of approximately 1500° F at the blade midspan. Metallographic examinations were made to determine the effect of microstructure on blade operation. Statistical analysis was applied to the observed times of failure.

APPARATUS AND PROCEDURE

The blades used in this investigation were of the following nominal composition (reference 3):

C	Mn	S	Cr
0.20-0.35	1.00 max.	1.00 max.	25.00-29.00
Ni	Mo	Fe	Co
1.75-3.75	5.00-6.00	2.00 max.	56.90-68.05

Before being mounted in the turbine wheel, all blades were radiographed for internal flaws and visually examined for external flaws. The shrouds of the blades were ground to a width of 0.270 inch, a length of 0.450 inch, and a thickness of 0.070 inch in order to eliminate shroud weight as a variable and to produce a uniform centrifugal stress of 20,000 pounds per square inch at the midpoint of the blades at operating speed. All blades except an as-cast control group were heat-treated as described in table I. Typical blades are shown in figure 1.

In order to expedite the heat-treating of the turbine blades, two electric furnaces were used, one having an atmosphere produced by the combustion of natural gas and the other an atmosphere of inert gas. Blades of groups 5 and 6 were treated in the combusted natural-gas-atmosphere furnace. The remaining groups were heat-treated in the inert atmosphere furnace and all blades were then aged in the furnace having the inert-gas atmosphere.

A gas turbine supplied with hot gases from a turbojet combustion chamber was used in evaluating the performance of the turbine blades.

The turbine operating temperature was indicated by a thermocouple that measured gas temperature in the inlet duct 12 inches upstream of the turbine inlet. This apparatus is described in references 1 and 4.

The turbine wheel had a total diameter of 12.5 inches and contained 142 blades. All the blades used in this program were installed in the wheel at the start of the investigation. The wheel was dynamically balanced prior to initial operation, and thereafter, as necessary.

The blade evaluation was conducted in the following manner: Combustion air was supplied to the turbine and the wheel was motored at approximately 6000 rpm for 5 minutes. Combustion was initiated and the wheel brought to operating conditions, a shaft speed of 22,500±200 rpm and an indicated inlet gas temperature of 1650±15° F. At these conditions, achieved in approximately 3 minutes, the blade temperature was estimated from previous operating experience to be 1500° F. Operating time was measured from the beginning to the termination of combustion. Upon failure of a blade, indicated by a change in the pitch of sound emitted from the unit, combustion was immediately terminated and the air flow reduced to a value such that the wheel motored at 6000 rpm. This air flow was maintained for 10 minutes in order to cool the assembly. Shutdowns were effected as quickly as possible to minimize the effects of vibration caused by wheel unbalance. The turbine wheel was removed and the failed blade, or blades, replaced by as-cast blades. Severely cracked blades were considered failures in order to minimize shutdowns and to facilitate operation. Blade fragments, when thrown from the wheel, became imbedded in asbestos packing and were thus preserved and did not ricochet to damage remaining blades.

The following blades from each group were selected and prepared for metallographic examination: (a) a blade that had not been operated, (b) a blade that failed relatively early, (c) a blade that failed near the mean life of the group, and (d) a blade that failed after comparatively long operation. These blade specimens were electrolytically etched in a solution of 10-percent nitric acid plus 10-percent ethylene glycol in ethyl alcohol. The service-failed blades were sectioned longitudinally, whereas the nonoperated blades were sectioned transversely at the blade midspan.

The service failed blades remaining from each group after metallographic specimens had been prepared were measured for hardness. Five Rockwell-A hardness measurements were made on each blade. The scale on these blades was not removed prior to taking the measurements. Hardness measurements were made on two nonoperated blades from each group.

In order to determine whether the blades of groups 5 and 6 were carburized or decarburized by the combusted natural-gas atmosphere, alloy specimens given the same treatment applied to blades of group 5 were used for a determination of surface carbon content. Five successive

0.001-inch-thick layers were machined off each specimen. A number of specimens were used so that corresponding layers could be combined to yield a sufficiently large amount of material to give an accurate carbon determination.

The statistical procedures, presented in the appendix, were employed to determine the significance of the observed differences between the lives of the as-cast blades and of the various heat-treated blade groups.

RESULTS AND DISCUSSION

The time of failure for the individual blades in each of the different groups is presented in table II. The mean life and standard deviation are also given in this table. The failure time for the individual blades of each group and the corresponding theoretical cumulative-frequency distribution (assuming normal distributions of blade failures) are presented in figure 2. The theoretical cumulative-frequency-distribution curves are presented for comparison in figure 3.

The heat treatment applied to group 5 produced the greatest increase in life over that of the as-cast blade group as shown in table II and figure 3. The nature of this improvement is apparent from the following comparison taken from table II:

	As cast	Group 5
First failure time (hr)	33.3	103.6
Mean life (hr)	78.0	150.8
Last failure time (hr)	114.1	197.4

The first failure time and the blade mean life of group 6 were also appreciably increased over the as-cast blades although not as much as that of group 5. In both cases, soaking at 2250° F was followed by cooling in a furnace to 1800° F and then by aging; an atmosphere produced by combustion of natural gases was used.

A statistical test of the joint equality of the mean and standard deviation was made to compare each of the heat-treated groups to the as-cast group. From this test, it was concluded that the blades of groups 1 and 2 are not different from the as-cast group with respect to mean life and uniformity, whereas, those of the remaining groups (3, 4, 5, and 6) differ from the as-cast blades with respect to either one or both of these parameters. For these four groups, a statistical analysis was made of the observed differences in mean lives and in standard deviations as compared with the as-cast group.

Analysis of the observed differences in mean lives between groups 5 and 6 and the as-cast group reveals that these differences are very significant resulting in the conclusion that treatments applied to groups 5 and 6 caused an increase in mean life; no significance can be attached to the observed differences in mean lives of groups 3 and 4 compared to that of the as-cast group.

The analysis of the standard deviation of individual blade lives of group 5 reveals no significant difference from that of the as-cast blades. In the case of the blades of groups 3 and 4, the difference between their respective standard deviations and that of the as-cast blade group is very significant. In the case of group 6 and the as-cast group, the difference in standard deviations is significant. Thus, the uniformities of groups 3, 4, and 6 are considered to be reduced. The results of the statistical study are summarized in table III.

The theoretical indices (see appendix) of initial (first) failure are 18.3 hours for the as-cast blades and 14.2, 8.3, -38.7, -77.9, 65.6, and 20.5 hours for groups 1 to 6, respectively, (table II). A negative index, for practical purposes, is interpreted as possible failure immediately on commencement of operation. This analysis indicates that the treatments of groups 5 and 6 have improved the time to initial failure.

Photomicrographs of the structure of a blade from each group before operation are shown in figure 4. A typical as-cast blade structure is shown in figure 4(a). A small amount of lamellar structure adjacent to the grain boundaries was observed. Structures of blades that were soaked at 2100° F for 1 and $1\frac{1}{2}$ hours, respectively, air cooled, and then aged at 1500° F for 72 hours are shown in figures 4(b) and 4(c). These structures show evidence of considerable aging and contain numerous precipitates. Structures of blades soaked at 2250° F for 1 and $1\frac{1}{2}$ hours, respectively, air-cooled, and aged at 1500° F for 72 hours are shown in figures 4(d) and 4(e). The as-cast dendritic structure is reduced in size and extent by the $1\frac{1}{2}$-hour treatment compared with the 1-hour treatment. Microstructures of blades soaked at 2250° F for 1 hour and for $1\frac{1}{2}$ hours followed by furnace cooling for $6\frac{1}{2}$ hours to 1800° F, air cooling and aging at 1500° F for 72 hours are shown in figure 4(f) and 4(g), respectively. An unusually large amount of lamellar structure is present in these blades (fig. 4(h)). There was no evidence of aging precipitate in the matrix of these specimens. There was no conclusive metallographic evidence that explained the variation in blade life within any of the groups.

Examination of the fractured blades revealed that failure for all blades except those of groups 5 and 6 was initiated by intergranular failure with ensuing transcrystalline failure. There was indication

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that, in the case of groups 5 and 6, failure may have been initiated by transcrystalline fracture.

A plot showing the variation of blade hardness with turbine operating time for blades of each group is presented in figure 5. The blades of groups 1 and 2 first hardened during operation and then decreased in hardness. Blades of groups 3, 4, 5, and 6 exhibited no change in hardness with turbine operating time.

The outstanding performance of the blades of groups 5 and 6 may be associated with the presence of the lamellar structure. The atmosphere used in heat-treating these blades was found to be decarburizing rather than neutral; this may be noted from table IV, which presents the relation between depth and carbon content for specimens given the same treatment (including atmosphere) that was applied to blades of group 6. Because blade failure is apparently initiated by surface cracking, anything affecting the surface may affect blade life. The stress-to-rupture life of this alloy at 1500° F and 30,000 pounds per square inch increases as the carbon content increases (reference 5). Hence, the atmosphere effects alone probably could not be expected to improve blade life and the lamellar structure may therefore be considered a contributing factor in increasing blade life.

The blades of groups 1 and 2 overaged during operation (fig. 5). Hence, overaging may be a factor contributing to the comparatively poor performance of blades of these groups. A shorter aging time at 1500° F may be required with this soaking temperature.

The results of this investigation and those of references 1 and 2 suggest a more comprehensive study of the association of heat-treating parameters with blade structure and with blade life.

SUMMARY OF RESULTS

The following results were obtained in an investigation of the effects of several heat treatments on both the life and the structure of small cast Haynes Stellite alloy 21 gas-turbine blades:

1. The heat treatment that produced the best result consisted in soaking at 2250° F for 1 hour, followed by furnace cooling to 1800° F in $6\frac{1}{2}$ hours, air cooling to room temperature, and subsequent aging at 1500° F for 72 hours. The second best performing group had the same heat treatment except for a soaking period of $1\frac{1}{2}$ hours.

2. The best performing group had a first failure time of 103.6 hours, a mean life of 150.8 hours, and a final failure time of 197.4 hours compared with 33.3, 78.0, and 114.1 hours, respectively, for the as-cast group.

3. Large quantities of lamellar structure were formed in the blades of the two best performing groups.

4. There was indication that blades of the two best groups failed in a transcrystalline manner, whereas, failure in the other blades was initiated by intergranular failure with ensuing transcrystalline failures.

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5. Blades soaked at 2100° F for either 1 or $1\frac{1}{2}$ hours, air-cooled, and aged at 1500° F for 72 hours overaged during operation. Blades of the remaining groups showed no change of hardness with operating time.

CONCLUSIONS

The investigation of the effects of several heat treatments on both the life and the structure of small cast Haynes Stellite alloy 21 blades led to the following conclusions:

1. Solution treatment, slow cooling, and subsequent aging of Haynes Stellite alloy 21 produce a lamellar structure that appears to have a marked improvement on the life of blades of this alloy.

2. Heat-treatment cycles reported herein were effective in producing lamellar structures in the blades studied; however, blades of different size and history may require a modification in the heat-treating conditions to obtain the lamellar structure.

National Advisory Committee for Aeronautics
Lewis Flight Propulsion Laboratory
Cleveland, Ohio, July 9, 1951

APPENDIX - STATISTICAL PROCEDURES

In order to determine whether differences in sample values of mean and standard deviation are significant or the result of chance, cognizance must be taken of the inherent variability of the statistics associated with comparatively small samples. A sample is defined as a group containing a finite number of items. By use of statistical techniques, the probability that differences in statistics are due to chance can be computed; hence the significance of the observed differences can be evaluated.

The mean and the standard deviations of a blade sample are, respectively:

$$\bar{x} = \frac{\sum_{1}^{N} x_i}{N}$$

and

$$\sigma \doteq \sqrt{\frac{\sum_{1}^{N} (\bar{x}-x_i)^2}{N}}$$

where

N	total number of blades in sample
$\bar{x}$	mean life for sample, hours
x_i	individual blade life, hours
σ	standard deviation of blade life in sample, hours

The following test (reference 6, p. 414) may be used to determine whether there is a difference between two populations; that is, whether either or both the mean and standard deviation have changed

$$\lambda_H = \left(\frac{\sigma_1}{\sigma_0}\right)^{N_1} \left(\frac{\sigma_2}{\sigma_0}\right)^{N_2}$$

where

$$\sigma_0^{\,2} = \frac{N_1\sigma_1^{\,2} + N_2\sigma_2^{\,2}}{N_1 + N_2} + \frac{N_1N_2}{(N_1+N_2)^2} (\bar{x}_1-\bar{x}_2)^2$$

and

N_1	number of items in first sample
N_2	number of items in second sample
$\overline{x}_1$	mean of first sample
$\overline{x}_2$	mean of second sample
λ_H	measure of probability of difference between populations
σ_0	combined estimate of standard deviation
σ_1	standard deviation of first sample
σ_2	standard deviation of second sample

The interpretation of the value of λ_H may be obtained from table 48 of reference 6 (p. 408).

The following equation (reference 6) may be utilized to determine whether the difference between two sample standard deviations is significant:

$$F = \frac{\sigma_1{}^2 N_1/(N_1-1)}{\sigma_2{}^2 N_2/(N_2-1)}$$

F	measure of probability of difference between sample standard deviations

The interpretation of the value of F may be obtained from table IX reference 6 (p. 476).

The following equation may be used to determine whether observed differences between sample means are significant:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\dfrac{\breve{\sigma}_1{}^2}{N_1} + \dfrac{\breve{\sigma}_2{}^2}{N_2}}}$$

where

t	measure of probability of difference between sample means
$\breve{\sigma}$	unbiased estimate of standard deviation of population, $\sigma\sqrt{\frac{N}{N-1}}$
$\breve{\sigma}_1$	unbiased estimate of standard deviation of population from which first sample was drawn

$\breve{\sigma}_2$ unbiased estimate of standard deviation of population from which second sample was drawn

The interpretation of the value of t may be obtained from table VII of reference 6 (p. 474).

It was assumed that the distribution of blade failures is normal. This assumption generally has no effect upon the conclusion relative to the significance of observed differences in mean values.

An indication or an index of the time to initial failure yielded by each of the heat treatments can be obtained by estimating from the group statistics, the mean life, and the standard deviation of an infinite number of blades (population) treated in the same manner, and by using the lower 3 standard-deviation limit as the practical lower boundary. The population estimated standard deviation is denoted by $\breve{\sigma}$ and is defined elsewhere in the appendix. The lower 3 standard-deviation limit is commonly used to define the lower limit of a population. Theoretically, 0.13 percent of the blades will lie below this limit.

REFERENCES

1. Hoffman, Charles A., and Yaker, Charles: Effects of an Aging Treatment on Life of Small Cast Vitallium Gas-Turbine Blades. NACA TN 2052, 1950.

2. Yaker, C., and Hoffman, C. A.: Effects of Some Solution Treatments Followed by an Aging Treatment on the Life of Small Cast Gas-Turbine Blades of a Cobalt-Chromium-Base Alloy. I - Effect of Solution-Treating Temperature. NACA TN 2320, 1951.

3. Anon.: Alloy Castings, Precision Investment, Corrosion and Heat Resistant. AMS 5385, SAE, Sept. 1, 1947.

4. Hoffman, Charles A., and Ault, G. Mervin: Application of Statistical Methods to Study of Gas-Turbine Blade Failures. NACA TN 1603, 1948.

5. Grant, Nicholas J.: The Stress Rupture and Creep Properties of Heat Resistant Gas Turbine Alloys. Trans. A.S.M., vol. 39, 1947, pp. 281-334.

6. Smith, James G., and Duncan, Acheson J.: Sampling Statistics and Applications. McGraw-Hill Book Co., Inc., 1945.

TABLE I - BLADE HEAT TREATMENTS[a]

Group	Soaking treatment		Cooling procedure	Furnace atmosphere
	Temperature (°F)	Time (hr)		
1	2100	1	Air cooled	Inert[b]
2	2100	$1\frac{1}{2}$	Air cooled	Inert[b]
3	2250	1	Air cooled	Inert[b]
4	2250	$1\frac{1}{2}$	Air cooled	Inert[b]
5	2250	1	Furnace cooled to 1800° in $6\frac{1}{2}$ hr, then air cooled to room temperature	Combusted natural gas[c]
6	2250	$1\frac{1}{2}$	Furnace cooled to 1800° in $6\frac{1}{2}$ hr, then air cooled to room temperature	Combusted natural gas[c]

[a] All groups subsequently aged for 72 hr at 1500° F in neutral atmosphere.

[b] Inert atmosphere was either argon or helium depending upon availability.

[c] Adjusted to be neutral or slightly reducing.

TABLE II - DATA FOR HAYNES STELLITE ALLOY 21 BLADES

Time to failure (hr)						
As-cast	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
33.3	47.0	36.3	16.5	16.5	103.6	75.2
56.2	54.9	41.1	24.0	37.2	114.1	76.2
58.6	58.6	45.5	44.6	44.2	123.2	78.5
58.6	60.2	49.0	46.7	44.6	129.8	83.6
58.6	61.7	51.6	47.9	46.1	130.7	86.7
63.0	62.9	53.3	50.8	49.9	131.2	86.7
69.9	66.8	56.9	54.2	59.6	132.3	106.5
72.0	68.8	58.6	69.8	60.4	132.6	107.4
72.0	70.9	60.4	71.6	61.8	135.6	107.4
75.2	74.0	61.7	72.1	68.6	141.5	110.6
77.0	74.4	66.7	73.2	76.2	148.7	114.1
78.5	82.8	66.7	74.4	83.6	150.5	123.2
78.5	83.6	67.4	74.8	86.7	153.6	130.7
83.4	83.6	68.7	75.9	98.7	165.6	133.2
83.6	83.9	68.8	85.4	107.4	169.6	135.6
83.6	92.0	70.3	96.6	128.4	180.6	136.7
89.9	94.6	71.6	104.9	159.4	189.4	140.0
89.9	98.7	78.5	106.5	184.3	190.2	159.4
94.6	123.2	85.4	140.0	195.8	196.8	180.6
112.6	131.2	123.2	181.5	209.6	197.4	181.5
112.6						
114.1						
Number of blades in group						
22	20	20	20	20	20	20
Mean life (hr)						
78.0	78.7	64.1	75.6	91.0	150.8	117.7
Standard deviation (hr)						
19.4	21.0	18.1	37.1	54.9	27.7	31.6
Unbiased estimate of population standard deviation						
19.9	21.5	18.6	38.1	56.3	28.4	32.4
Theoretical index of first failure (hr)						
18.3	14.2	8.3	-38.7	-77.9	65.6	20.5

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TABLE III - SIGNIFICANCE OF OBSERVED EFFECTS OF HEAT TREATMENTS

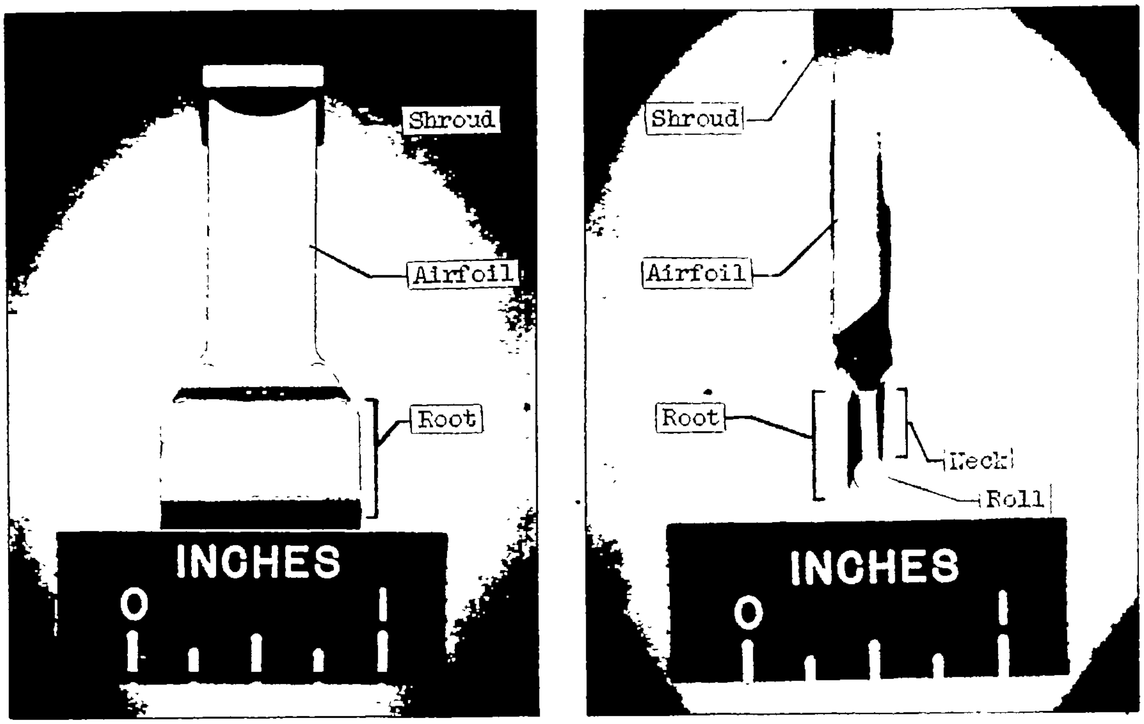
Group	Mean and standard deviation, jointly	Mean life	Standard deviation (uniformity)
1	Unaffected		
2	Unaffected		
3	Affected[a]	Unaffected	Reduced[b]
4	Affected[b]	Unaffected	Reduced[b]
5	Affected[b]	Improved[b]	Unaffected
6	Affected[b]	Improved[b]	Reduced[a]

[a] High degree of assurance that change has taken place, 0.05 level of significance.

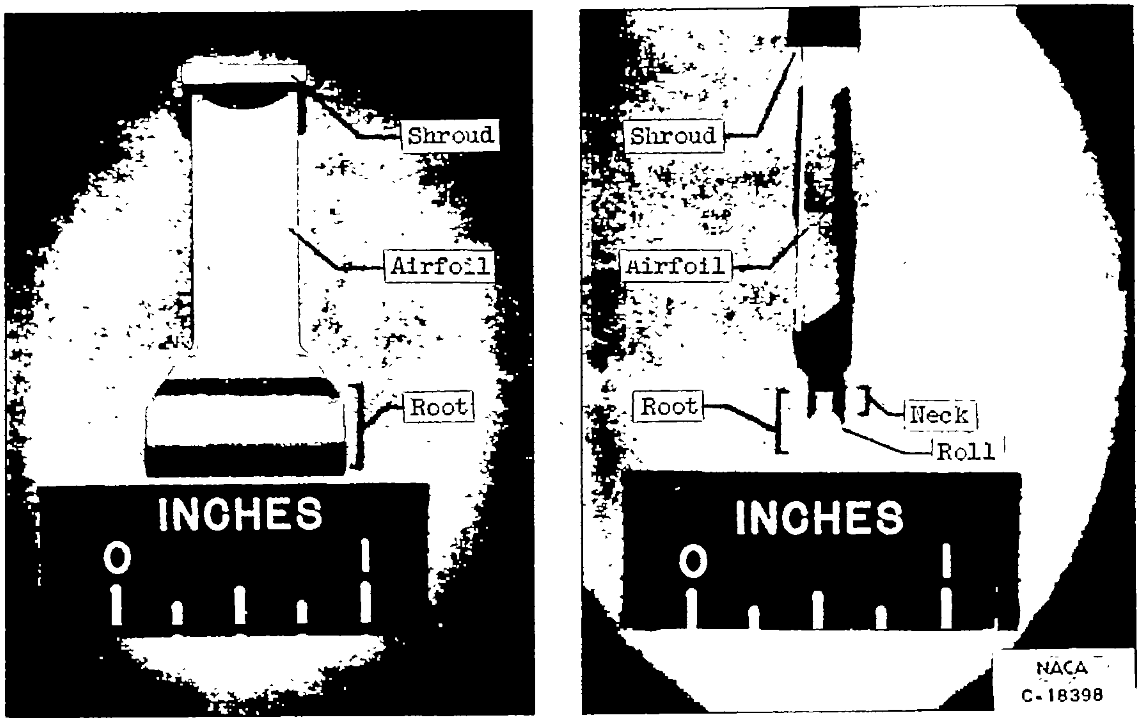
[b] Very high degree of assurance that change has taken place, 0.01 level of significance.

TABLE IV - RELATION OF DEPTH TO CARBON CONTENT FOR SPECIMENS HAVING SAME TREATMENT AS GROUP 6

Depth (in.)	Carbon content (percent)
0.001	0.13
.002	.18
.003	.25
.004	.30
.005	.32

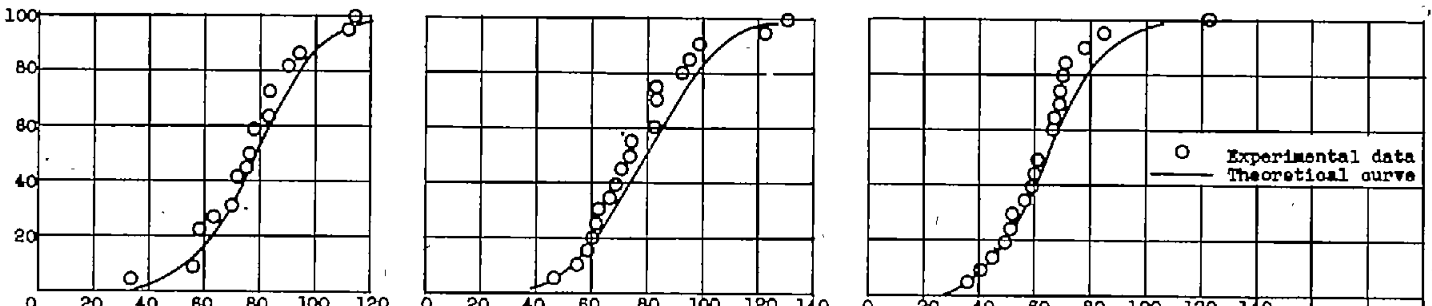


(a) Long-necked type.

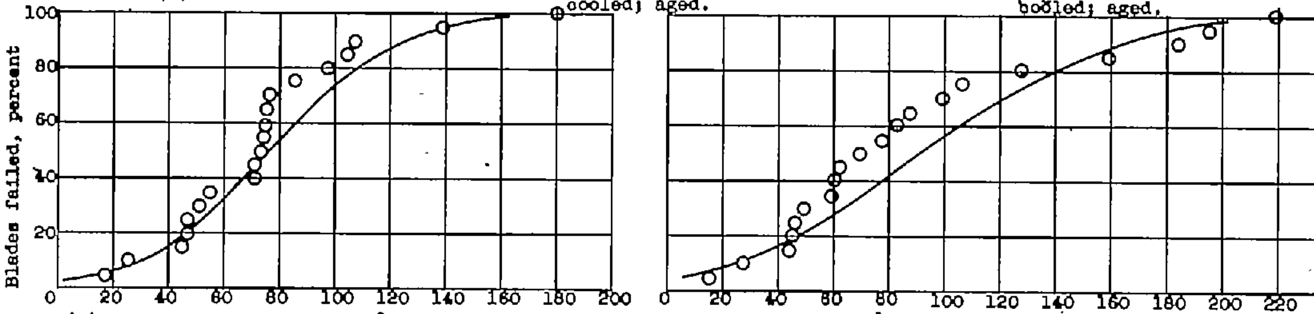


(b) Short-necked type.

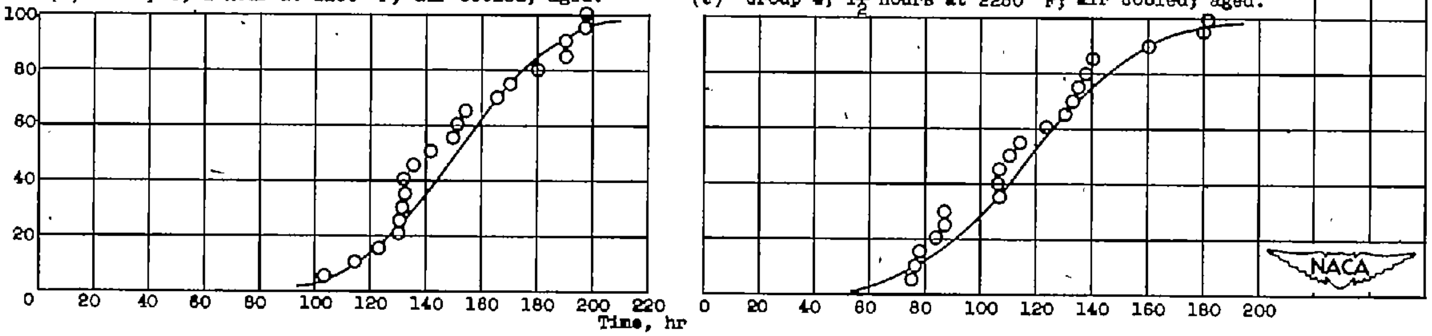
Figure 1. - Typical gas-turbine blades.



(a) As cast.
(b) Group 1; 1 hour at 2100° F; air cooled; aged.
(c) Group 2; $1\frac{1}{2}$ hours at 2100° F; air cooled; aged.



(d) Group 3; 1 hour at 2250° F; air cooled; aged.
(e) Group 4; $1\frac{1}{2}$ hours at 2250° F; air cooled; aged.



(f) Group 5; 1 hour at 2250° F; furnace cooled to 1800° F in $6\frac{1}{2}$ hours; air cooled; aged.
(g) Group 6; $1\frac{1}{2}$ hours at 2250° F; furnace cooled to 1800° F in $6\frac{1}{2}$ hours; air cooled; aged.

Figure 2. - Cumulative-frequency-distribution curves for as-cast and heat-treated blade groups.

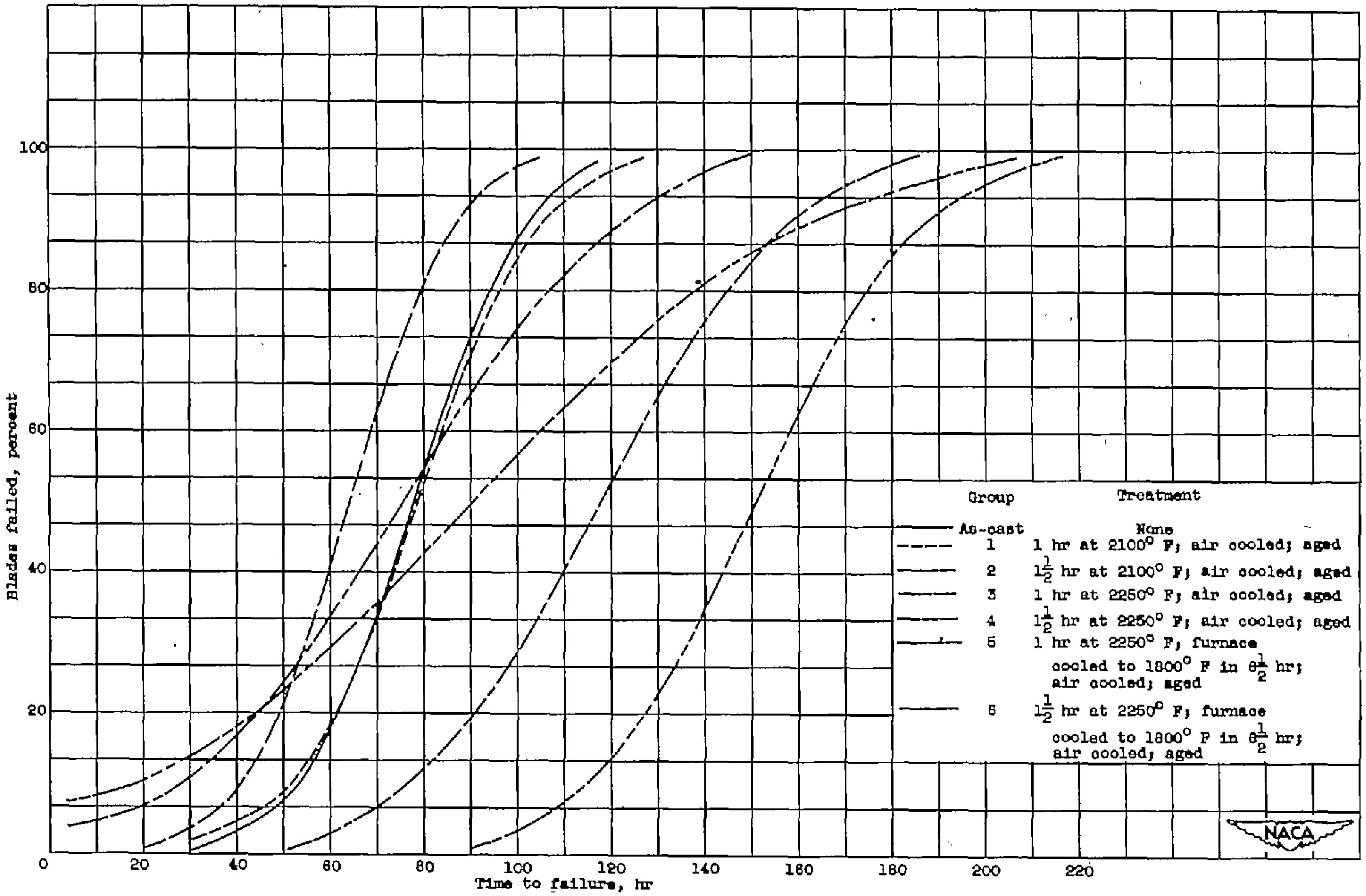
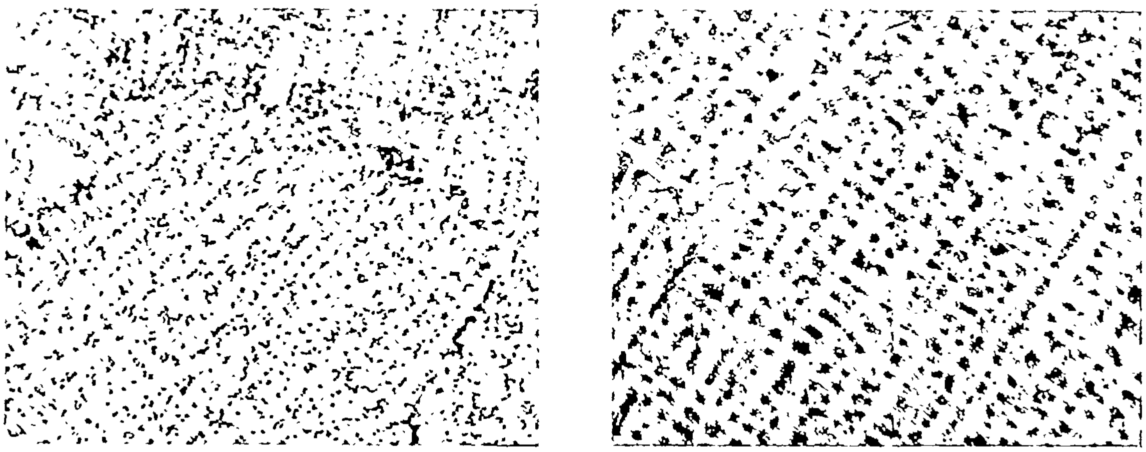
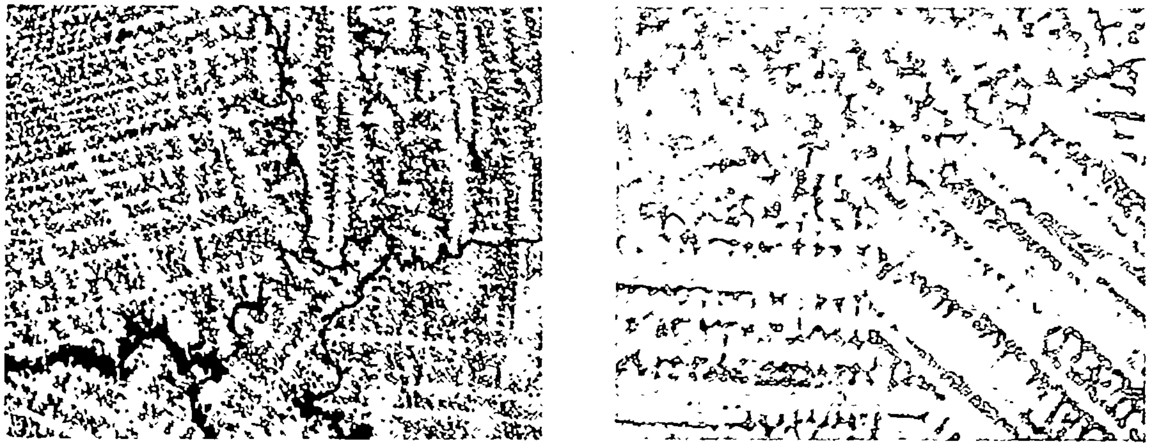


Figure 3. - Theoretical cumulative-frequency-distribution curves for as-cast and heat-treated blade groups.



(a) As cast.

(b) Group 1: 1 hour at 2100° F; air cooled; aged.



(c) Group 2: $1\frac{1}{2}$ hours at 2100° F; air cooled; aged.

(d) Group 3: 1 hour at 2250° F; air cooled; aged.

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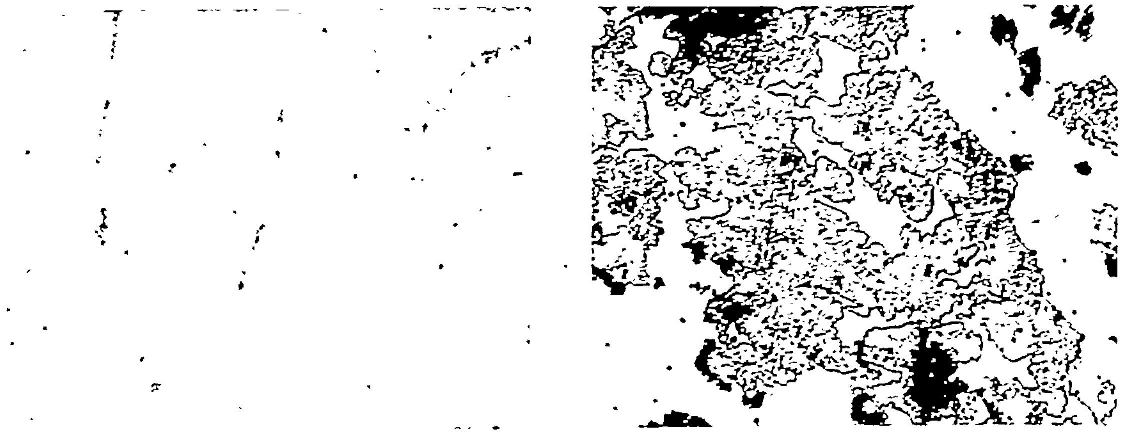
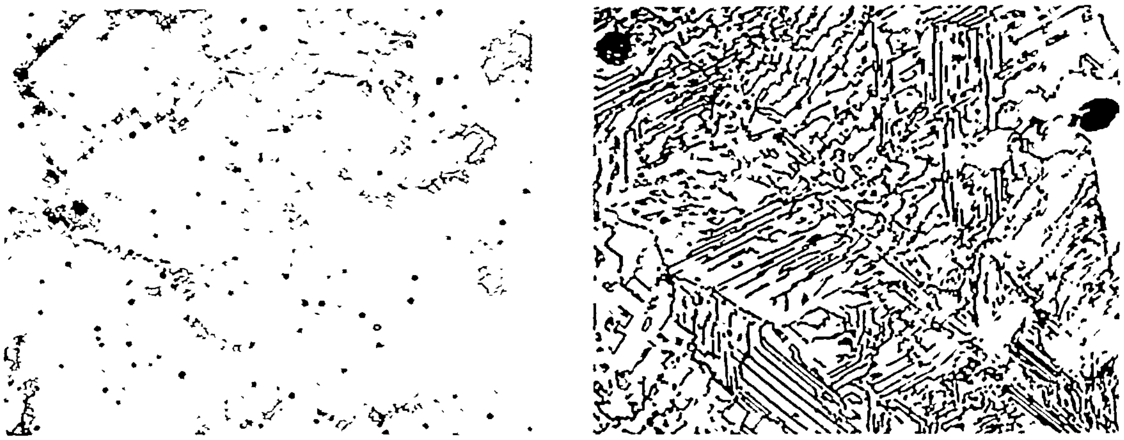
Figure 4. - As-cast and solution-treated and aged blade structures before operation. Etchant, 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. (Photographs at X75 unless otherwise noted.)



(e) Group 4: $1\frac{1}{2}$ hours at 2250° F; air cooled; aged.

(f) Group 5: 1 hour at 2250° F; Furnace cooled to 1800° F in $6\frac{1}{2}$ hours; air cooled; aged.



(g) Group 6: $1\frac{1}{2}$ hours at 2250° F; furnace cooled to 1800° F in $6\frac{1}{2}$ hours; air cooled; aged.

(h) Lamellar structure found in blades of groups 5 and 6 (X750).

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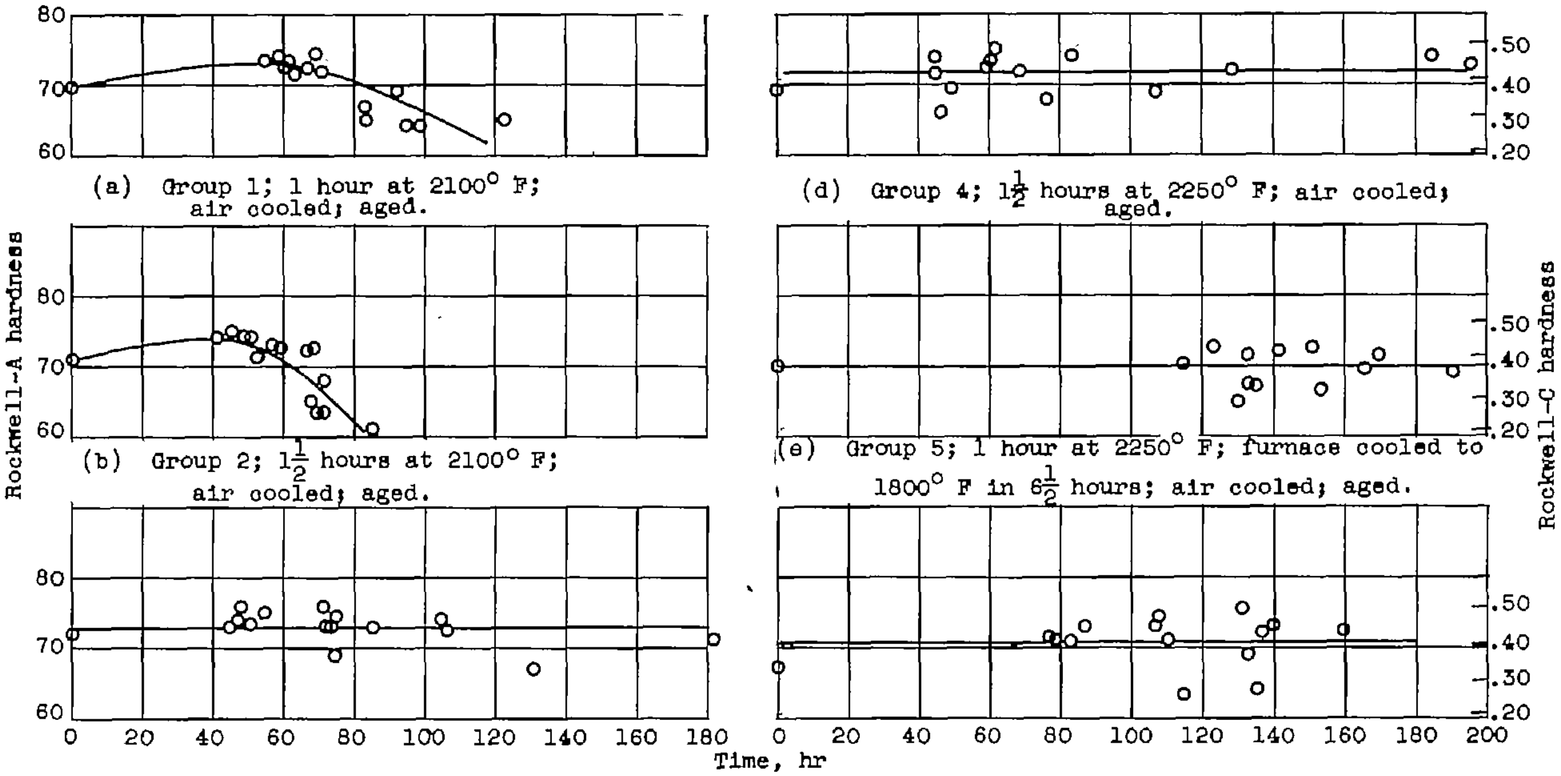
Figure 4. - Concluded. As-cast and solution-treated and aged blade structures before operation. Etchant, 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. (Photographs at X75 unless otherwise noted.)



(a) Group 1; 1 hour at 2100° F; air cooled; aged.

(d) Group 4; $1\frac{1}{2}$ hours at 2250° F; air cooled; aged.

(b) Group 2; $1\frac{1}{2}$ hours at 2100° F; air cooled; aged.

(e) Group 5; 1 hour at 2250° F; furnace cooled to 1800° F in $6\frac{1}{2}$ hours; air cooled; aged.

(c) Group 3; 1 hour at 2250° F; air cooled; aged.

(f) Group 6; $1\frac{1}{2}$ hours at 2250° F; furnace cooled to 1800° F in $6\frac{1}{2}$ hours; air cooled; aged.

Figure 5. - Variation of blade hardness with turbine operating time. Each point represents average of five measurements.

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