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EFFECT OF SOME SELECTED HEAT TREATMENTS ON THE OPERATING LIFE OF CAST HS-21 TURBINE BLADES

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SUMMARY

Turbine blades of cast HS-21 were heat treated in various ways, and the effect on the service life was measured by running the blades to failure in a J33-9 turbojet engine.

The effects of heat treatment were found to depend upon the initial structure of the cast blades. Blades from one manufacturer performed best in the as-cast condition. Those from a second manufacturer showed some differences in microstructure from the first and performed best after aging 48 hours at 1500° F. Solution treatments at 2050° F and above often caused eutectic melting, the severity of which increased with increasing temperature. This in turn damaged the blades so that the possible benefits of heat treatment were lost.

A heat treatment which had increased the average life of small turbosupercharger blades of cast HS-21 by as much as 200 percent reduced the performance of turbine blades from both sources studied in this investigation. This reduced performance was due to differences in the as-cast microstructure. The microstructure of the small turbosupercharger blades was fine and responded well to solution treatment. In contrast, the turbine blades contained large areas of interdendritic segregation. These areas underwent eutectic melting during solution treatment, which lowered the performance of the blades.

Before the full benefits of heat treatment can be realized, better control of casting conditions must be exercised. Where possible, the cooling rates and other casting variables must be controlled to produce uniform structures with finely distributed carbides and a minimum of interdendritic segregation.

INTRODUCTION

Prior studies have been conducted at the NACA Lewis laboratory to determine the effect of heat treatment on the engine operating life of cast HS-21 turbine blades. This work has been done in the type B turbosupercharger (refs. 1 to 3). In the first of these investigations (ref. 1), the operating life was increased from an average of 55.2 hours for the as-cast blades to 63.6 hours for blades which had been aged at 1500° F for 48 hours prior to operation. In the second investigation (ref. 2), the effects of several solution treatments prior to aging were studied. Operating results showed that the mean life of blades could be increased to as much as 87.9 hours. The solution treatments were 1/2 hour at 2100°, 2250°, and 2350° F. These temperatures were high enough to dissolve the carbides present in the as-cast structure into the solid solution matrix of the alloy. The higher the temperature of solution treatment, the more complete was the solution of the carbides. The dissolved carbides were then reprecipitated by subsequent aging at 1500° F. Use of a prior solution treatment resulted in a more uniform dispersion of carbide particles in the microstructure after aging than aging alone. Air cooling from the solution-treating temperatures resulted in longer operating lives than furnace cooling.

The third in this series of studies (ref. 3) showed that the best life of turbosupercharger blades was associated with a lamellar pattern of carbide precipitation resembling pearlite. The mean operating life of the blades containing this structure was nearly double that of the as-cast blades. In addition, the time to the first blade failure was more than tripled. This microstructure was produced by the following treatment: 1 hour at 2250° F, slow furnace cool to 1800° F, air cool to room temperature, and age 72 hours at 1500° F.

These results showed that the operating life of cast blades could be substantially improved by proper heat treatment. Laboratory tests by other investigators (e.g., ref. 4) had also demonstrated the benefits of heat treatment in increasing the high-temperature creep and rupture strengths of cast tensile specimens.

In accordance with these findings, the NACA Lewis laboratory undertook additional research on the fundamental effects of heat treatment on high-temperature alloys and on the improvement in mechanical properties which might be attained by proper heat treatment.

First, 11 different cobalt-base alloys were studied to determine those which could develop lamellar structures by heat treatment and to identify the minor phases present (ref. 5). Second, a fundamental study was made of the relation of stress-rupture life to heat treatment, microstructure, hardness, and ductility (refs. 6 and 7). In reference 7, the work was conducted on wrought HS-21 bar stock in order to reduce scatter from casting inhomogeneities. The highest stress-rupture life was associated with a fine and uniform dispersion of carbide particles in the matrix. This microstructure was obtained by solution treating, air cooling, and double aging. The first aging was conducted at a low temperature and produced a fine scattering of nucleation sites. These provided a base for subsequent growth of visible precipitate during the second aging at a higher temperature. In addition, the presence of lamellar pearlite was found to decrease the stress-rupture life and to increase the ductility of the alloy. The changes in these properties varied with the relative amounts of pearlite and scattered precipitate. A heavy, Widmanstätten type of carbide precipitation was associated with both poor stress-rupture life and low ductility.

This study also showed that solution treatment is necessary to develop the highest stress-rupture strength in wrought HS-21. Solution treatment distributes the carbon and carbide-forming elements throughout the solid-solution matrix. In this form they can be reacted at a lower temperature to precipitate in a manner which can be controlled by the conditions of aging or isothermal transformation. The final precipitate can thus be obtained in a uniformly dispersed structure or in various lamellar forms, as desired.

With some materials, the particles present in the matrix before heat treatment may not be in their most stable form. This is true for nonequilibrium carbides, such as Cr_3C_2 and Cr_7C_3, which are found in some of the cast alloys. Holding these alloys at temperatures of 1200° F or higher allows these carbides to react with additional carbide-forming elements to form other carbides which are more stable and have lower carbon-to-metal ratios (e.g., $Cr_{23}C_6$). Lane and Grant (ref. 8) have described this as an alternate form of aging in which prior solution treatment is not needed. A limitation on this type of aging is that the precipitates formed during aging are clustered about the original, interdendritic carbides or other particles of the cast structure. For this reason, aging alone does not give as fine and uniformly dispersed distribution of precipitates as when the aging is preceded by solution treatment. Also, this type of aging appears to be restricted to cast alloys. It could not be used with wrought alloys in which the precipitants have already reacted to their stable forms during rolling and forging.

The present investigation was conducted to determine whether the knowledge of heat treatment gained from experience with cast turbosupercharger blades and from studies of heat-treated wrought alloy could be used to improve the operating life of large cast turbojet blades. The specific purposes of this investigation were:

(1) To determine the effects of a series of selected heat treatments on the mean operating life, uniformity of blade performance, and the time to first failure of cast turbine blades of HS-21.

(2) To correlate the engine operating data and heat treatments with the observed microstructural behavior.

MATERIALS, APPARATUS, AND PROCEDURE

Turbine blades. - Cast J33-9 turbojet blades of HS-21 alloy having the following nominal percentage chemical composition were used:

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C	Cr	Ni	Co	Mo	Fe	Mn
0.20-0.35	25-29	1.75-3.75	Bal.	5-6	2.00 max	1.00 max

The blades were obtained from two sources, denoted A and B. Three turbine wheels containing heat-treated blades were run. Only blades from source A were used in the first and second wheels, while blades from both sources were used in the third wheel.

Heat treatments. - The heat treatments studied are listed in figure 1. As-cast blade groups (groups 1 to 4) were included in the three wheels as standards for comparison. This was done so that slight differences in wheel operating characteristics, which might exist despite the careful control of blade temperatures and stresses, could be taken into account in making comparisons.

Blades given only a 48-hour age at 1500° F were included in the first and third wheels (groups 5 and 6). This is a conventional aging treatment used for cast HS-21. A number of groups of blades were run in which this aging treatment was preceded by several solution treatments followed by air cooling (1/2 hr at 2150° F, 24 hr at 2050° F, 1/2 hr at 2250° F, and 24 hr at 2250° F, groups 7 to 10, respectively). These tests showed whether or not solution treatment can improve the operating life of the cast blades when followed by the conventional aging treatment.

Other groups of blades were run in which the temperature of aging was lowered to 1200° F (groups 11 to 14). In these groups, the aging treatment was preceded by solution treatments varying from 4 hours at 2050° F to 24 hours at 2175° F. The aging temperature of 1200° F was studied because prior work on wrought HS-21 had indicated that a higher stress-rupture life was obtained by aging at 1200° F after solution treatment than by aging at 1500° F after solution treatment (ref. 7).

Aging treatments at 1950° F were also studied (groups 15 to 20). The variations included aging alone and solution treatment followed by aging. These treatments gave structures with high ductility. Note that several groups of these blades were soaked at 2000° F prior to solution treatment. This was done to homogenize the structure and minimize eutectic melting during solution treatment.

Double-aging treatments were tried (groups 21 to 23), since earlier work had shown this type of treatment to produce highest stress-rupture life in wrought HS-21 (ref. 7). The solution treatment was increased to 72 hours at 2250° F in group 23 to see if a very prolonged solution treatment would recover properties lost by shorter solution treatments.

The remaining groups of blades (groups 24 and 25) were solution treated 1 hour at 2250° F, furnace cooled to an aging temperature of 1800° F, and then re-aged for 72 hours at 1500° F. This treatment is the one that gave best results with type B turbosupercharger blades (ref. 3).

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Engine operation. - The blades were installed in a J33-9 turbojet engine and operated under simulated service conditions. The operating cycle consisted of 20 minutes; 15 minutes were at full rated power and 5 minutes were at idle, acceleration, and deceleration. Under full-power conditions, the stress and temperature in the blade in the zone of fracture (approximately 2 in. above the base) were 21,000 psi and 1500° F, respectively.

Cycling was continued 8 hours per day until a blade fractured. After each blade failure, the remaining blades were examined. Those which were cracked or otherwise damaged were removed. Replacement blades were cast HS-21 blades from Air Force stock. Further details on engine operation and instrumentation may be found in earlier NACA reports (refs. 9 to 12).

Metallographic studies. - Metallographic examinations were made on blades after heat treatment and after failure in the engine. These studies showed the microstructural changes due to heat treatment and to operation in the engine. Surface corrosion and paths of fracture in the failed blades were also examined.

RESULTS

Engine Operation

The cumulative engine time at rated power at which blade failures occurred is shown in figures 1 to 9. Individual failures are represented by points, and the scatter is shown by the length of the bands.

As-cast blades (fig. 2). - Blades from source A tested in the as-cast condition in the second and third wheels (groups 2 and 3) showed an increase of about 22 percent in mean life over the same blades run in the first wheel (group 1). Statistical analysis shows that there were minor changes in operating conditions between the time of the first wheel and the second and third wheels at the 80 percent confidence level. This is less than what is ordinarily considered significant, and the three wheels can be said to have operated almost identically.

As-cast blades from source B tested in the third wheel (group 4) performed better than blades from source A run in the same condition and in the same wheel (group 3). Running of the third wheel was stopped after 91.0 hours, at which time none of the as-cast blades from source B had failed. The mean life of these blades would therefore be at least 91.0 hours. This is 17.7 hours, or 24 percent, better than the mean life of the as-cast blades from source A run in the same wheel.

Aging alone (fig. 3). - Aging 48 hours at 1500° F (group 5) increased the mean life of blades from source A by about 80 percent over the as-cast condition (group 1). It also improved the time to first failure but increased the scatter in performance. Blades from source B given this same aging treatment (group 6) had a lower operating life than as-cast blades from this source (group 4). 3591

Solution treatment and aging (figs. 4 to 7). - In general, solution treatments before aging did not improve blade performance. The results are grouped in this section about common aging treatments to show changes due to different solution treatments.

The effect of various solution treatments followed by aging 48 hours at 1500° F is shown in figure 4. Solution treating for 1/2 hour at 2150° F followed by this aging (group 7) increased the mean life about 70 percent over that of the as-cast blades run in the first wheel. The time to first failure was practically unchanged and the over-all scatter was increased. While the improvement in mean life was less than that obtained by aging alone (group 5), the last blades to fail in group 7 ran for encouragingly long times. The use of solution treatment would be justified if the early failures were eliminated. Examination revealed eutectic melting in several of the blades of group 7 which might have caused the early failures.

In the second wheel, therefore, a group of blades was run in which the solution-treating temperature was dropped to 2050° F (group 8) to reduce the tendency toward eutectic melting. The time at 2050° F was increased to 24 hours in an effort to obtain the same amount of solution treatment, and aging was again 48 hours at 1500° F. This group of blades had a mean life only 25 percent better than the as-cast blades run in the same wheel (group 2). The scatter was reduced from that obtained with the 1/2-hour solution treatment at 2150° F (group 7), and there was a slight improvement in the time to first failure. However, the increase in mean life was well below that obtained in group 7, and the over-all improvement was less than that obtained by aging alone (group 5).

In group 9 of the third wheel, the solution-treating time was again 1/2 hour and the temperature was raised to 2250° F. This was followed by the same aging treatment of 48 hours at 1500° F. The mean life of the blades of this group dropped to only a small fraction of that of the as-cast blades. Increasing the time of solution treatment to 24 hours at 2250° F, however, followed again by aging 48 hours at 1500° F (group 10), recovered the mean life lost by the 1/2-hour solution treatment. The performance of the blades of group 10 was about the same as that of the as-cast blades (group 3), but well below that of the blades aged alone (group 5). In neither of these cases was solution treatment at 2250° F beneficial, while in the one case it was very damaging.

The effect of various solution treatments followed by aging 48 hours at 1200° F is shown in figure 5. These treatments (groups 11 to 14) did not improve the performance as expected from the study of stress-rupture life on wrought material (ref. 7). Of the various solution treatments used before aging at 1200° F, only 24 hours at 2050° F (group 12) gave a better mean life than that of the as-cast blades (group 2). This improvement was only slight and less than could be obtained by other heat treatments.

Aging temperatures of 1200° and 1500° F did not give much difference in the results, as can be seen by comparing groups 8 and 12 in figure 6. In both of these groups, solution treatment was 24 hours at 2050° F before aging for 48 hours at 1500° and 1200° F. For other solution treatments, aging at 1200° F might have produced differences.

All blades aged or transformed at 1950° F performed poorer than the as-cast blades, as shown in figure 7. This was true whether the blades were aged alone (group 15) or were solution treated and aged (group 16). Furnace cooling and aging at 1950° F following solution treatment was also unsuccessful (groups 17 to 19). Aging at 1500° F after furnace cooling and aging at 1950° F (group 20) recovered some of the strength, but the performance was still poorer than that of the as-cast blades.

Double aging (fig. 8). - Double-aging treatments, in which blades were solution treated and aged 24 hours at 1200° F plus 48 hours at 1500° F (groups 21 to 23) failed to increase blade life. None of the groups showed a significant improvement in performance over that of the as-cast condition. Note that double aging after 1/2 hour at 2250° F (group 21) greatly increased the performance over that of the same solution treatment followed by a single age at 1500° F (group 9). The long-time solution treatment used in group 23 gave the poorest results of the double-aged groups.

Treatment of reference 3 (fig. 9). - The heat treatment which was most successful in improving blade performance in the type B turbosupercharger (ref. 3) did not improve the life of the J33 jet engine turbine blades of cast HS-21. Blades given this heat treatment (groups 24 and 25) were poorer than the as-cast blades.

In reviewing the engine results, the occurrence of eutectic melting should be considered. Instances of eutectic melting were observed whenever the solution-treating temperature was above 2050° F. Some aging treatments, particularly the double-aging treatments, owe their effectiveness to a high degree of solution treatment. However, the damaging effects of eutectic melting which generally accompanied a high degree of solution treatment could more than offset the benefits gained from aging.

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Metallurgical Studies of As-Cast and Heat-Treated Blades

As-cast structure. - Photomicrographs of cast blades from both sources are presented in figures 10 and 11. Dendritic segregation, typical of cast materials, was present in all the blades. Carbides were precipitated both as small, irregular islands and as a lamellar formation resembling pearlite. The carbide islands were generally distributed through the interior of the grains, where both their size and the distance between them tended to increase as the section size increased (e.g., in going from the trailing tip at the top of the blade to the midchord at the base). Pearlite, when present, was generally located in small patches along grain boundaries. Occassionally, areas in blades from both sources were observed which had an especially heavy concentration of pearlite precipitate, such as shown in figure 11(c). While there were noticeable variations in the microstructure of the as-cast blades from the same source, there was also a general tendency of the blades from source B to contain more pearlite than those from source A. The interdendritic eutectic areas also appeared larger in the blades from source B. The grain size of all blades was predominately macroscopic, considerably larger than A.S.T.M. 1.

Solution treating. - The degree of solution treatment obtained by holding the cast blades at temperatures of 2050° F and above is shown in figures 12 and 13. Four hours at 2050° F was found to be insufficient to dissolve all the carbides into the matrix (figs. 12(a) and 13(a)). Increasing the time and temperature to 24 hours and 2175° F, respectively (figs. 12(b) and 13(b)), dissolves more of the carbides, particularly with blades from source A. However, it also results in an increase in the number and severity of the partial voids which probably are due to eutectic melting. These voids occur in areas formerly occupied by interdendritic carbides. After 24 hours at 2250° F, solution of the carbides is complete, but the occurrence of eutectic melting is especially severe, particularly in blades from source B (fig. 13(c)). There was also some grain boundary melting in this case.

Solution treatment generally resulted in a recrystallized skin of small grains at the leading and trailing edges of the blades. An example of this in blades before operation is shown in figure 14. A decrease in the amount of carbide precipitation at the surface was noted in several cases.

Aging and effects of prior solution treatments on aged structures. - Aging the cast blades at 1500° F resulted in the formation of fine particles of precipitate clustered about the primary carbides. This is shown in figure 15(a), for which the aging time was 48 hours. Different solution treatments followed by this same aging treatment gave the microstructures shown in figures 15(b) to (e). In general, increasing the time or temperature of solution treatment gave a wider distribution of carbide precipitation during aging at 1500° F. Figure 16 shows the microstructure after solution treatment and aging at 1200° F. Except for small patches of pearlite that are sometimes observed along the grain boundaries, aging at 1200° F has produced no apparent change in the solution-treated structure.

The microstructures after double aging, using a 24-hour age at 1200° F between solution treating and aging at 1500° F, are shown in figure 17 for three conditions of solution treatment. One-half hour at 2250° F (fig. 17(b)) gave a wider distribution of precipitation during aging than 1 hour at 2150° F (fig. 17(a)), while 72 hours at 2250° F gave a heavy Widmanstätten type of precipitate (fig. 17(c)).

An aging temperature of 1950° F was too high to cause significant precipitation, whether used as a straight aging treatment or preceded by solution treatment. In the first case (fig. 18), aging at 1950° F dissolved some of the as-cast carbides, particularly in the grain boundaries. There was also a general tendency to spheroidize the carbide particles.

Effect of furnace cooling. - Microstructures produced in turbine blades which had been furnace cooled after solution treatment and then aged are shown in figures 19 and 20. Figure 19 (group 24) shows the microstructure for the heat treatment which gave the best operating life for type B supercharger blades (ref. 3). Carbide precipitation after this type of treatment was almost entirely in a lamellar form resembling pearlite. Blades in group 25 had an identical microstructure to these. (N.B. - Actually, both groups 24 and 25 were intended to have the same heat treatment, but, due to experimental difficulties, the furnace cooled from 2250° to 1800° F in $2\frac{1}{2}$ hr with group 25 rather than $6\frac{1}{2}$ hr, as desired. To compensate for this, the blades in group 25 were held in the furnace at 1800° F for an additional 4 hr before air cooling.)

Blades that had been furnace cooled to 1950° F after solution treating 24 hours at 2050° or 2175° F and then aged 2 hours at 1950° F (groups 17 and 18) had an essentially solution-treated structure, as shown in figure 20. Increasing the time at 1950° F to 24 hours (group 19) resulted in a small amount of pearlitic precipitation. Adding a second aging treatment at 1500° F after furnace cooling and aging at 1950° F (group 20) increased the amounts of pearlite and general precipitation.

Metallurgical Studies of Failed Blades

Aging during engine operation. - Extensive aging during operation in the turbine wheel occurred in the case of as-cast blades (groups 1 and 4). The scattered precipitate which formed about the primary carbides during engine operation is shown in figure 21. This figure should be compared with figures 10 and 11, which show the structure of the as-cast blades before operation. The amount of the scattered precipitate increased with the time of operation. Pearlitic precipitation at grain boundaries which was present before operation is also shown in figure 21. The structure of the as-cast blades after operation is similar to that produced by aging alone at 1500° F (groups 5 and 6, fig. 15(a)). Precipitation during engine operation was less for blades which had been aged 48 hours at 1500° F prior to operation (groups 5 and 6, fig. 15(a); group 7, fig. 15(b)). This was true whether the aging was done on the cast blades (fig. 22) or was preceded by solution treatment (figs. 23 and 24).

Blades that had been solution treated did not undergo any appreciable changes in microstructure during aging at 1200° F. These blades showed essentially solution-treated structures corresponding to the degree of solution treatment given them. Precipitation did occur under the operating conditions, but not as rapidly as might have been expected. The early failures in such groups of blades frequently showed little precipitation, even after 9.1 hours of operation as shown in figure 25(a) (first failure in group 11). Continued operation increased the precipitation, as shown in the last blade failure of this group (fig. 25(b)). The effect of increasing the time and temperature of solution treatment is seen by comparing figures 25(b), 26, and 27. All these blades were aged at 1200° F after solution treatment, and all were operated in the engine for comparable times. The greater the amount of solution treatment, the more widely distributed is the precipitation which occurs during engine operation. The dark spots in these photomicrographs are areas in which eutectic melting occurred. Melting of this nature may have decreased the operating life from that which might have otherwise been obtained.

Blade-failure mechanisms. - The majority of blades appeared to fail by a stress-rupture mechanism. Many blades were removed because of a large number of stress-rupture cracks in the airfoil, usually in a zone from $1\frac{1}{2}$ to $2\frac{1}{2}$ inches above the base. Figures 28 and 29 show the fractured edge of several blades which failed in a typical, jagged manner through the grain boundaries. Figure 30 shows a crack in a section just below a fracture edge. Eutectic melting along grain boundaries might contribute to these cracks when high solution-treating temperatures were used. Only a small number of blades had some of the characteristics of fatigue failures.

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DISCUSSION

One of the advantages suggested for heat treatment is that it can reduce variability in properties from blade to blade due to differences in casting conditions. Heat treatment, it is proposed, can produce a set of blades with uniform strength and operating characteristics.

Casting variables include the pouring temperature, pouring rate, mold temperature, and the time spent in the molds. These factors influence grain size and microstructure and, consequently, the high-temperature creep and rupture strength (refs. 13 and 14).

In the production blades used in the present investigation, the control over the casting conditions was limited to that employed in commercial practice. Thus, variations in the microstructure of corresponding sections taken from different blades were found to occur. Also, the microstructure of a single blade varied with the location in the blade, being influenced by the relative rates of cooling of different blade sections due to differences in size and position. These variations were mainly differences in the amount, size, and distribution of the carbide precipitates. These carbides were present either as separate islands occurring interdendritically in the matrix or as a pearlite type of precipitation along grain boundaries. The major difference between the microstructures of blades from sources A and B was the occurrence of a greater amount of pearlitic precipitation and larger interdendritic areas in the blades from source B.

The most important finding of this investigation is that the response to heat treatment of cast turbine blades of HS-21 is particularly sensitive to the original condition of the blades. Heat treatment increased rather than reduced the variability in properties. A particular heat treatment can improve one lot of blades and damage another. This is shown by comparing the improved performance obtained by aging blades from source A for 48 hours at 1500° F with the reduced performance of blades from source B given the same treatment (fig. 3). In some instances, an improvement in the mean life of a set of heat-treated blades is offset by an increase in the variability; compare, for example, the results of groups 1 and 7. These results do not agree with the proposition that heat treatment will reduce variations in properties of cast blades. This variability can apparently only be reduced by careful control of the casting variables.

Solution treatment is a fundamentally sound method of increasing strength by improving the precipitation pattern. However, its use on cast HS-21 turbine blades is restricted by eutectic melting occurring at high solution temperatures in areas of dendritic segregation. This melting reduces the operating life of the blades. A limited solution treatment prior to aging and operation has markedly extended the life of the final blade failure in at least one group (group 7). Such behavior offers some encouragement for the use of solution treatment, provided that the early failures can be eliminated.

The heat treatment given groups 24 and 25, which had increased the life of small cast turbosupercharger blades by as much as 200 percent, (ref. 3) reduced the performance of the large turbine blades used in this investigation. This was due to differences in the carbide formations in the two sizes of parts. The interdendritic carbides in the small as-cast blades were in the form of partially spheroidized structures (fig. 31). Because of the fineness of these structures and lack of large interdendritic pools of eutectics, relatively little difficulty in solution treating would be expected. Voids or rosettes resulting from melting were found in the smaller blades, but they were much smaller than those found in the large blades of the present investigation. Also, the structure of the small blades after heat treatment contained a finer and more uniform dispersion of carbides than did the large blades given the same treatment (see fig. 32). Thus, if the structures of the blades in this investigation had been controlled to prevent the formation of large eutectic pools and interdendritic carbides, many of the heat treatments might have substantially improved the engine performance.

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SUMMARY OF RESULTS

An investigation has been conducted to determine the effects of selected heat treatments on the performance of turbojet blades of cast HS-21. The results of this study are as follows:

1. The effects of heat treatment depend upon the initial structure of the cast blades. Before the full benefits of heat treatment can be realized, better control of casting conditions must be exercised. Where possible, the cooling rates and other casting variables must be controlled to produce uniform structures with finely distributed carbides and a minimum of interdendritic segregation.

2. Turbine blades from one manufacturer performed best in the as-cast condition, while blades from the other manufacturer performed best after aging 48 hours at 1500° F.

3. The heat treatment that increased the mean operating life of small turbosupercharger blades by as much as 200 percent reduced the performance of turbine blades from both sources studied in this investigation. This was because of differences in the as-cast microstructure. The microstructure of the small turbosupercharger blades was fine and responded well to solution treatment, whereas, that of the turbine blades contained large areas of interdendritic segregation which underwent eutectic melting during solution treatment and lowered their performance in the engine.

4. The lot of turbine blades which performed best after aging was also improved, relative to the as-cast condition, by several heat treatments which included solution treating before aging. The improvements, however, were less than that obtained by aging alone. In some cases, possible benefits were lost by varying degrees of eutectic melting during solution treatment.

5. High solution-treating temperatures should be avoided. Solution treatment above 2050° F caused eutectic melting, the severity of which increased with increasing temperature.

Lewis Flight Propulsion Laboratory
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Group	Number of blades	Blade source	Wheel number	Heat treatment						Mean life, hr
				Solution treatment			Aging treatment			
				Time, hr	Temperature, °F	Cooling	Time, hr	Temperature, °F	Cooling	
1	11	A	1	None			None (as-cast)			58.3
2	4	A	2	None			None (as-cast)			68.8
3	2	A	3	None			None (as-cast)			73.3
4	3	B	3	None			None (as-cast)			>91.0
5	6	A	1	None			48	1500	Air cooled	106.0
6	5	B	3	None			48	1500	Air cooled	57.4
7	6	A	1	1/2	2150	Air cooled	48	1500	Air cooled	99.8
8	6	A	2	24	2050	Air cooled	48	1500	Air cooled	86.0
9	5	A	3	1/2	2250	Air cooled	48	1500	Air cooled	8.2
10	3	A	3	24	2250	Air cooled	48	1500	Air cooled	>79.2
11	6	A	2	4	2050	Air cooled	48	1200	Air cooled	46.4
12	6	A	2	24	2050	Air cooled	48	1200	Air cooled	82.6
13	6	A	2	24	2100	Air cooled	48	1200	Air cooled	20.5
14	6	A	2	24	2175	Air cooled	48	1200	Air cooled	37.2
15	6	A	2	None			72	1950	Air cooled	33.8
16	4	A	1	6 15	2000 plus 2250	Air cooled	72	1950	Air cooled	21.7
17	6	A	2	24	2050	Furnace cooled to 1950° F	2	1950	Air cooled	42.9
18	6	A	2	24	2175	Furnace cooled to 1950° F	2	1950	Air cooled	39.7
19	6	A	1	6 15	2000 plus 2250	Furnace cooled to 1950° F	24	1950	Air cooled	49.5
20	6	A	1	6 15	2000 plus 2250	Furnace cooled to 1950° F	24 48	1950 plus 1500	Air cooled Air cooled	51.9
21	5	A	3	1/2	2250	Air cooled	24 48	1200 plus 1500	Air cooled	>70.3
22	5	B	3	1	2150	Air cooled	24 48	1200 plus 1500	Air cooled	>55.8
23	4	B	3	72	2250	Air cooled	24 48	1200 plus 1500	Air cooled	14.6
24	4	A	3	1	2250	Furnace cooled ($6\frac{1}{2}$ hr) to 1800° F, air cooled	72	1500	Air cooled	53.2
25	5	B	3	1	2250	Furnace cooled ($2\frac{1}{2}$ hr) to 1800° F	4 72	1800 plus 1500	Air cooled Air cooled	17.1

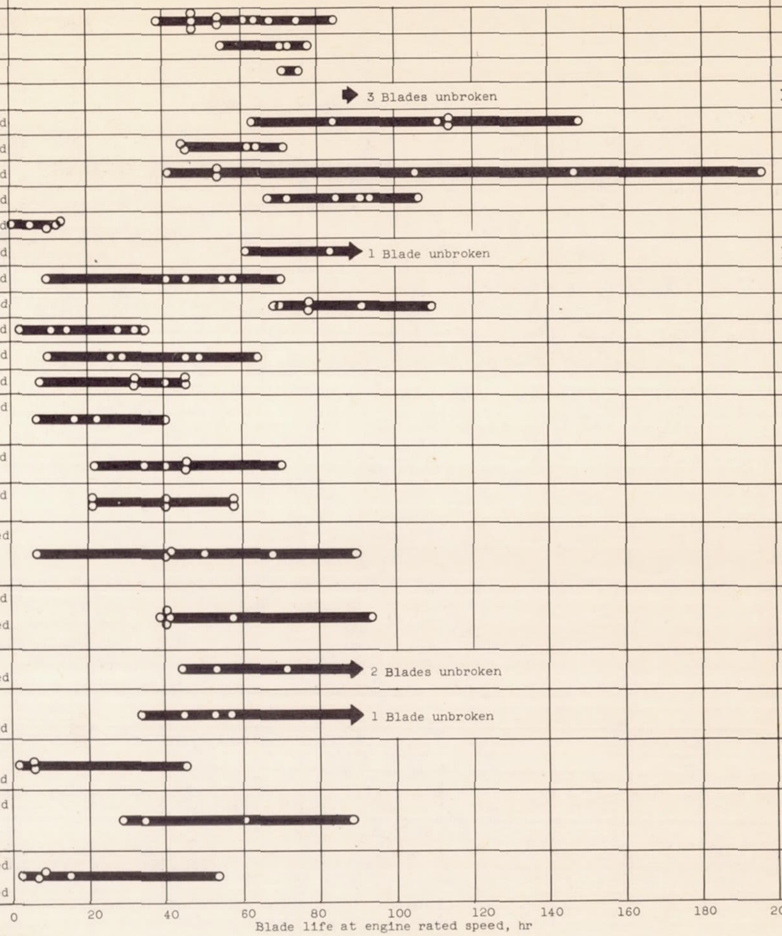


Figure 1. - Blade heat treatments and engine results.

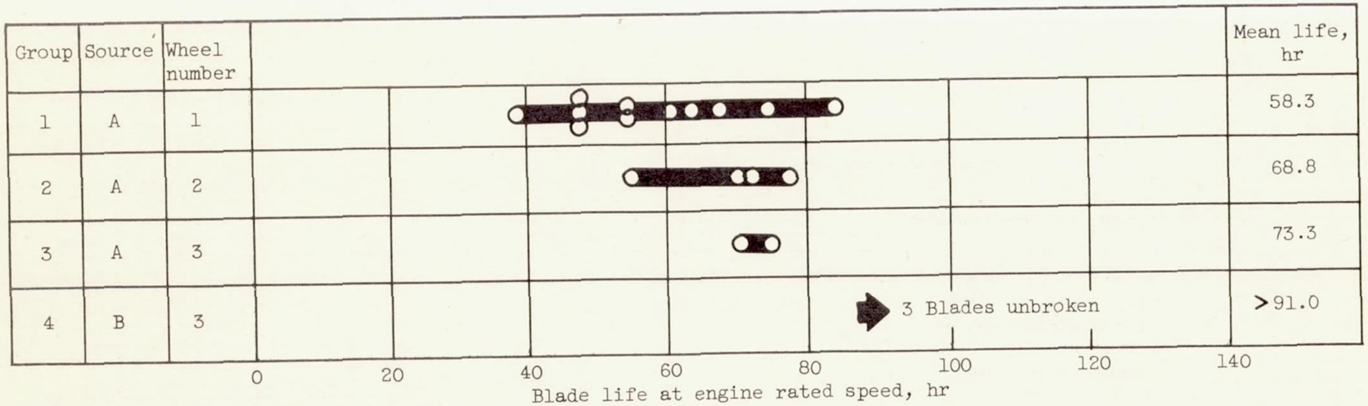


Figure 2. - Comparison of blade lives run in as-cast condition in several wheels.

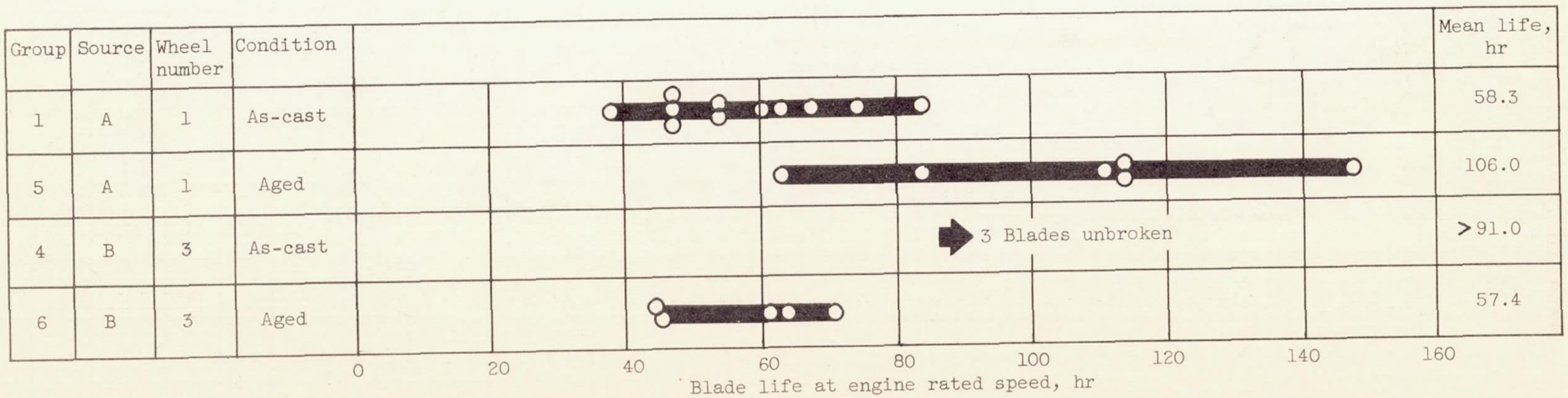


Figure 3. - Effect of aging 48 hours at 1500° F on life of as-cast blades.

Group	Source	Wheel number	Solution treatment	Aging treatment	Mean life, hr
1	A	1	None	None (as-cast)	58.3
5	A	1	None	48 Hr at 1500° F	106.0
7	A	1	$\frac{1}{2}$ Hr at 2150° F	48 Hr at 1500° F	99.8
2	A	2	None	None (as-cast)	68.8
8	A	2	24 Hr at 2050° F	48 Hr at 1500° F	86.0
3	A	3	None	None (as-cast)	73.3
9	A	3	$\frac{1}{2}$ Hr at 2250° F	48 Hr at 1500° F	8.2
10	A	3	24 Hr at 2250° F	48 Hr at 1500° F	>79.2

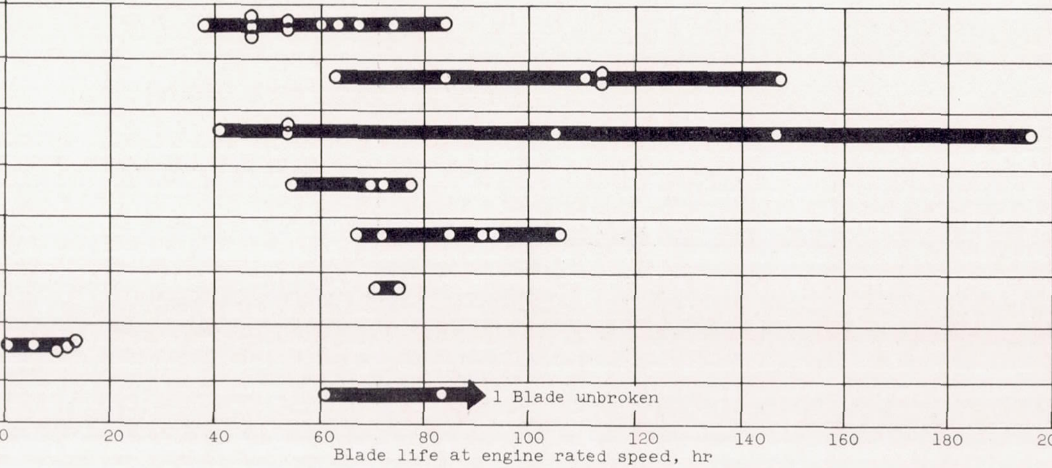


Figure 4. - Effect of various solution treatments before aging 48 hours at 1500° F.

Group	Source	Wheel number	Solution treatment	Aging treatment	Mean life, hr
2	A	2	None	None (as-cast)	68.8
11	A	2	4 Hr at 2050° F	48 Hr at 1200° F	46.4
12	A	2	24 Hr at 2050° F	48 Hr at 1200° F	82.6
13	A	2	24 Hr at 2175° F	48 Hr at 1200° F	20.5
14	A	2	24 Hr at 2250° F	48 Hr at 1200° F	37.2

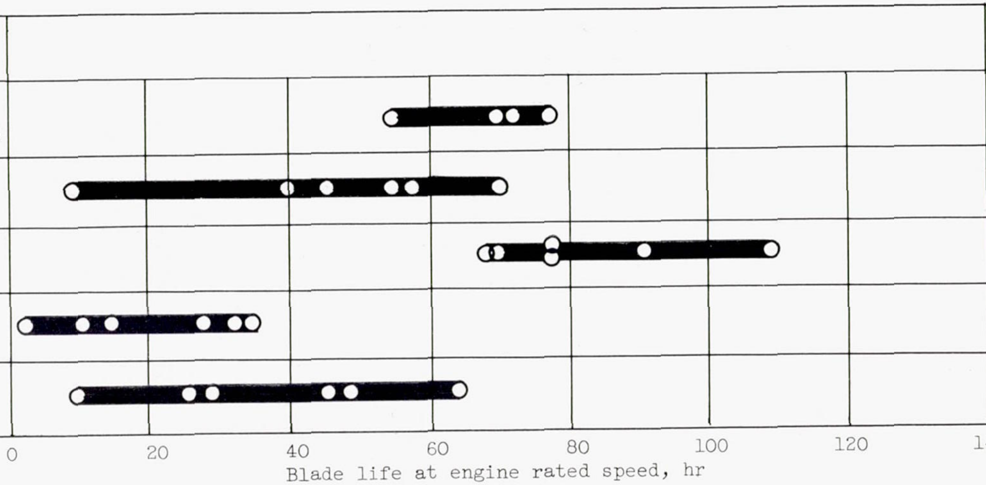


Figure 5. - Effect of various solution treatments before aging 48 hours at 1200° F.

Group	Source	Wheel number	Solution treatment	Aging treatment	Mean life, hr
2	A	2	None	None (as-cast)	68.8
8	A	2	24 Hr at 2050° F	48 Hr at 1500° F	86.0
12	A	2	24 Hr at 2050° F	48 Hr at 1200° F	82.6

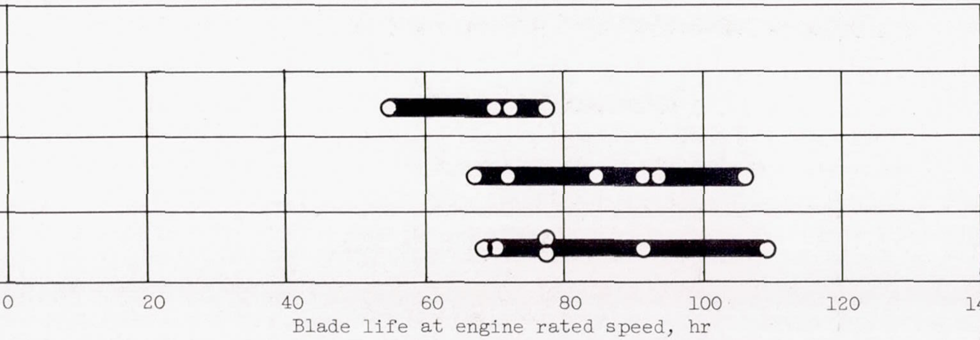


Figure 6. - Comparison of aging at 1500° and 1200° F after solution treatment.

Group	Source	Wheel number	Solution treatment	Aging treatment	Mean life, hr
1	A	1	None	None (as-cast)	58.3
2	A	2	None	None (as-cast)	68.8
15	A	2	None	72 Hr at 1950° F	33.8
16	A	1	6 Hr at 2000° F 15 Hr at 2250° F Air cooled to room temp.	72 Hr at 1950° F	21.7
17	A	2	24 Hr at 2050° F Furnace cooled to 1950° F	2 Hr at 1950° F	42.9
18	A	2	24 Hr at 2175° F Furnace cooled to 1950° F	2 Hr at 1950° F	39.7
19	A	1	6 Hr at 2000° F 15 Hr at 2250° F Furnace cooled to 1950° F	24 Hr at 1950° F	49.5
20	A	1	6 Hr at 2000° F 15 Hr at 2250° F Furnace cooled to 1950° F	24 Hr at 1950° F 48 Hr at 1500° F	51.9

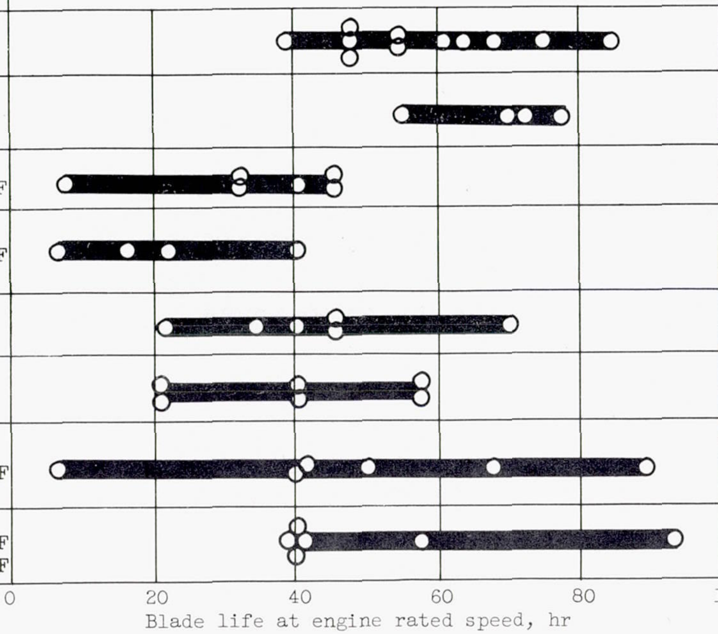


Figure 7. - Effect of aging or isothermal transformation at 1950° F.

Group	Source	Wheel number	Solution treatment	Aging treatment	Mean life, hr
3	A	3	None	None (as-cast)	73.3
9	A	3	$\frac{1}{2}$ Hr at 2250° F	48 Hr at 1500° F	8.2
21	A	3	$\frac{1}{2}$ Hr at 2250° F	24 Hr at 1200° F 48 Hr at 1500° F	> 70.3
4	B	3	None	None (as-cast)	> 91.0
22	B	3	$\frac{1}{2}$ Hr at 2150° F	24 Hr at 1200° F 48 Hr at 1500° F	> 55.8
23	B	3	72 Hr at 2250° F	24 Hr at 1200° F 48 Hr at 1500° F	14.6

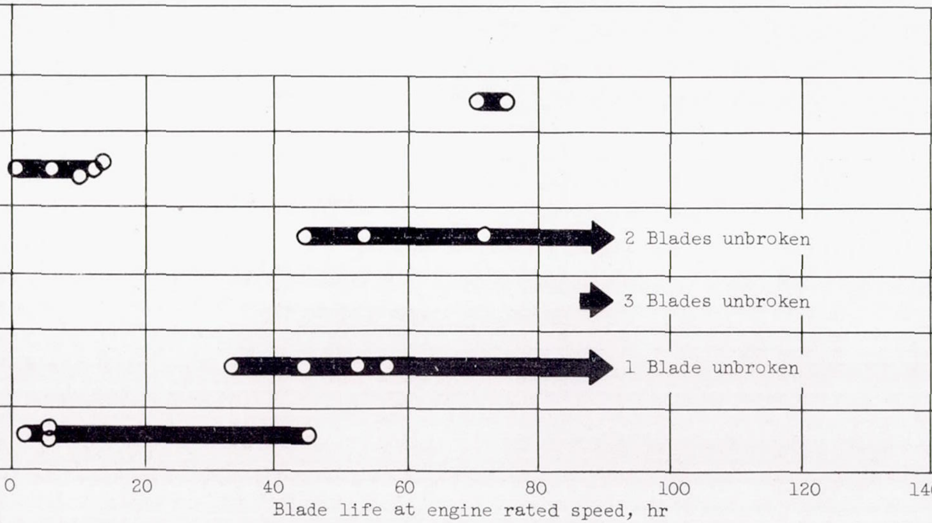


Figure 8. - Effect of double-aging heat treatments.

Group	Source	Wheel number	Solution treatment	Aging treatment	Mean life, hr
3	A	3	None	None (as-cast)	73.3
24	A	3	1 Hr at 2250° F Furnace cooled ($6\frac{1}{2}$ hr) to 1800° F	72 Hr at 1500° F	53.2
4	B	3	None	None (as-cast)	> 91.0
25	B	3	1 Hr at 2250° F Furnace cooled ($2\frac{1}{2}$ hr) to 1800° F	4 Hr at 1800° F 72 Hr at 1500° F	17.1

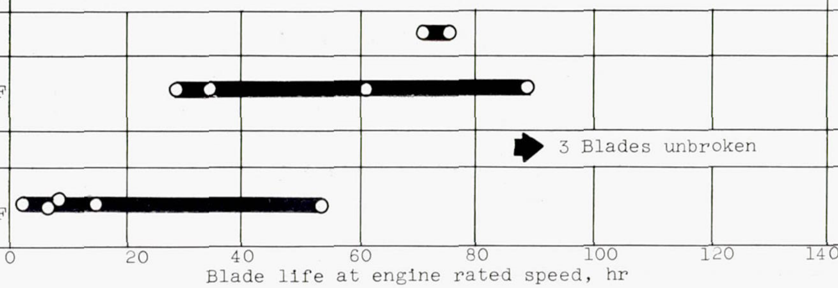
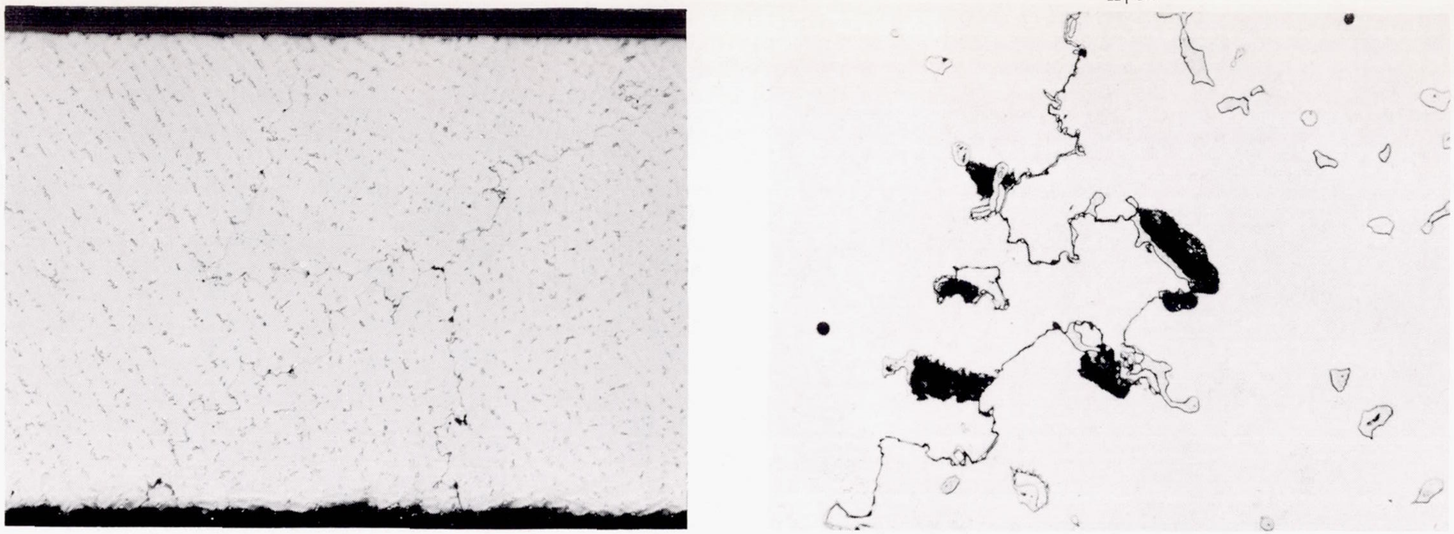
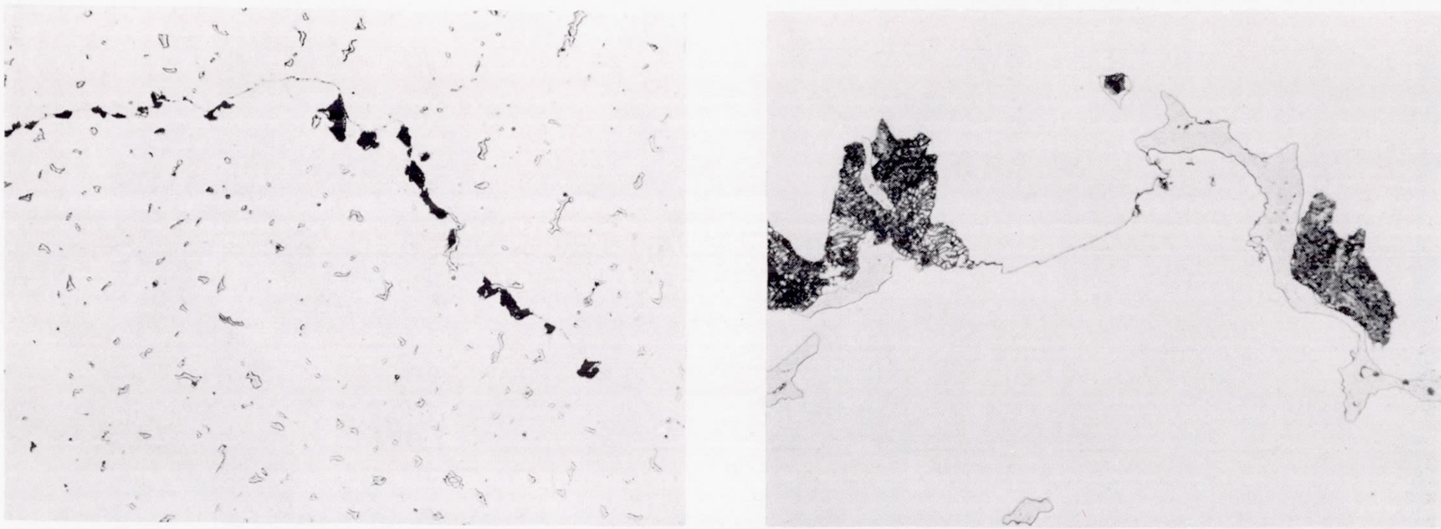


Figure 9. - Effect of treatment described in reference 3.

X100 X750



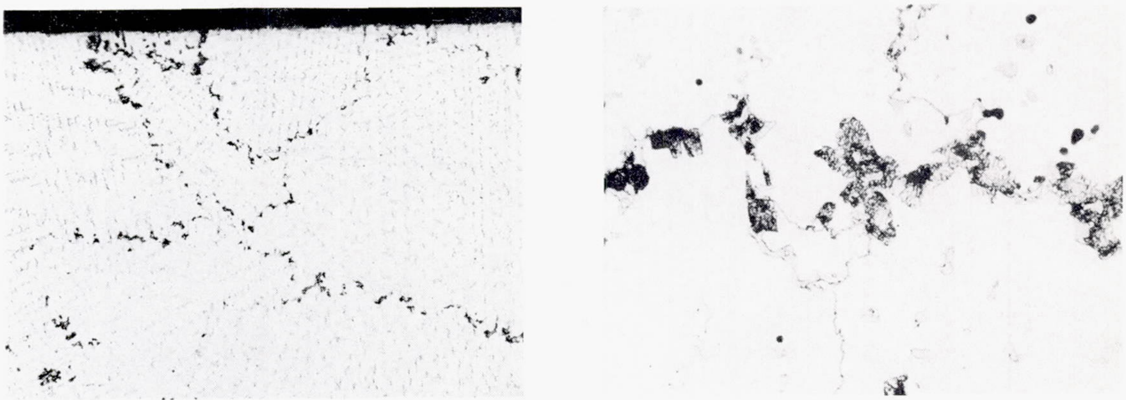
(a) Typical structure in small sections of blades.



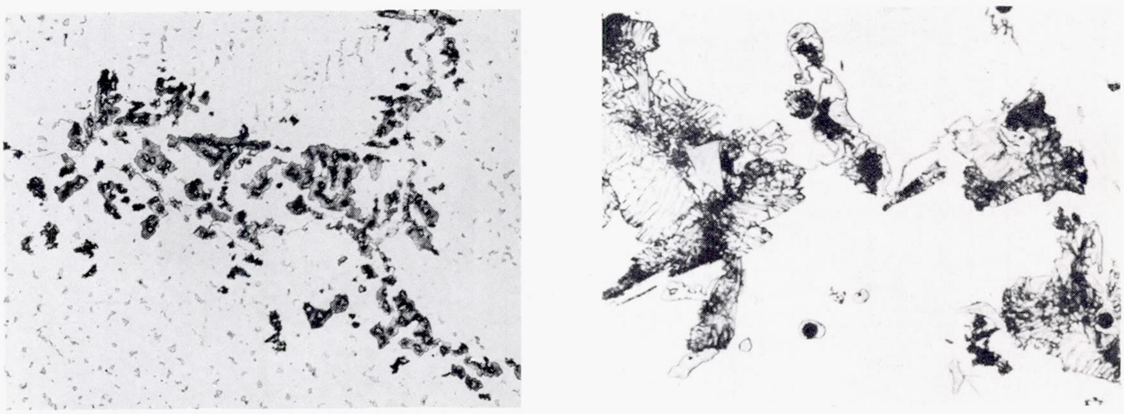
(b) Typical structure in large sections of blades. C-38620

Figure 10. - Microstructure of cast HS-21 turbine blades from source A in as-cast condition (groups 1 to 3). Electrolytically etched in 5 percent aqua regia.

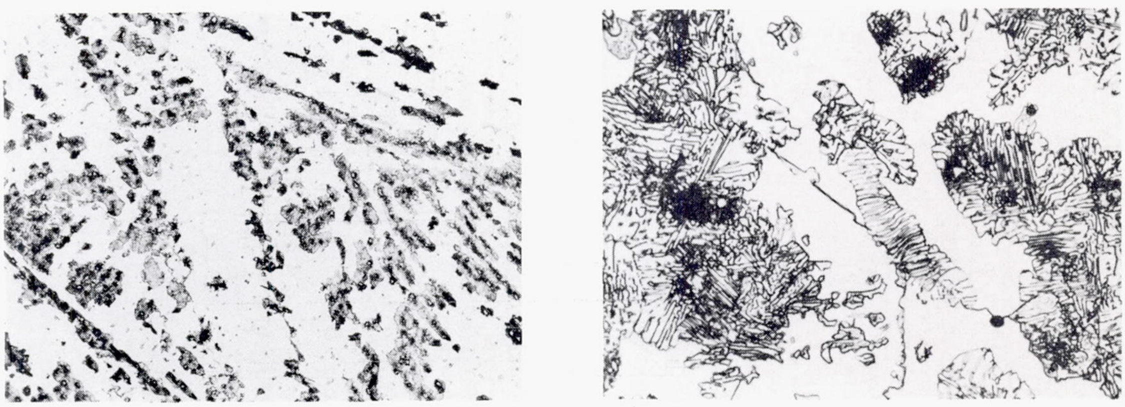
X100 X750



(a) Typical structure in small sections of blades.



(b) Typical structure in large sections of blades.



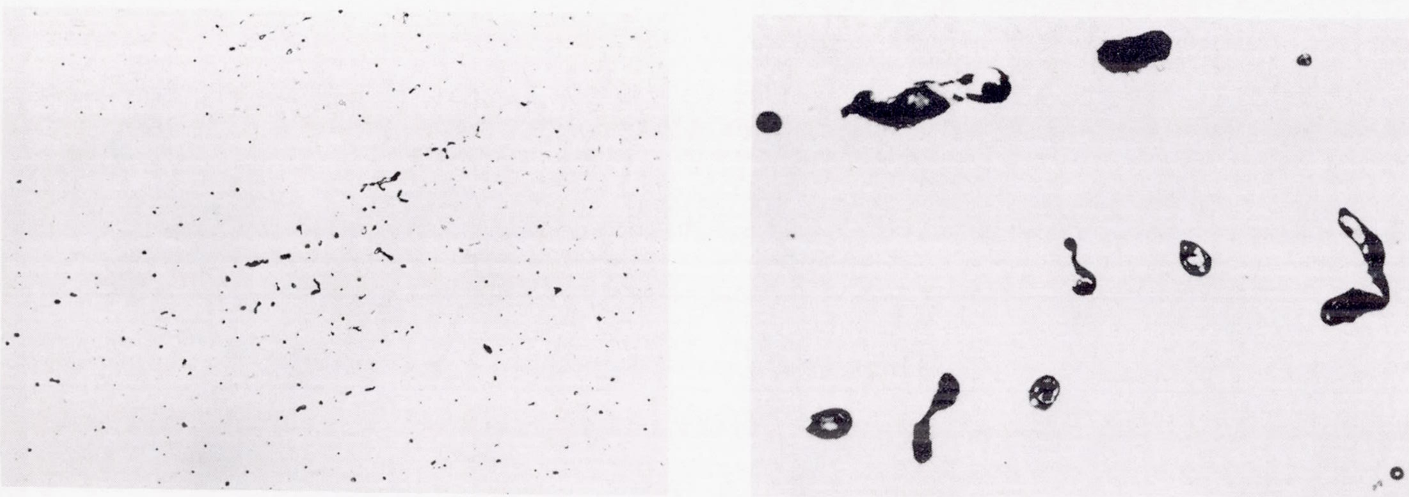
C-38621

(c) Heavy concentration of pearlite precipitation.

Figure 11. - Microstructure of cast HS-21 turbine blades from source B in as-cast condition (group 4). Electrolytically etched in 5 percent aqua regia.

X100 X750

(a) 4 Hours at 2050° F.

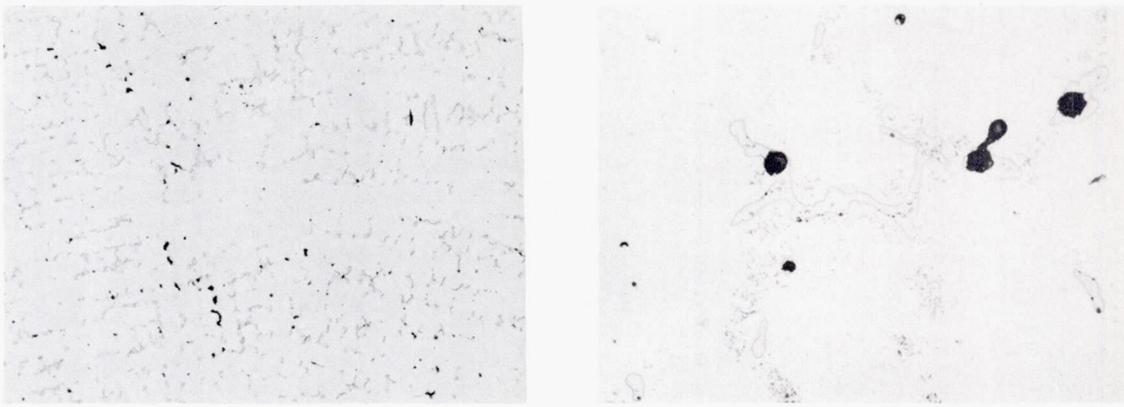


C-38622

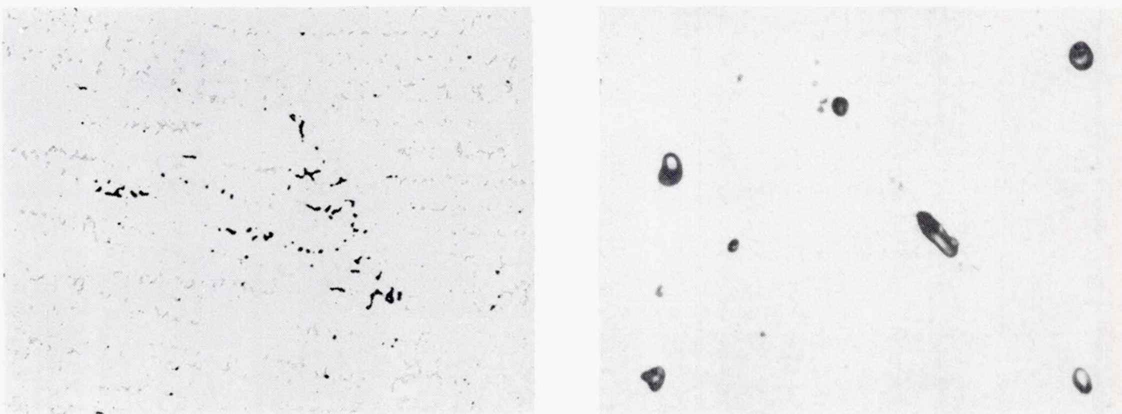
(b) 24 Hours at 2175° F.

Figure 12. - Response of cast HS-21 turbine blades from source A to solution treatment. Electrolytically etched in 5 percent aqua regja.

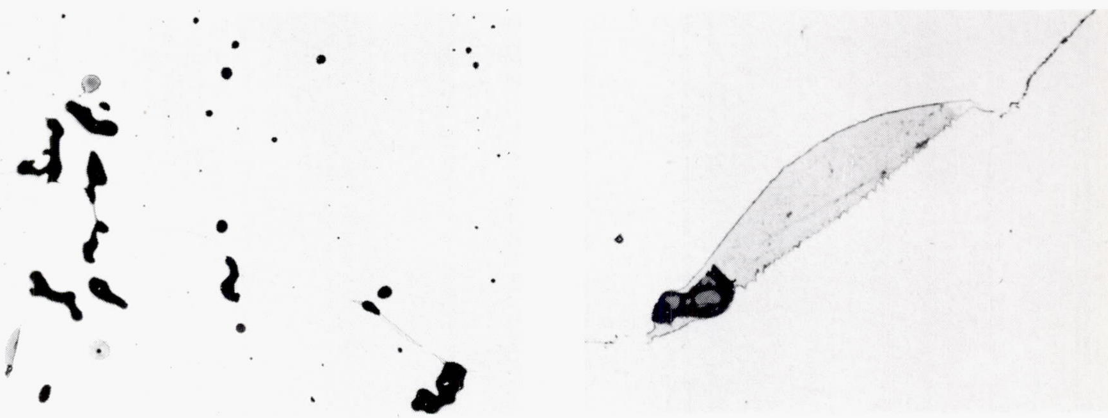
X100 X750



(a) 4 Hours at 2050° F.



(b) 24 Hours at 2175° F.



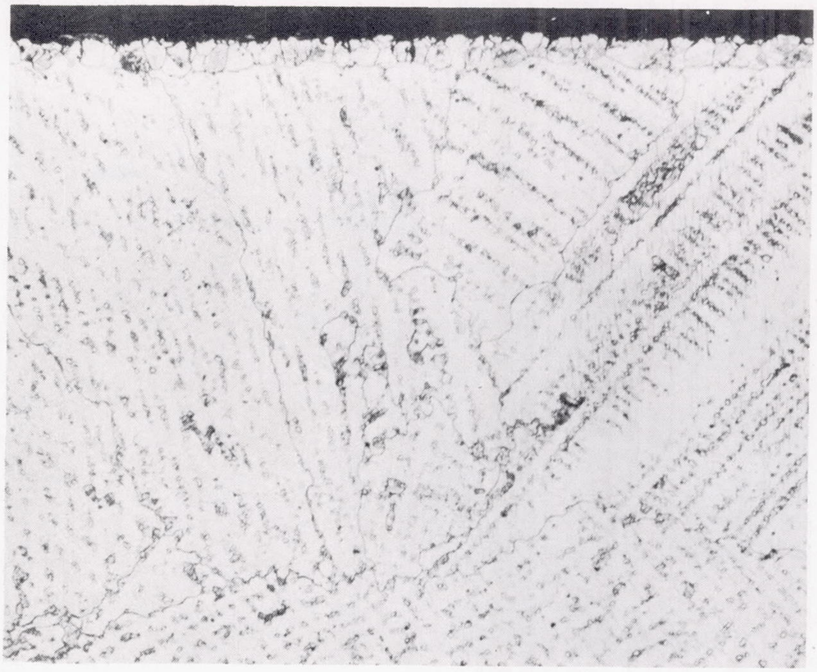
(c) 24 Hours at 2250° F.

C-38623

Figure 13. - Response of cast HS-21 turbine blades from source B to solution treatment. Electrolytically etched in 5 percent aqua regia.

3591

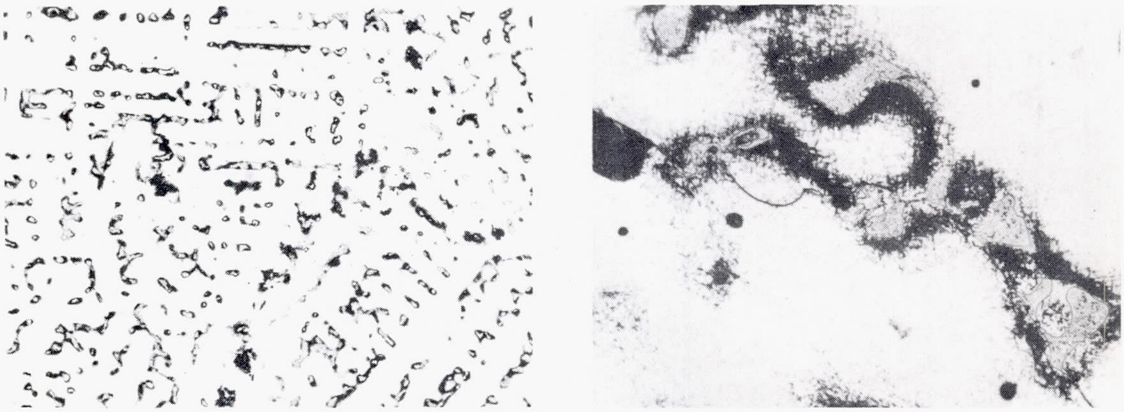
X100



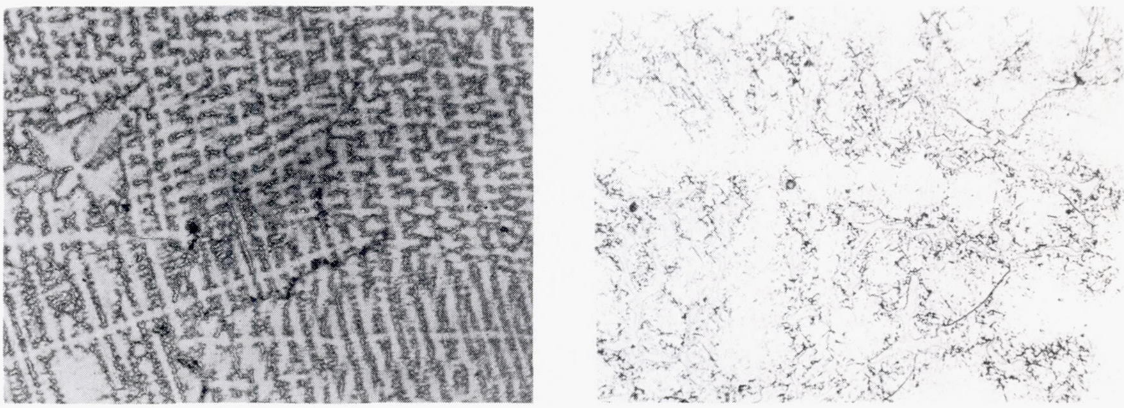
C-38624

Figure 14. - Recrystallized layer of small grains at edge of heat-treated blade from group 17 (solution treated 24 hr at 2050° F, furnace cooled to 1950° F, aged 2 hr at 1950° F, and air cooled). Electrolytically etched in 5 percent aqua regia.

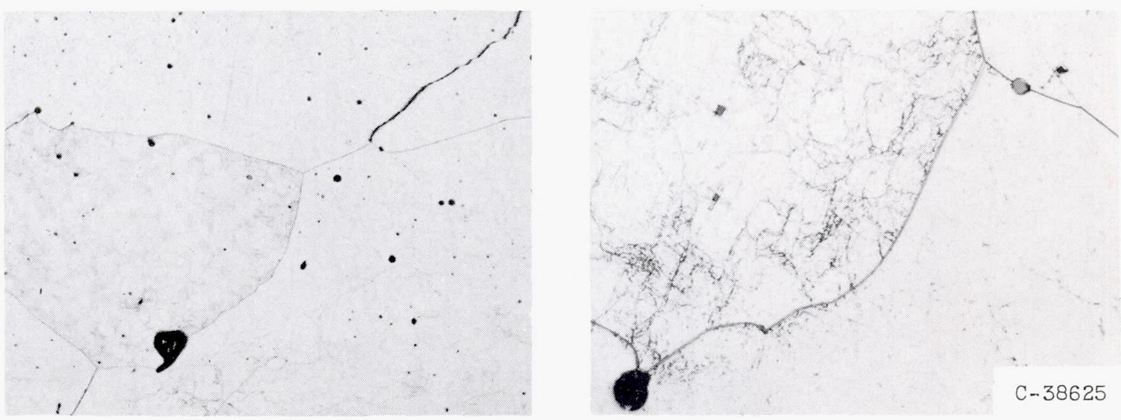
X100 X750



(a) No prior solution treatment (groups 5 and 6).



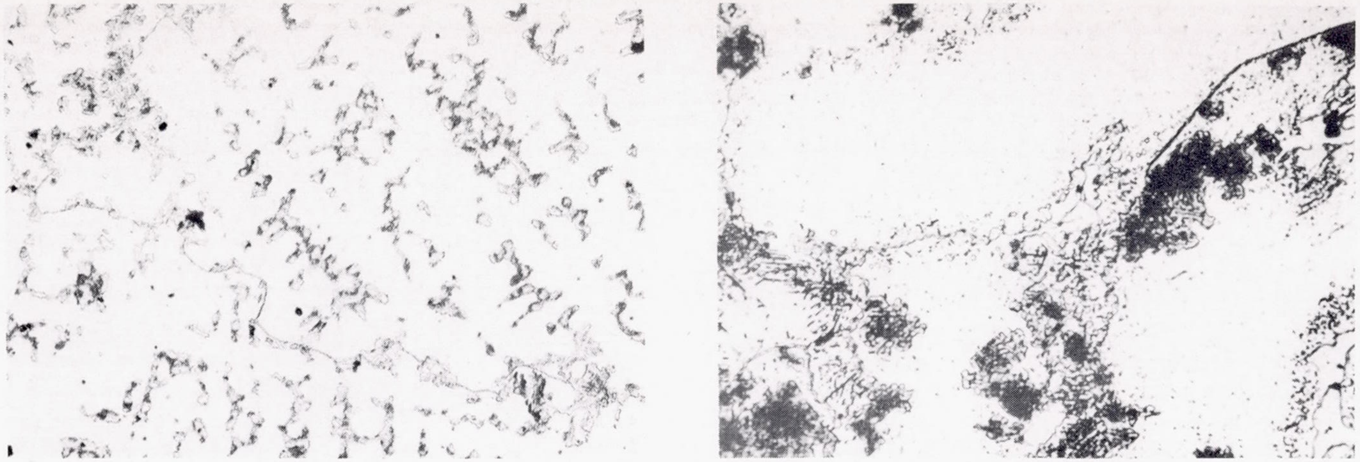
(b) Solution treated 1/2 hour at 2150° F and air cooled prior to aging (group 7).



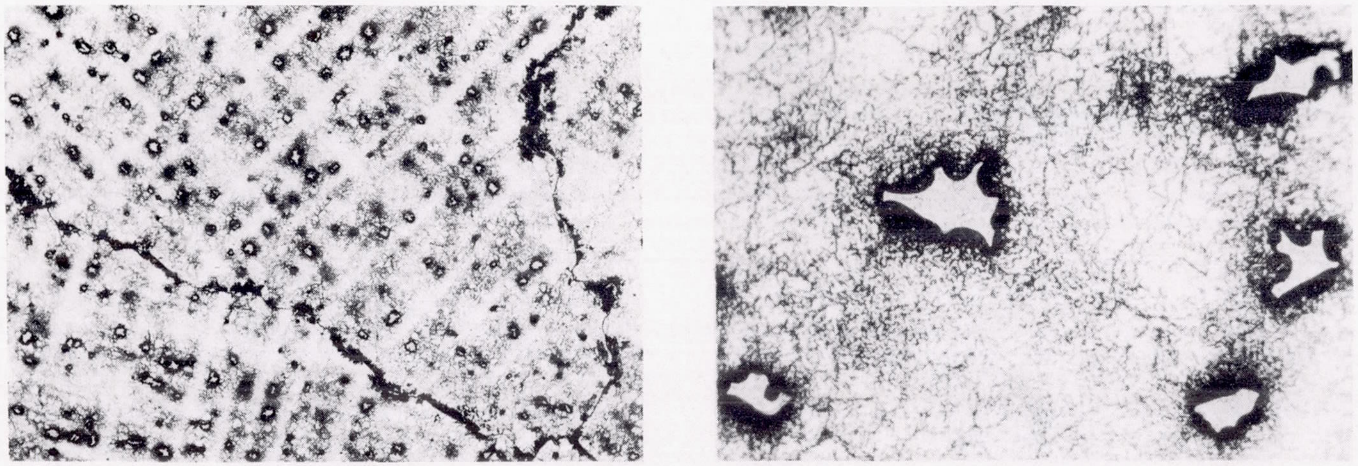
(c) Solution treated 1/2 hour at 2250° F and air cooled prior to aging (group 9).

Figure 15. - Microstructure of cast HS-21 turbine blades after aging 48 hours at 1500° F. Electrolytically etched in 5 percent aqua regia.

X100 X750



(d) Solution treated 24 hours at 2050° F and air cooled prior to aging (group 8).

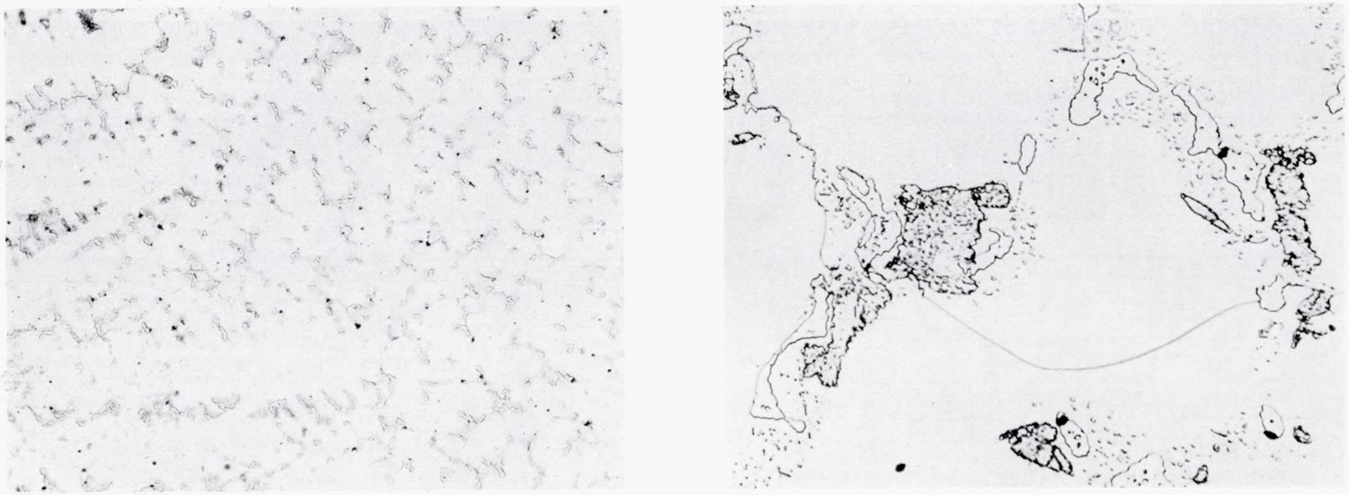


C-38626

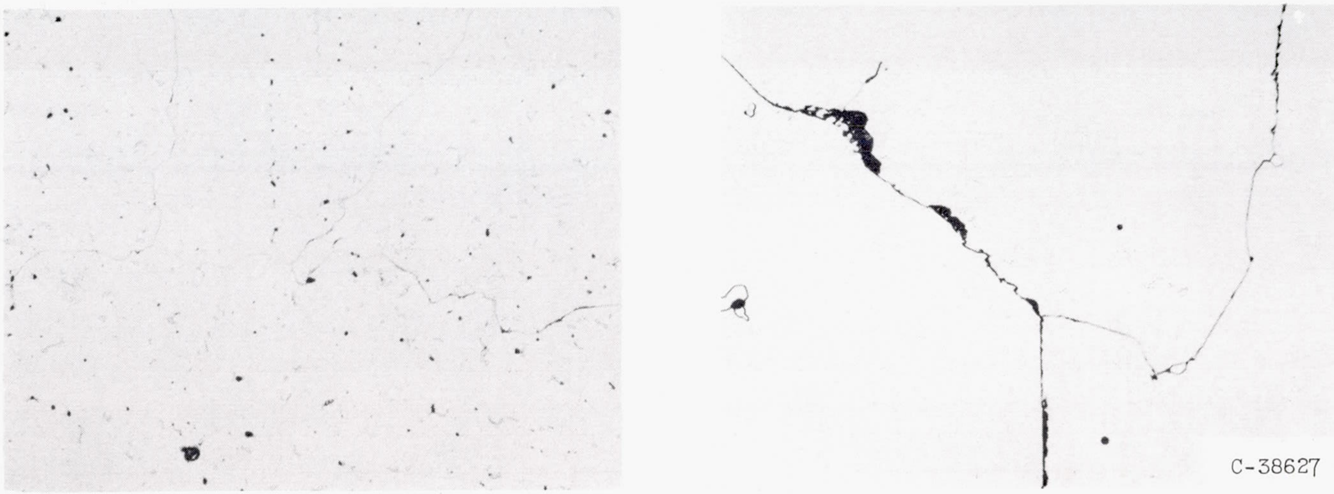
(e) Solution treated 24 hours at 2250° F and air cooled prior to aging (group 10).

Figure 15. - Concluded. Microstructure of cast HS-21 turbine blades after aging 48 hours at 1500° F. Electrolytically etched in 5 percent aqua regia.

X100 X750



(a) Solution treated 4 hours at 2050° F and air cooled prior to aging (group 11).

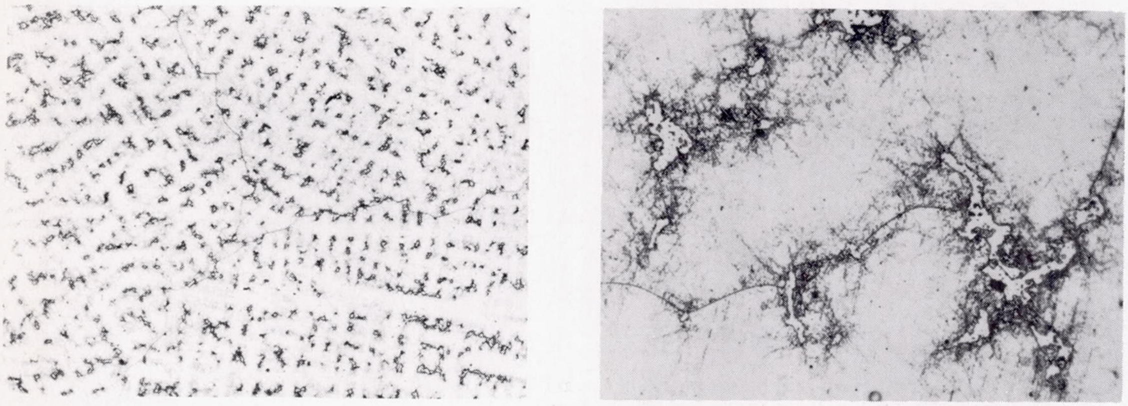


(b) Solution treated 24 hours at 2175° F and air cooled prior to aging (group 14).

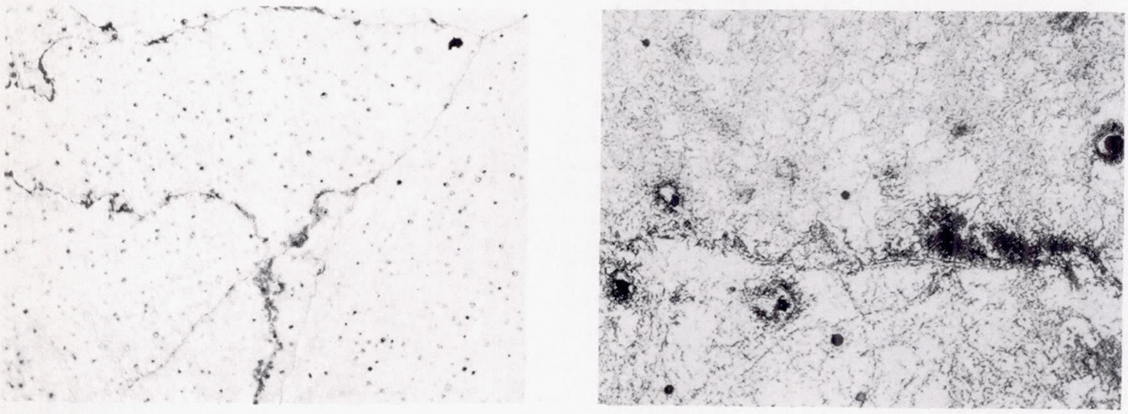
Figure 16. - Microstructure of cast HS-21 turbine blades after aging 48 hours at 1200° F. Electrolytically etched in 5 percent aqua regia.

3591

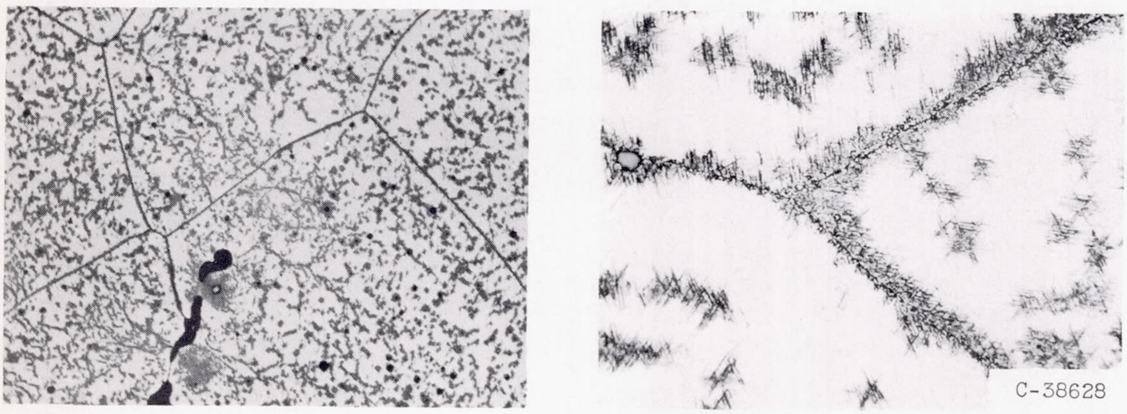
X100 X750



(a) Solution treated 1 hour at 2150° F and air cooled prior to aging (group 22).



(b) Solution treated 1/2 hour at 2250° F and air cooled prior to aging (group 21).



(c) Solution treated 72 hours at 2250° F and air cooled prior to aging (group 23).

Figure 17. - Microstructure of cast HS-21 turbine blades after double aging 24 hours at 1200° F plus 48 hours at 1500° F. Electrolytically etched in 5 percent aqua regia.

3591

X100 X750

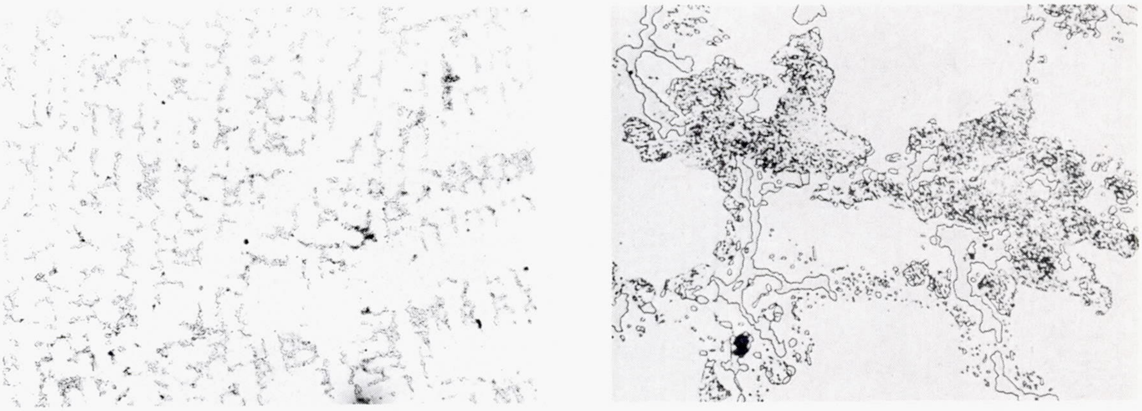


Figure 18. - Microstructure of cast HS-21 turbine blades after aging 72 hours at 1950° F (group 15). Electrolytically etched in 5 percent aqua regia.

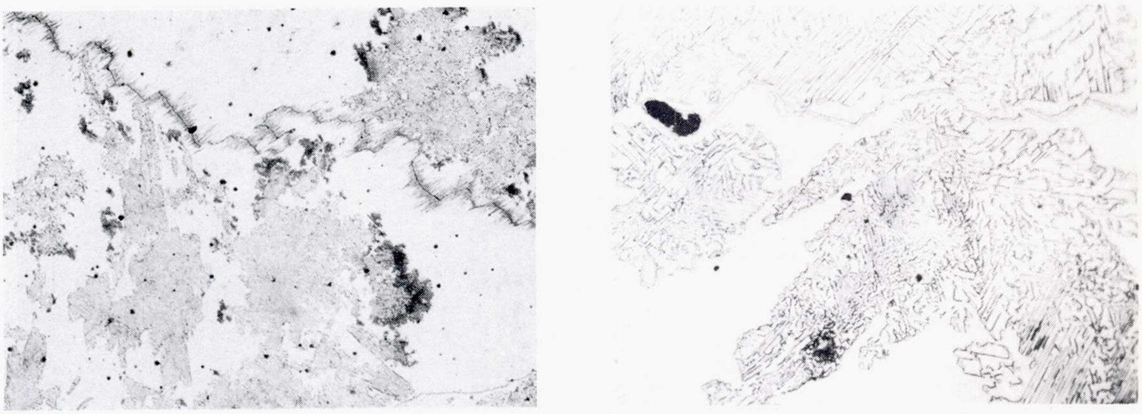


Figure 19. - Microstructure of cast HS-21 turbine blades after solution treating 1 hour at 2250° F, furnace cooling over $6\frac{1}{2}$ hours to 1800° F, air cooling to room temperature, and aging 72 hours at 1500° F (group 19). Electrolytically etched in 5 percent aqua regia.

Figure 20. - Microstructure of cast HS-21 turbine blades after solution treating 24 hours at 2175° F, furnace cooling to 1950° F, and aging 2 hours at 1950° F (group 15). Electrolytically etched in 5 percent aqua regia.

X100 X750

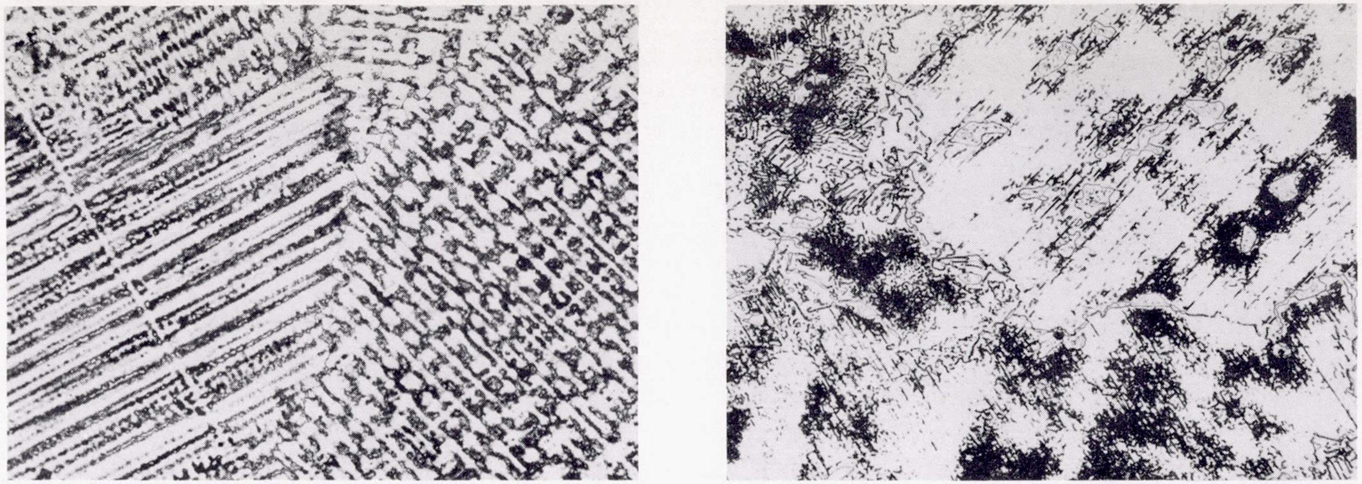
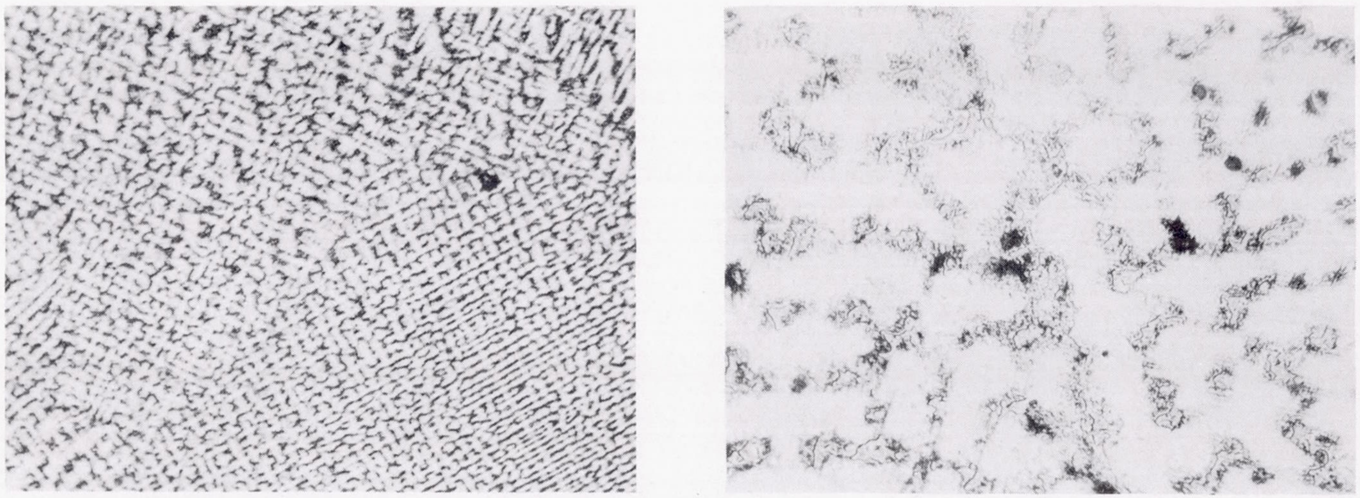


Figure 21. - Microstructure of cast HS-21 blade operated 77.8 hours at rated speed without previous heat treatment. Electrolytically etched in 5 percent aqua regia.



C-38630

Figure 22. - Microstructure of cast HS-21 blade aged 48 hours at 1500° F after operation for 114.2 hours. Electrolytically etched in 5 percent aqua regia.

X100 X750

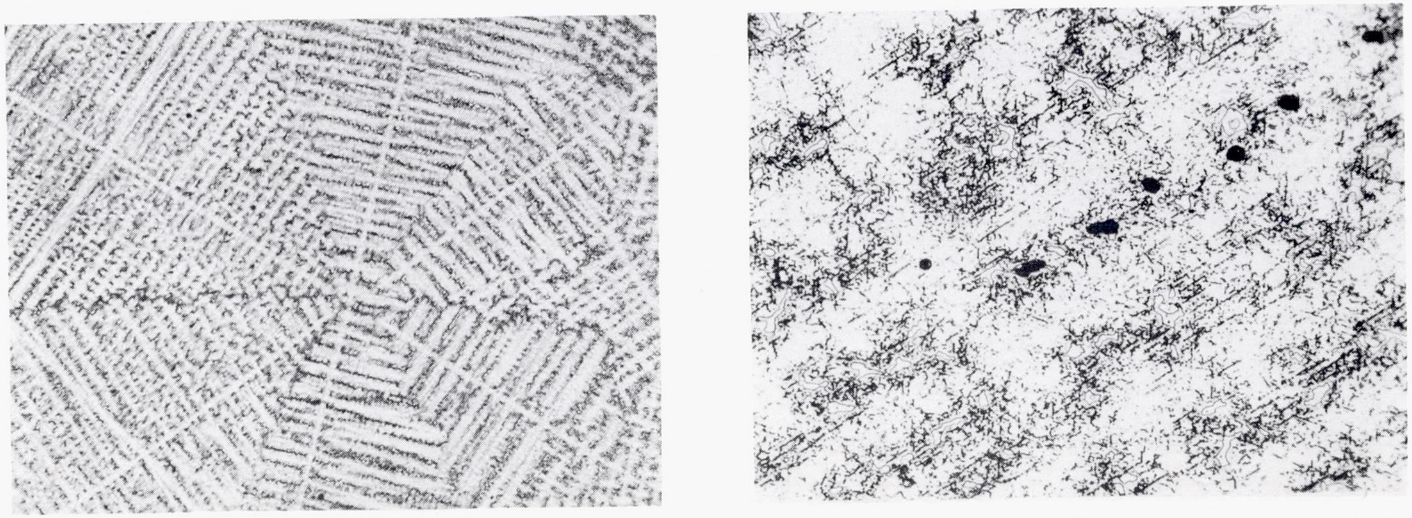
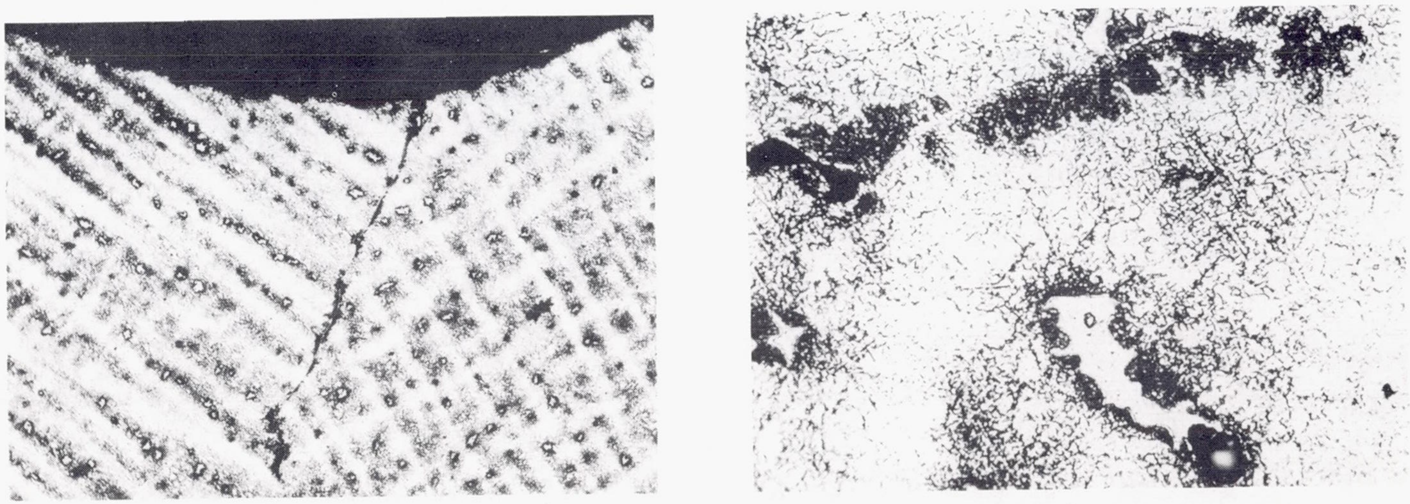


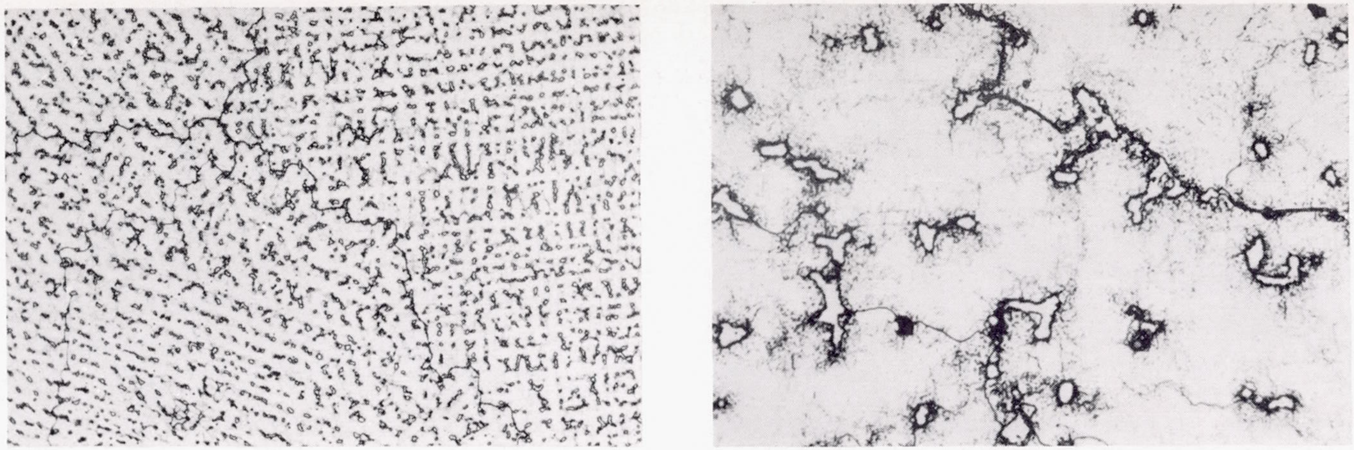
Figure 23. - Microstructure of cast HS-21 turbine blade solution treated 1/2 hour at 2150° F, air cooled, and aged 48 hours at 1500° F after operation for 196.13 hours at rated speed (group 3). Electrolytically etched in 5 percent aqua regia.



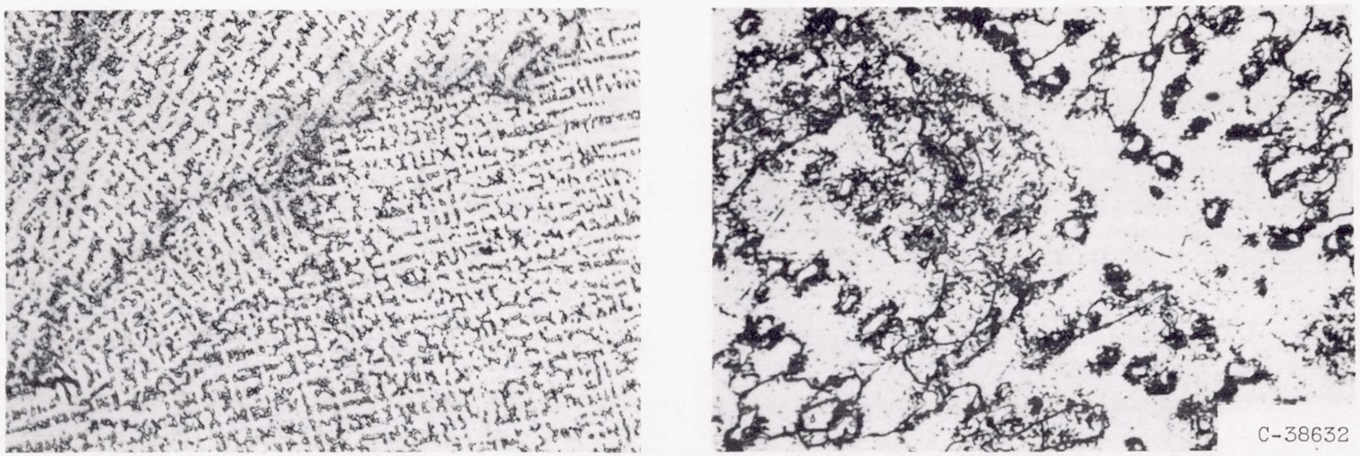
C-38631

Figure 24. - Microstructure of cast HS-21 turbine blade solution treated 24 hours at 2250° F, air cooled, and aged 48 hours at 1500° F after operation 60.75 hours at rated speed (group 18). Electrolytically etched in 5 percent aqua regia.

X100 X750



(a) 9.1-Hour operation at rated speed.



(b) 70.2-Hour operation at rated speed.

Figure 25. - Microstructure of cast HS-21 turbine blade solution treated 4 hours at 2050° F, air cooled, and aged 48 hours at 1200° F after operation in engine (group 11). Electrolytically etched in 5 percent aqua regia.

X100 X750

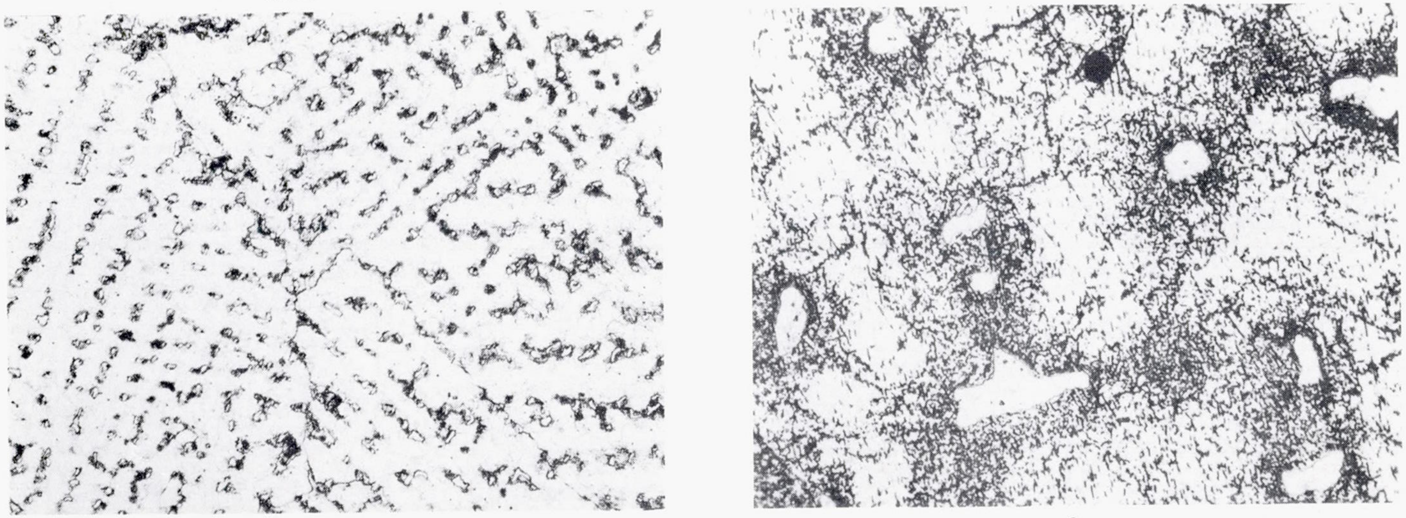
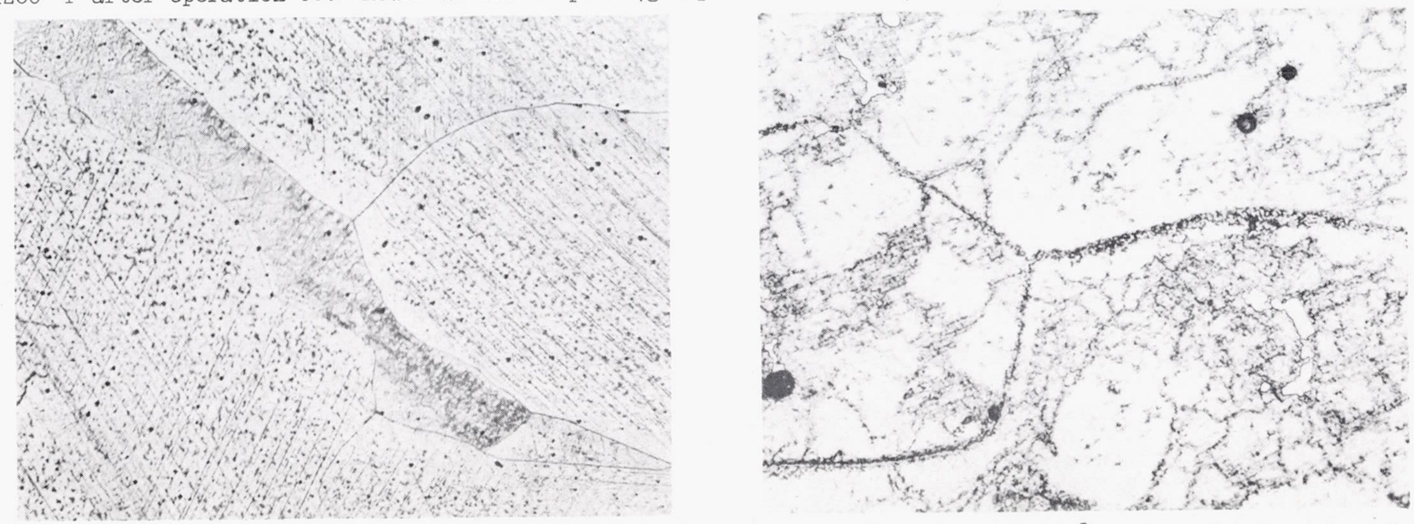


Figure 26. - Microstructure of cast HS-21 turbine blade solution treated 24 hours at 2050° F, air cooled, and aged 48 hours at 1200° F after operation 68.4 hours at rated speed (group 12). Electrolytically etched in 5 percent aqua regia.



C-38633

Figure 27. - Microstructure of cast HS-21 turbine blade solution treated 24 hours at 2175° F, air cooled, and aged 48 hours at 1200° F after operation 64.1 hours at rated speed (group 14). Electrolytically etched in 5 percent aqua regia.

3591

X100

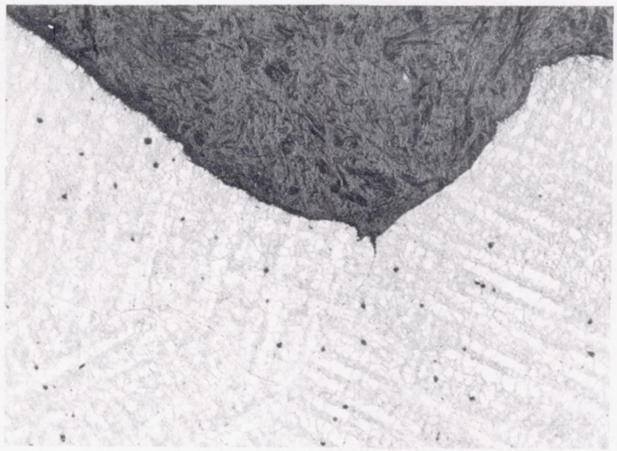


Figure 28. - Fracture of blade from group 14. Electrolytically etched in 5 percent aqua regia.

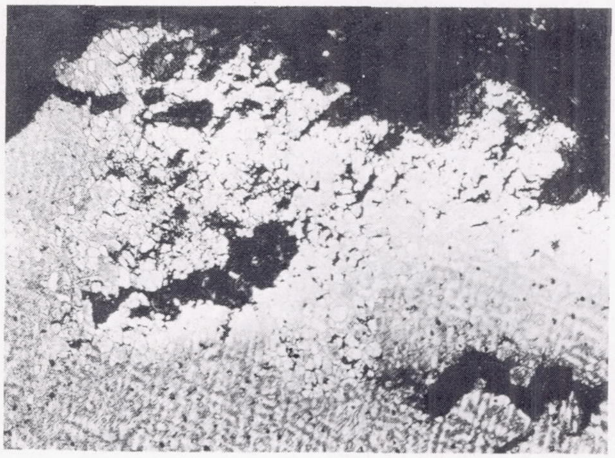
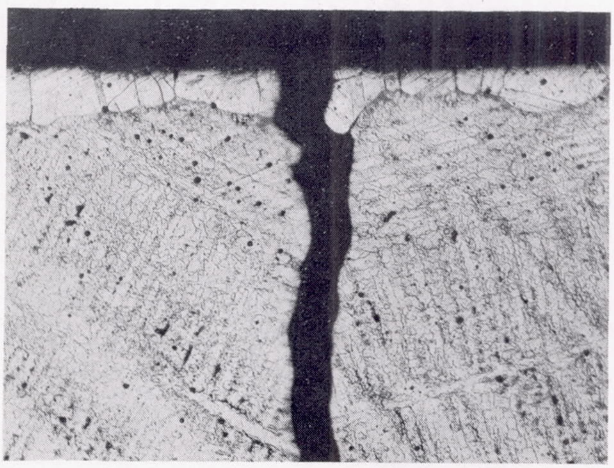


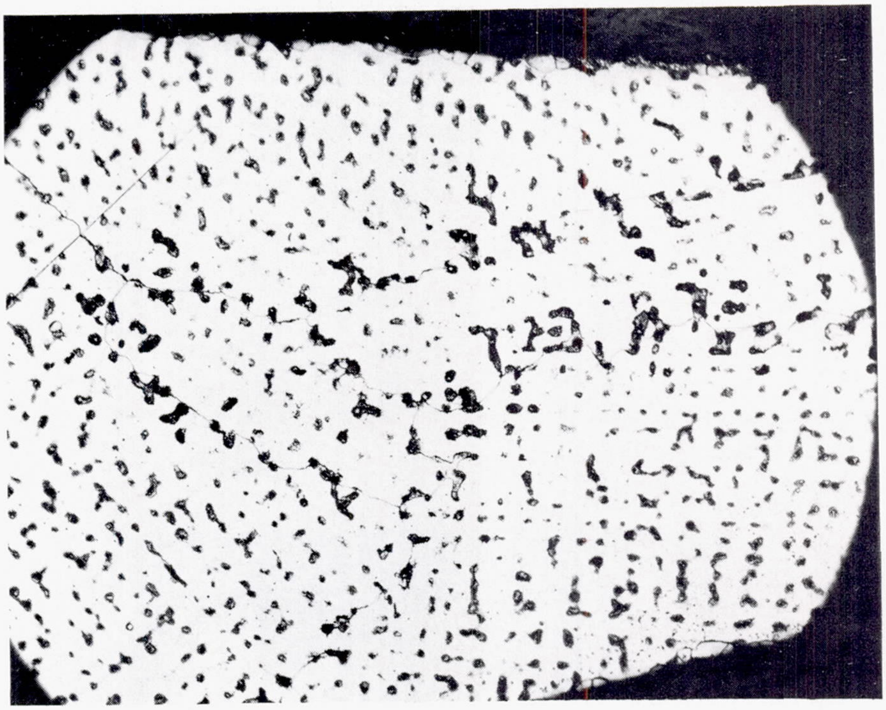
Figure 29. - Fracture of blade from group 8. Electrolytically etched in 5 percent aqua regia.



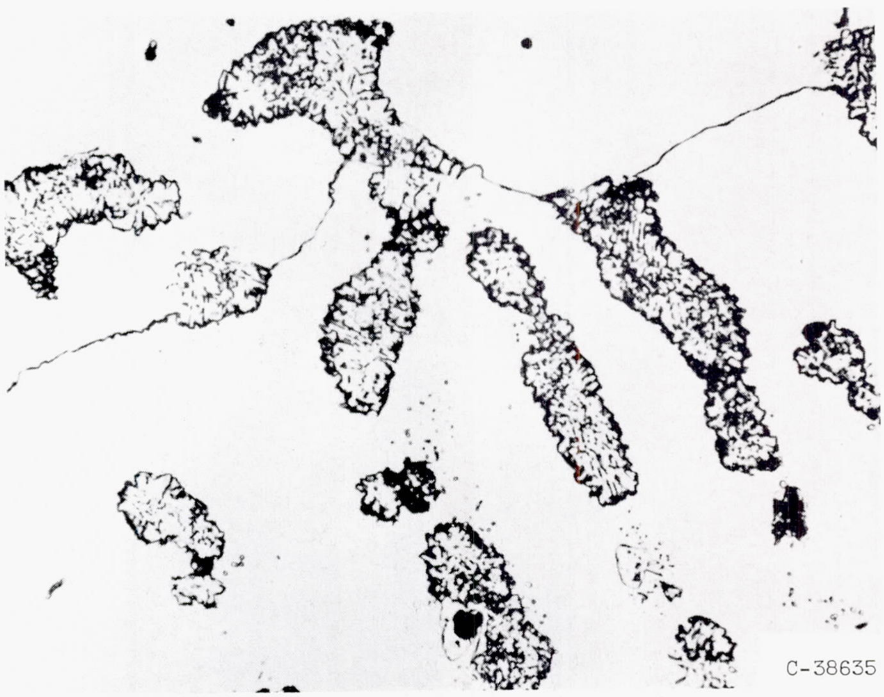
C-38634

Figure 30. - Crack below fractured edge of blade from group 13. Electrolytically etched in 5 percent aqua regia.

3591



X100

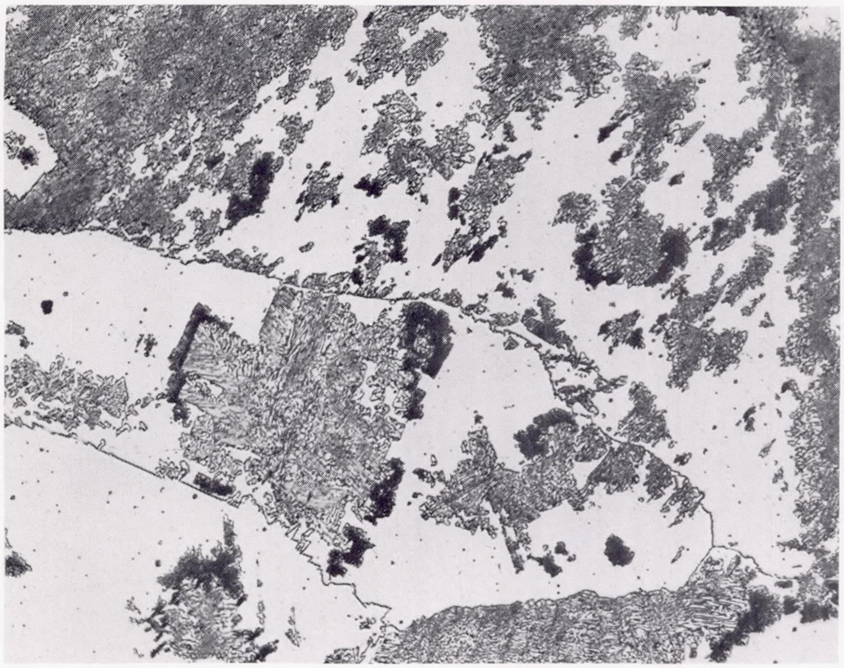


C-38635

X750

Figure 31. - Microstructure of as-cast specimens cut from small turbosupercharger blades. Electrolytically etched in 5 percent aqua regia.

3591



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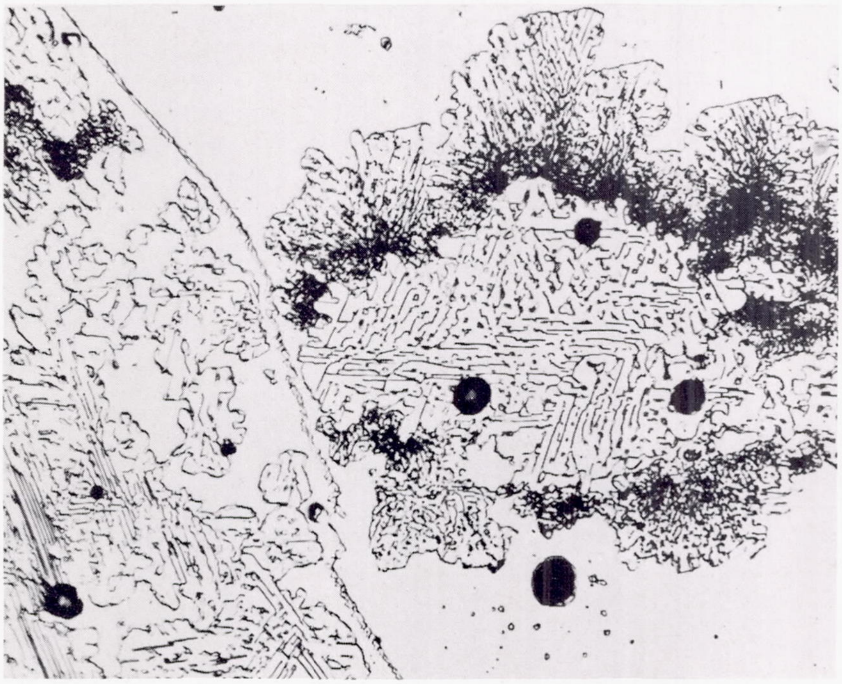

X750 C-38636

Figure 32. - Microstructure of specimens cut from small turbosupercharger blades given heat treatment of reference 3 (1 hr at 2150° F, furnace cooled to 1800° F in 6 hr, air cooled, and aged 72 hr at 1500° F). Electrolytically etched in 5 percent aqua regia.

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