REJUVENATION OF USED TURBINE BLADES BY HOT ISOSTATIC PROCESSING

by

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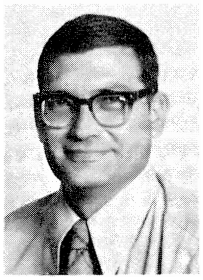

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ABSTRACT

The creep properties of gas turbine blades will deteriorate with prolonged service exposure. This deterioration is primarily due to internal microstructural changes and the formation of creep voids or cavitation. Development work has shown that HIP processing is the best available treatment for recovery of properties in used blades. The results obtained on a complete engine set of Inconel X-750 blades indicate that HIP processing is capable of restoring new or near new creep resistance to used blades.

INTRODUCTION

The hot gas path components in land base gas turbines are generally designed for a theoretical life of 100,000 hours with creep resistance being the primary limitation for blades. In calculating blade life, the designer has to rely on extrapolation of relatively short term (100 to 10,000 hours) test data and the application of a suitable safety factor both of which are subject to considerable variance. Given these inherent design limitations, it is difficult to predict the exact life of a turbine blade without periodic monitoring of the creep properties to determine the extent of service damage and the remaining life. As a result of such test programs, extensive data has been generated on the service behaviour of gas turbine blading which permits a realistic assessment of remaining blade life. Almost all blade alloys deteriorate during service; however, there is generally considerable scatter among the various units, making it difficult to establish any definitive life limits without being unduly conservative. Usually, when the creep rupture life of a serviced blade falls below the specified minimum life for a new blade, the blades become suspect and recommendations are made to either replace or reheat treat. However, neither of these solutions is completely satisfactory because replacement blades are expensive and reheat treatment has not always proved to be satisfactory. Therefore, a development was undertaken to apply hot isostatic press (HIP) technology to the recovery of creep damage in used turbine blades. Actual serviced blades were used in the program which culminated by processing a complete set of blades for return to engine service.

Nature of Service Damage in Turbine Blades

Two distinct types of damage are recognized, surface damage and internal degradation. Surface damage may be due to either mechanical impact or corrosion and is generally confined to the blade airfoil. In both cases, light damage can be removed by blending or dressing. Blades with severe surface damage or cracks are scrapped.

The primary concern of the present work is internal damage. Microstructural changes, resulting from extended exposure at high temperature under stress, are responsible for a reduction in mechanical properties. Three forms of internal degradation have been verified; precipitate coarsening or overaging, changes in grain boundary carbides and cavitation or void formation.

A considerable fraction of the intermediate temperature strength of nickel-base turbine blade alloys results from the fine γ' precipitate Ni_3 (Al, Ti). The γ' particles generally coarsen according to a time to the ⅓ power growth law with a corresponding decrease in strength. Also grain boundary carbide morphology and amount can change with time. Since the alloy heat treatments which cause carbide formation are generally optimized for short term properties, long term changes in carbide structure are usually detrimental, particularly with respect to such properties as ductility and notch sensitivity. Cavitation represents the initial step in creep failure. It consists of the nucleation and growth of voids on grain boundaries. With time, the isolated voids link up to form cracks. Cavitation has been reported in test specimens tested for long times as intermediate stress levels [1,2,3,4]; i.e., typical turbine blade operating conditions. In some but not all cases [5], the voids have been observed directly, although their presence has been inferred from experimental evidence. It appears that material has to be near or in tertiary creep before cavitation can readily be detected by optical microscopy.

It is not known to what extent each of the above mechanisms contributes to turbine blade degradation during service. It is also probable that each alloy will respond differently to a particular temperature stress combination. Figure 1 shows the typical variation in stress rupture life determined at 735°C (1350°F) with service time for forged Inconel X-750 blades. The data for the machines was taken from McCall [6]. It should be noted that the tests conducted by us were conducted at 345 MPa (50 Ksi), while McCall's data resulted from tests at 310 MPa (45 Ksi). Both data sources display considerable scatter; some is undoubtedly due to variations in initial (new) material properties and differences in machine operating conditions. Additional reasons for large scatter are that the data includes values from both W62 row 3 blades and W92 rows 4 and 5 blades. Figure 1 indicates that, after 40,000 hours service, about half of the blades evaluated could not meet the new blade stress rupture specification value of 100 hours at 345 MPa/735°C. The blades which were selected for the HIP rejuvenation program had been in service for approximately 45,000 hours and exhibited the lowest life of all blades tested (Figure 1) (15 to 35 hours as received).

Blade Restoration Alternatives

Of the three types of internal service damage discussed in the previous section, precipitate coarsening and changes in grain boundary carbides should generally be reversible by conventional heat treatment involving complete solutioning followed by controlled precipitation at lower temperatures. With regard to creep voids, it is not clear if cavitation damage can be removed by conventional heat treatment. Davies et al [5, 8] report that in Nimonic 80A test bars, cavitation can be "sintered out" at 750°C if the test is interrupted during secondary creep; a test bar reheat treated in early tertiary creep failed "prematurely" after three recovery treatments. All of the specimens tested by Davies et al exhibited unusually low ductility (approximately 2%) for a forged Ni-base alloy. This may have been due to the use of a non-standard initial heat treatment for their material. Hart and Gayter [7] studied the effect of complete reheat treatment cycles on specimens of Nimonic 75, Nimonic 90, Nimonic 105 and Incoloy 800. Some Nimonic 75 test bars exhibited increased stress rupture life as a result of reheat treatment, while in other bars the total life was appreciably decreased. In the case of Nimonic 90, reheat treatment resulted in considerably increased total life; however, ductility was generally reduced. Test bars given repeated reheat treatments indicated that life improvements could not be achieved indefinitely; each successive cycle resulted in a smaller improvement. The response of Nimonic 105 was similar to Nimonic 90. Reheat treated Incoloy 800 test bars exhibited only slightly increased life over specimens tested directly to failure. McCall [6] reports his experience with standard reheat treatment of used Inconel X-750 turbine blades. His results are superimposed on Figure 1. Although there is a distinct improvement, there is a continual decrease in stress rupture life from new blade properties.

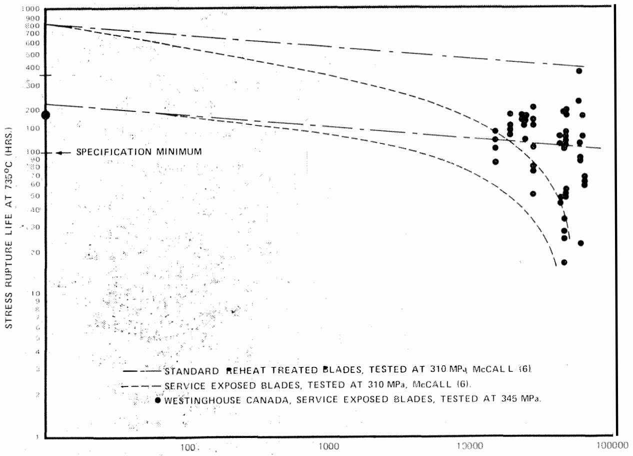


Figure 1. The Variation of Remaining Stress Rupture Life at 735°C with Service Time in Forged Inconel Alloy X-750 Turbine Blades.

The above results suggest that normal reheat treatment can partially restore blade properties; however, it does not appear to be capable of full property recovery even though the microstructures are comparable to new blades. This implies that cavitation may be present and was not removed by conventional reheat treatment. An alternative to ensure void removal is hot isostatic press (HIP) processing which has demonstrated its ability to remove even gross internal shrinkage porosity in investment castings, as illustrated in Figure 2. To evaluate the potential of HIP processing for used blades, a preliminary study was conducted on samples removed from the same blades and subjected to either conventional reheat treatment or HIP treatment.

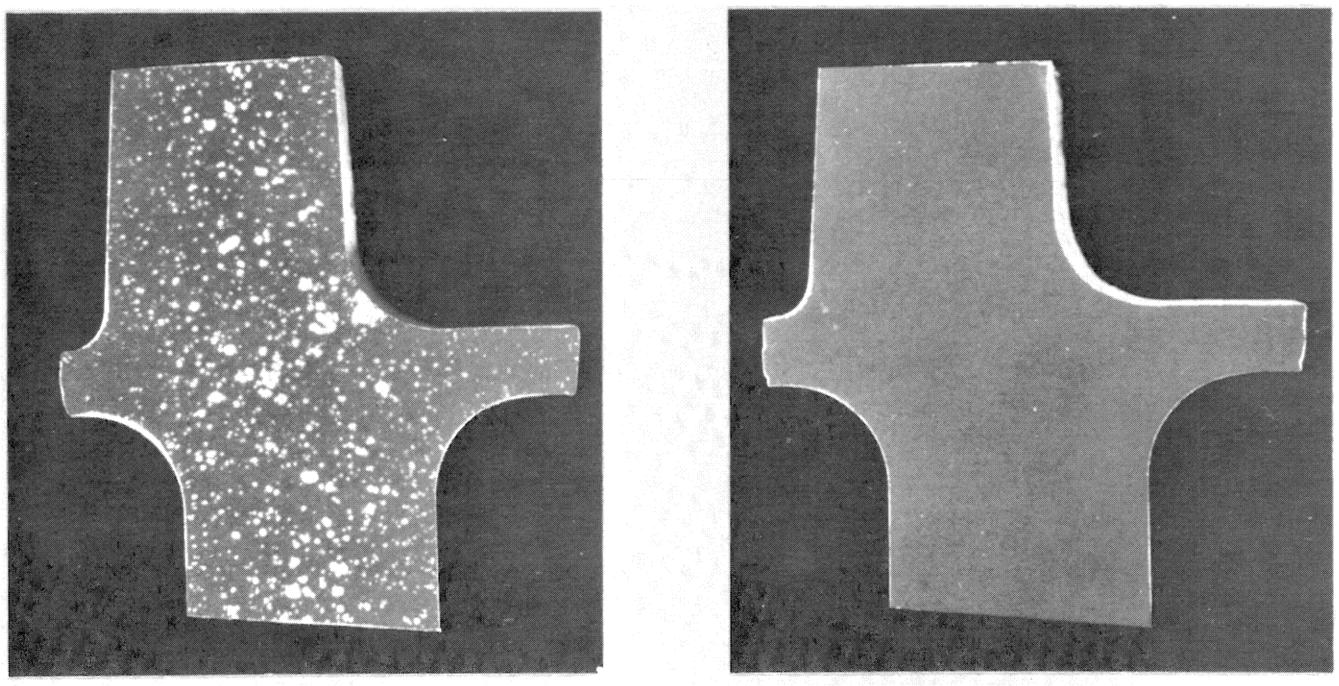
The results of this work, presented in Figure 3, clearly show that the HIP processed material is superior to both commercial and laboratory conventional reheat treated material. The laboratory treated blades should represent the maximum property improvement attainable by this approach, since ideal temperature control and cooling rates were employed and the microstructure was fully restored. Therefore, the improvement achieved using the HIP cycle must be due to complete removal of service damage.

With the distinct advantage of HIP reheat treatment evident in Figure 3, a cooperative program was conducted with Trans Canada Pipe Lines to process a complete blade set and return them to service. The blades are forged Inconel X-750, with 45,000 hours of service and are identified as Set A in Figure 3.

RESULTS AND DISCUSSION

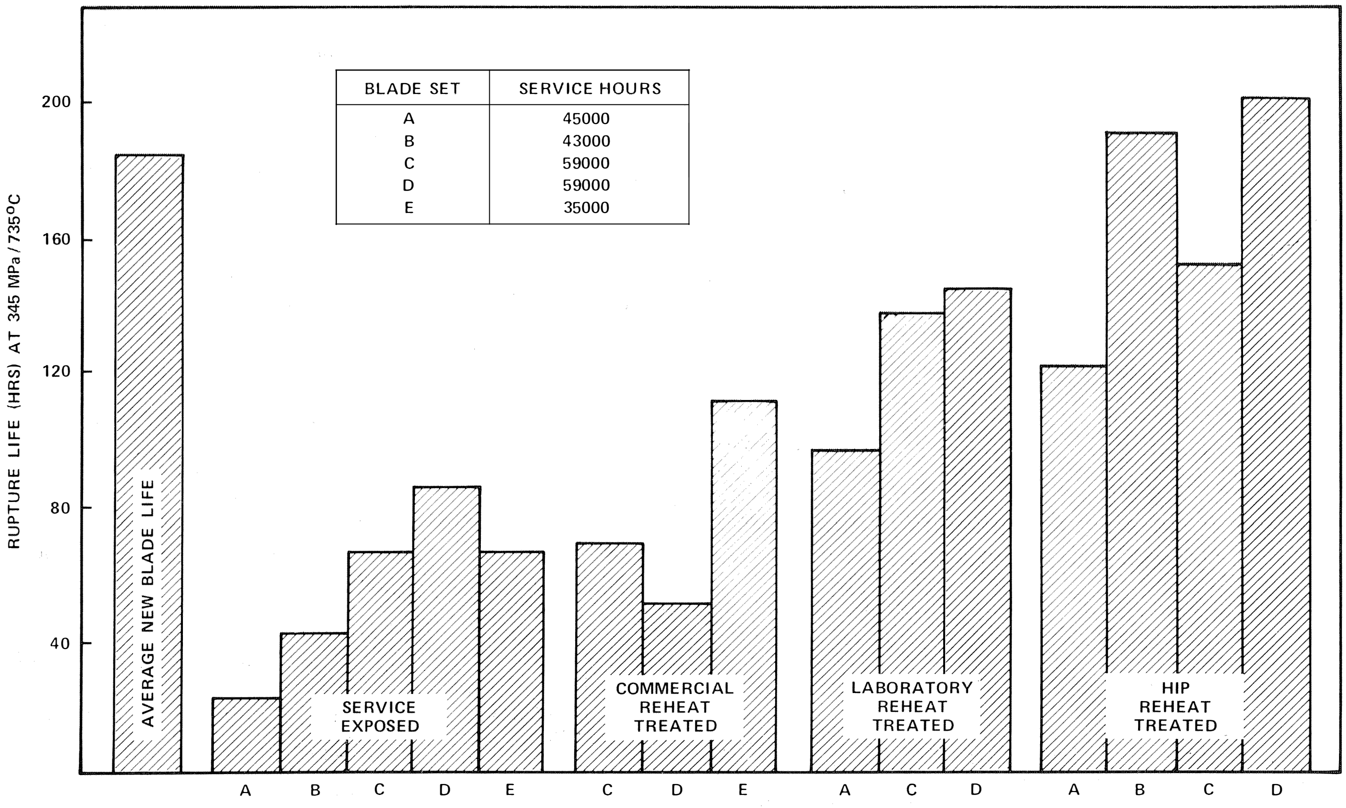
HIP Processing

The HIP system described in this paper was obtained from Autoclave Engineers. It is shown schematically in Figure 4. The system consists of a five zone vertical furnace, 300 mm (12 in.) I. D. by 900 mm (36 in.) high located in a steel pressure



(a) (b)

Figure 2. Fluorescent Penetrant Indications on Sections Cut from the Root-Airfoil Transition of Investment Cast Turbine Blades. (a) As Cast; (b) Cast Plus HIP Processed.



BLADE SET	SERVICE HOURS
A	45000
B	43000
C	59000
D	59000
E	35000

Figure 3. Comparison of Stress Rupture Life at 345 MPa/735°C (50 KSI/1350°F) in Service Exposed, Commercially Reheat Treated. Laboratory Reheat Treated and HIP Reheat Treated Used Inconel X-750 Turbine Blades.

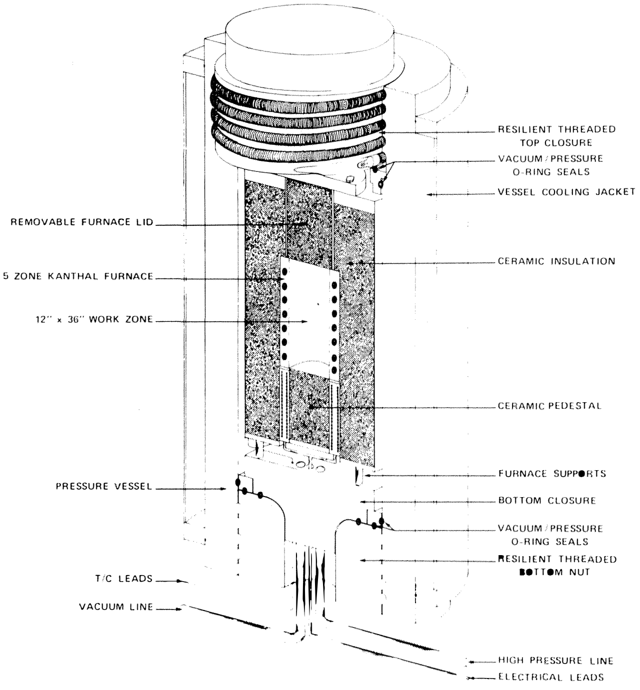


Figure 4. Schematic of the HIP Vessel and Furnace.

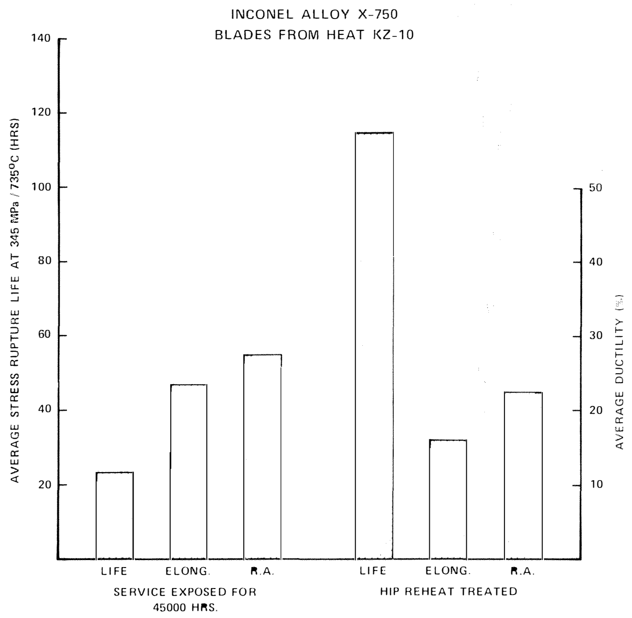


Figure 5. Bar Chart Comparison of Before and After Stress Rupture Properties at 345 MPa/735°C (50 KSI/1350°F) of the HIP Processed Blade Set.

vessel which can be pressurized to 140 MPa (20 Ksi) with argon. The furnace is capable of temperatures up to 1230°C (2250°F). For maximum life of the Kanthal elements, the temperature is maintained at 800°C (1470°F) between cycles. The vessel is pressurized by two diaphragm compressors operated in series and the pressurizing argon is normally reclaimed at the conclusion of each cycle.

The hot load/unload feature of the system facilitates rapid cycles but dictates that measures must be taken to avoid excessive surface attack. This is accomplished by inert gas shrouding during loading and unloading and several evacuation/backfill cycles prior to increasing the temperature and pressure to process levels.

In order to avoid distortion during processing, the blades are carefully placed in a special fixture and stacked in separate tiers such that they are individually supported and not subjected to any undue loads.

Creep and Stress Rupture Properties

Five sample blades from the engine set were sectioned and tested to provide before and after stress rupture properties and microstructural samples. The sample blades used to evaluate the HIP processed condition were distributed among the blades being processed during both HIP processing and subsequent heat treatment. Mechanical test bars were machined from the roots and airfoils of the sample blades; root and airfoil properties were comparable within experimental scatter. The test bars were 3.75 mm (0.150 in.) in diameter with a gauge length of 15 mm (0.600 in.).

The service exposed and HIP processed conditions were initially established by testing ten specimens of each condition at 345 MPa/735°C/(50 Ksi/1350°F). The averaged results are presented in Figure 5. The results are nearly identical to the Set A results in Figure 3, which indicates that with due care, production scale HIP processing can duplicate preliminary laboratory results.

In addition to the above results, material in both the service exposed and HIP reheat treated condition was tested at various stress/temperature combinations. Test parameters were chosen so as to yield an average life of 100 hours for the HIP treated material. The results are presented in the Larson-Miller plot of Figure 6. The HIP processed results fall nearly in the centre of the Inconel X-750 scatterband [10] indicating that this condition is comparable to what one could expect for new blade properties.

It should be noted that service damage is only clearly apparent in the tests conducted at lower temperatures (up to 735°C), which is higher than the actual service temperature for Inconel X-750. In the higher temperature tests, the difference becomes less pronounced, apparently because the failure mechanism becomes insensitive to microstructural changes and cavities. This result indicates that testing of serviced blades should always be conducted at as low a temperature as possible to approximate the use temperature.

Short term creep rupture tests were conducted at three stress/temperature levels. Representative creep curves are presented in Figure 7. In all cases, the HIP reheat treated material clearly exhibits a secondary creep stage which is virtually absent in the service exposed material. Again, as previously noted in Figure 6, the differences between the service exposed and HIP processed material decrease as test temperature is increased.

Microstructural Observations

Comparison of service exposed and HIP reheat treated material revealed that, in both cases, the grain size was ASTM No. 3. This observation is important because it demonstrates that improved creep resistance in the HIP processed material is due to removal of service damage and was not obtained by increasing the grain size at the expense of tensile and fatigue properties.

Metallographic examination of airfoil sections showed negligible internal oxidation, nitriding or alloy depletion at the

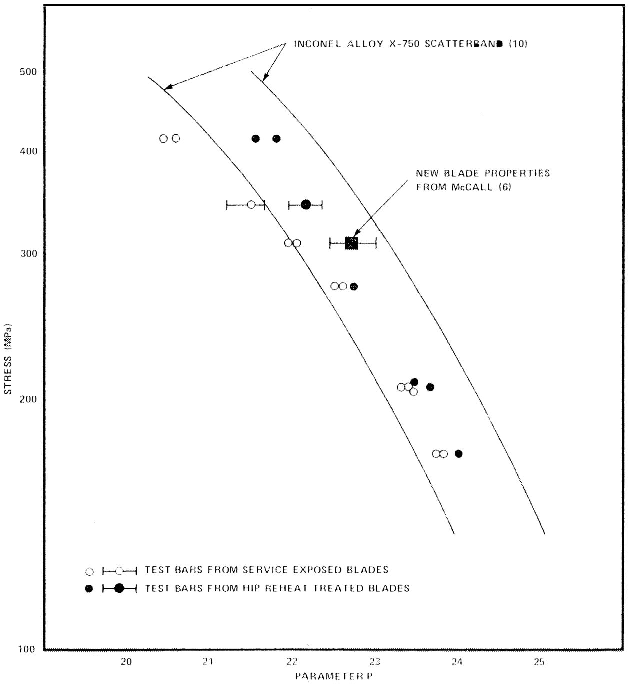


Figure 6. Larson-Miller Plot ($P = T \times 10^{-3}$ ($20 + \log t$). T in °K, t in hours) Showing Service Exposed, New and HIP Processed Blade Stress Rupture Properties.

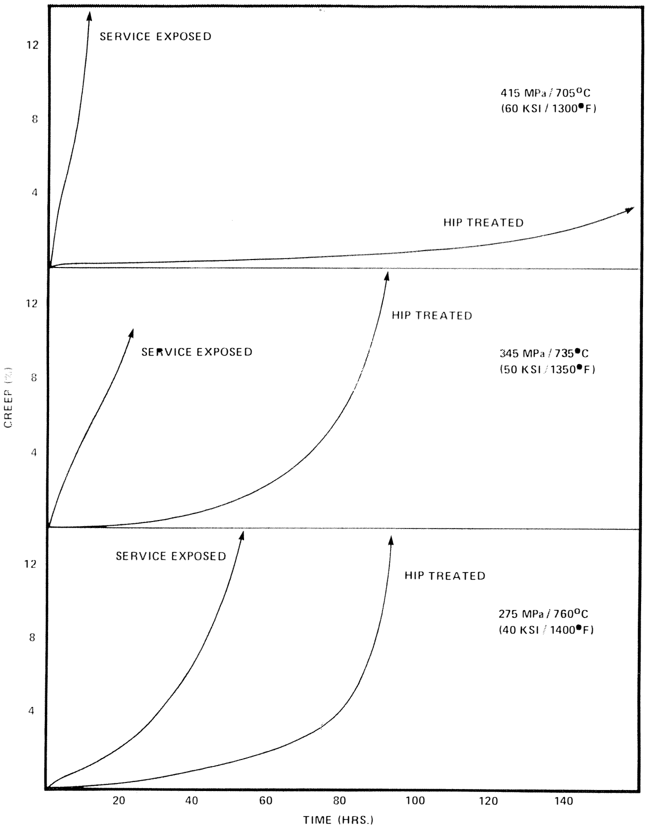


Figure 7. Creep Rupture Curves Comparing the Service Exposed and HIP Reheat Treated Conditions at Three Stress/Temperature Combinations.

surface in either material condition. This observation indicates that surface protection measures during HIP processing were adequate.

The only obvious microstructural differences between service exposed and HIP treated material were revealed in shadowed carbon replicas. The HIP treated microstructure, Figure 8, is comparable to that reported for new material by Raymond [9]. The intragranular γ' is spherical, 0.15 to 0.2 μm in diameter, while the grain boundaries have a well defined "denuded" zone containing nearly unresolved γ' particles approximately 0.01 μm in size. By comparison, the intragranular γ' in service exposed materials is cuboidal, 0.2 μm in size, indicating that some coarsening has occurred (Figure 9). Considerably more γ' coarsening is apparent near the grain boundaries. The original denuded zone has divided into three zones, Figure 9 (b); very little if any γ' is observed immediately adjacent to the grain boundary; in the central zone of γ' particles are cuboidal and range in size from 0.1 to 0.15 μm; the zone furthest from the grain boundary contains coarsened spherical γ' 0.02 to 0.04 μm in diameter. The considerable γ' coarsening in the regions next to the grain boundaries is believed primarily responsible for the lower service exposed properties. The severely overaged condition would result in reduced strength leading to the localization of deformation to the grain boundary areas. Such inhomogeneous deformation will result in cavitation and eventual failure at the preferred failure sites; i.e., the grain boundaries.

Although no clear cut evidence of cavitation or creep voids could be observed microscopically, their presence is inferred from the literature and mechanical test results. It would, in any event, be difficult to distinguish voids from other microstructural features such as pulled out grain boundary carbides.

With regard to grain boundary morphology, there appears to be a heavier carbide film in the service exposed material which was subsequently broken up during the HIP reheat treatment; however, a quantitative analysis of the relative amounts and effect was not carried out.

CONCLUDING REMARKS

The results of the present work indicate the following:

(i) HIP reheat treatment appears to be the best available process for restoring new or near-new creep resistance to used Inconel X-750 turbine blades.

(ii) The successful treatment of a complete blade set indicates that the process is commercially viable.

(iii) Cost estimates indicate that used blades can be rejuvenated at a fraction of the cost of a new set of blades.

The set of HIP processed blades discussed in this paper are scheduled to return to service in June, 1977. Sample blades will be removed periodically and creep rupture tested to establish the service life potential for HIP processed blades.

Initial experiments of a similar nature to the present work have been conducted on other blade alloys such as Udimet 520. The preliminary results appear equally promising providing that suitable process parameters are employed.

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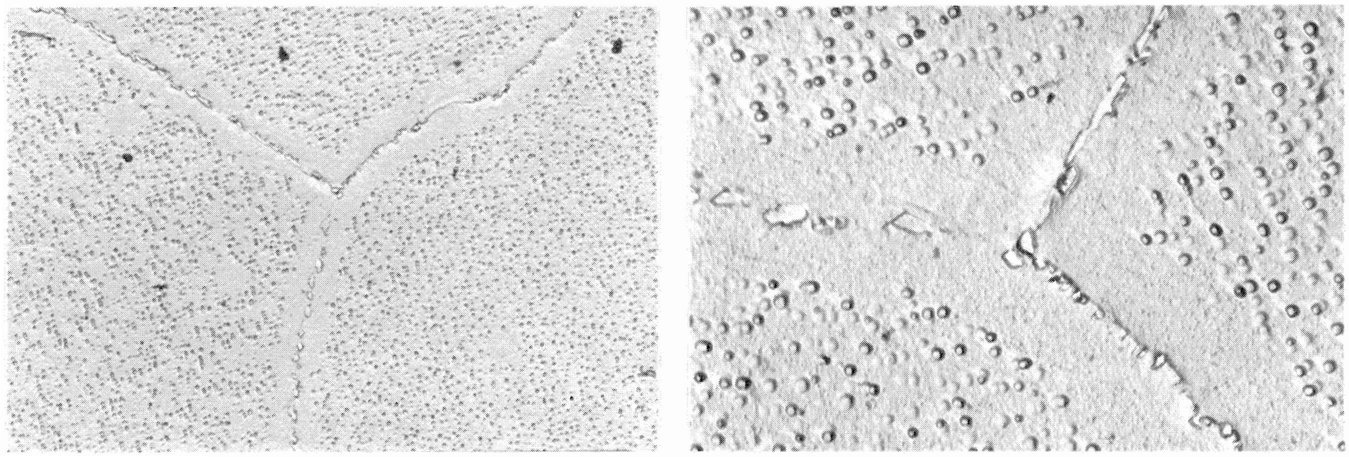
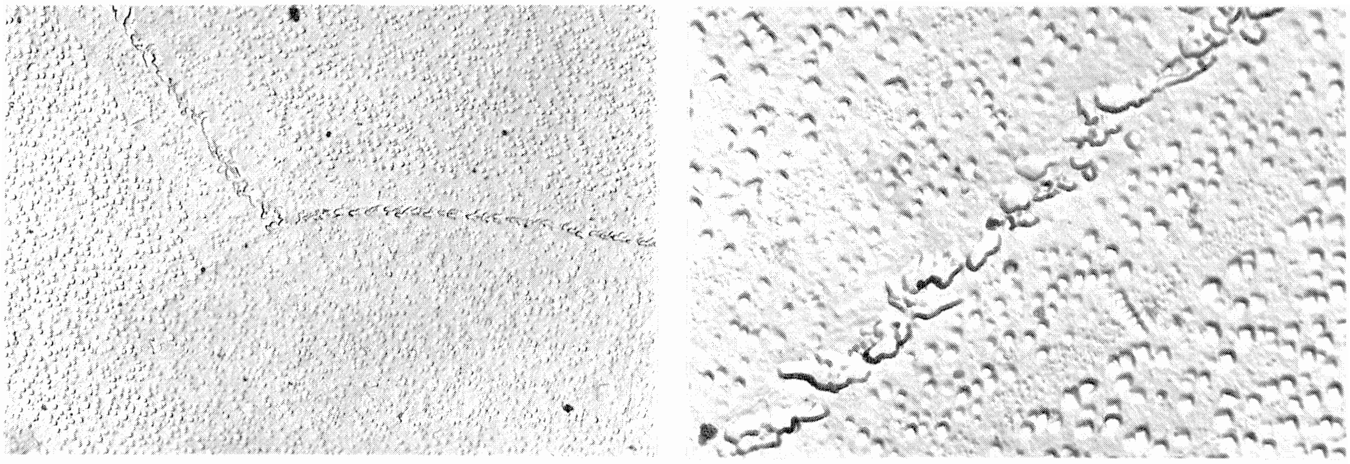


(a) (b)

Figure 8. Carbon Replicas Showing the Microstructure of an HIP Processed Blade. (1) 3500X; (b) 10500X.



(a) (b)

Figure 9. Carbon Replicas of the Microstructure of a Service Exposed Blade. (a) 3500X; (6) 10500X.

to Westinghouse Canada for support and permission to publish the results. The cooperation of Trans Canada Pipe Lines is also recognized.

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