GUIDELINES FOR RELIABLE EXTENSION OF TURBINE BLADE LIFE

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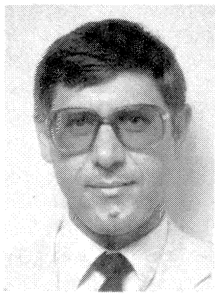

Joseph Liburdi graduated in 1967 from the University of Windsor with a B.S. in Engineering Materials. After graduation he joined Westinghouse Canada, where, as Manager of the Metallurgical Section, he was responsible for metallurgical support to the gas and steam turbine departments, as well as for HIP process development.

In 1979 he established Liburdi Engineering Limited, which specializes in engineering analysis and blade repairs for the turbine industry.

James Wilson graduated from the University of Waterloo in 1974 with a B.S. in Mechanical Engineering. After graduation he joined the gas turbine design department of Westinghouse Canada, where he was involved in the design of a wide variety of rotating and stationary components for the new CW352 gas turbine. In particular, he applied finite element analysis methods to the analysis of rotating and stationary turbine airfoils.

In 1980, he joined Liburdi Engineering Limited, where he is responsible for mechanical design and analysis of blade repair limits.

ABSTRACT

The first task in extending the life of gas turbine parts is to develop meaningful life trend and aging characteristics for each material. Components that have reached their critical life limit can then be hot isostatic press (HIP) rejuvenated and returned to service. Data are presented on the service experience with the first set of blades rejuvenated in 1977, confirming the stability of the process.

Blades which have suffered impact damage or tip rubs can often be restored by welding. However, it is important to analyse in detail the stress distribution in each blade and to consider the mechanical and metallurgical characteristics of the airfoil geometry, weld configuration and filler metal strength.

Stress profiles and life predictions are calculated for weld repaired turbine blades, comparing low strength and high strength filler metal welds. The stress levels in the tip repaired region and in the hole region of a blade with a lashing wire are calculated using finite element analysis. The results indicate that, although a lower strength repair is acceptable in the tip area, it will cause reduced life in a notch or lashing wire hole application.

INTRODUCTION

At the Sixth Turbomachinery Symposium in 1977, a paper [1] was presented by Westinghouse outlining what appears to be the first application of HIP rejuvenation to industrial gas turbine blades. The W62, Inconel X-750 power blades have been in service on the TransCanada PipeLines system since June 1977 and have now accumulated an additional 36,000 hours since they were hot isostatically pressed. Sample blades were recently examined in detail for metallurgical stability and remaining life, and the results are presented in this paper.

In addition to rejuvenation of mechanical properties, the repairability of physical damage resulting from foreign object impact or rubbing will be discussed. This is an important consideration since, in most cases, blades will require weld restoration as well as HIP reheat treatment.

The general guidelines for repair limits outlined in our recent paper [2] will be refined through the use of finite element analysis to include the effect of dissimilar filler metal strengths. Caution must be exercised when contemplating repairs to turbine blades to ensure that the strength and coefficient of expansion of the filler material are compatible with the base material. Otherwise, reductions in creep strength and design margin of safety can occur which can seriously impair the long term reliability of the part.

REJUVENATION

Blade Life Evaluation

The life of high temperature gas turbine blades is dependent on a complex interaction involving metallurgical factors such as creep strength and microstructural stability; mechanical factors such as creep, stress, metal temperature and fatigue excitation; and environmental aspects such as hot corrosion and foreign object damage.

The turbine user must realize these limitations and not rely solely on the manufacturer's recommended lives. Instead, each user should supplement the manufacturer's information with his own specific data on life trends. This can be best accomplished by establishing a gas path component management program [2, 3], which records the exact life of all components and obtains specific information on the actual condition of the blades by periodically examining representative samples. The evaluation should include a detailed examination of the microstructure, as well as stress rupture tests for remaining life. The mechanical tests must be performed at the lower temperature range (generally below 850°C) to properly detect creep damage.

In particular, one must avoid generalizations pertaining to the life or reported behaviour of similar alloys. For example, In738, which is a popular blade alloy, when examined after approximately 30,000 hours of service, exhibited radically different results, depending on the engine and application [4]. In one case, as illustrated in Figure 1, the material was found to be stable and virtually unaltered; whereas, in a different application, the metal temperatures were probably higher, and the structure was severely overaged, resulting in premature creep failure.

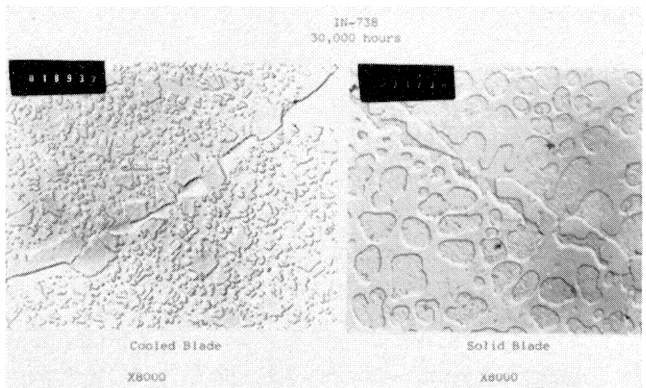

Figure 1. Electron Microscope Replicas of the Microstructures Exhibited by Two In738 Blades After Approximately 30,000 Hours of Service in Different Engines. The Structure on the Left, from a Cooled Blade, is Virtually Unaltered; Whereas, the Microstructure on the Right, from an Uncooled Blade Which Was Probably Exposed to Higher Metal Temperatures, Is Severely Overaged and Failed in Creep. Original Magnification × 8,000.

Inconel X-750 Blades

The usefulness of a life trend plot can be best illustrated for the Inconel X-750 family of blades shown in Figure 2. These are uncooled, solid blades which are relatively easy to test.

The blades in question were removed from service in 1977, after approximately 45,000 hours of service. As indicated by the life trend curve, they had not yet reached their critical creep life, but because the properties fell below the specified minimum level, it was decided to rejuvenate the blades at this time. Subsequent investigations [3, 5] revealed that the premature decrease in life was probably due to a slightly weaker chemistry, and possibly original heat treatment. As noted in the original paper [1], conventional reheat treatment was not capable of fully restoring the properties, and superior results were obtained by adding hot isostatic pressing to the recovery cycle.

In order to assess the stability and life of the HIP rejuvenated blades, the customer agreed to remove representative blades after approximately 8,000 [5], 24,000 [2] and 36,000 hours of additional service. Blades from the weakest heat treatment were chosen, in order to obtain those in the worst condition. The blades were examined both microstructurally and mechanically for residual creep life.

The results of stress rupture tests taken from the blade airfoil are illustrated in Figures 2 and 3. The graphs clearly illustrate that the mechanical properties have remained stable and the blades are suitable for continued service.

The microstructural analysis shown in Figure 4 confirms that the alloy is behaving in a stable manner. The structure is typical of Inconel X-750 and shows little or no sign of overaging.

It is important to note that credit for the success of the rejuvenation should not be attributed solely to the use of HIP, but rather to the selection and optimization of the HIP and reheat treatment parameters used in the processing of the parts. It is possible that, had the cycles not been optimized, the parts might not have responded as well.

Inconel 700 Blades

In contrast, Inconel 700 blades from the same engines exhibit virtually no creep damage after approximately 100,000 hours of service (Figure 5). However, blades are often rejected because of foreign object damage, tip rubs or hot corrosion. In the past, these damaged blades could not be weld repaired or coated because they did not respond well to reheat treatment [6].

Fortunately, after prolonged testing, we were successful in developing an optimized reheat treatment cycle, incorporating hot isostatic pressing, which restored the creep properties consistently. The process has been applied since 1980 to several sets of weld repaired and coated blades, and all have responded well.

The stress rupture results after HIP rejuvenation, shown in Figure 5, are consistent with new material properties, and the ductility was restored to the required levels. The microstructure illustrated in Figure 6 is typical of new Inconel 700, with no detrimental acicular phases evident.

Although Inconel 700 blades can now be salvaged, users should exercise extreme caution to ensure that the reheat treatment parameters have been adequately tested over several heats of material, and that sample blades are destructively evaluated to qualify each batch of repaired blades. Otherwise, it is possible that the blades will not respond uniformly and that the properties of some blades can be drastically lower.

Hot Isostatic Pressing

Since 1977, the use of hot isostatic pressing in the gas turbine industry has increased dramatically to include not only rejuvenation, but also the healing of casting defects in new blades. Unfortunately, this popularity appears to have created confusion and skepticism among some users, as well as abuses of the process. It is, therefore, essential that we briefly review why HIP is used and perhaps remove some of the mystique surrounding the process.

Hot isostatic pressing should be regarded as a heat treating function in which, instead of vacuum, the parts are exposed to a uniform gas pressure which is effective in collapsing internal cavities. The microstructure of the material can be drastically altered by the exposure to high temperatures, and steps must be taken in subsequent heat treatment cycles to restore the desirable phases and grain boundary features. Therefore, it is essential that the cycles or temperatures used be consistent with the heat treatment of the alloy. This requires extensive metallurgical experience with the different superalloy systems, and the flexibility to tailor specific cycles for the more sensitive materials rather than to utilize the more economical, commercially available batch runs.

The exact parameters used for both HIP and vacuum reheat treatment are often proprietary, and, as a result, the same alloy can be subjected to a variety of treatments with varying results. This generally puts the onus on the user, who does not have the in-depth metallurgical expertise to pass judgment on whether his parts are being treated properly. Perhaps industry standards should be established to provide safeguards.

With regard to potential applications, HIP can be used for more than the rejuvenation of creep damage. In the repair of used blades, hot isostatic pressing is often included in the work scope to improve weld homogeneity and minimize post weld cracking, or, as in the case of Inconel 700, to improve the response to heat treatment. In each case, if used properly, HIP

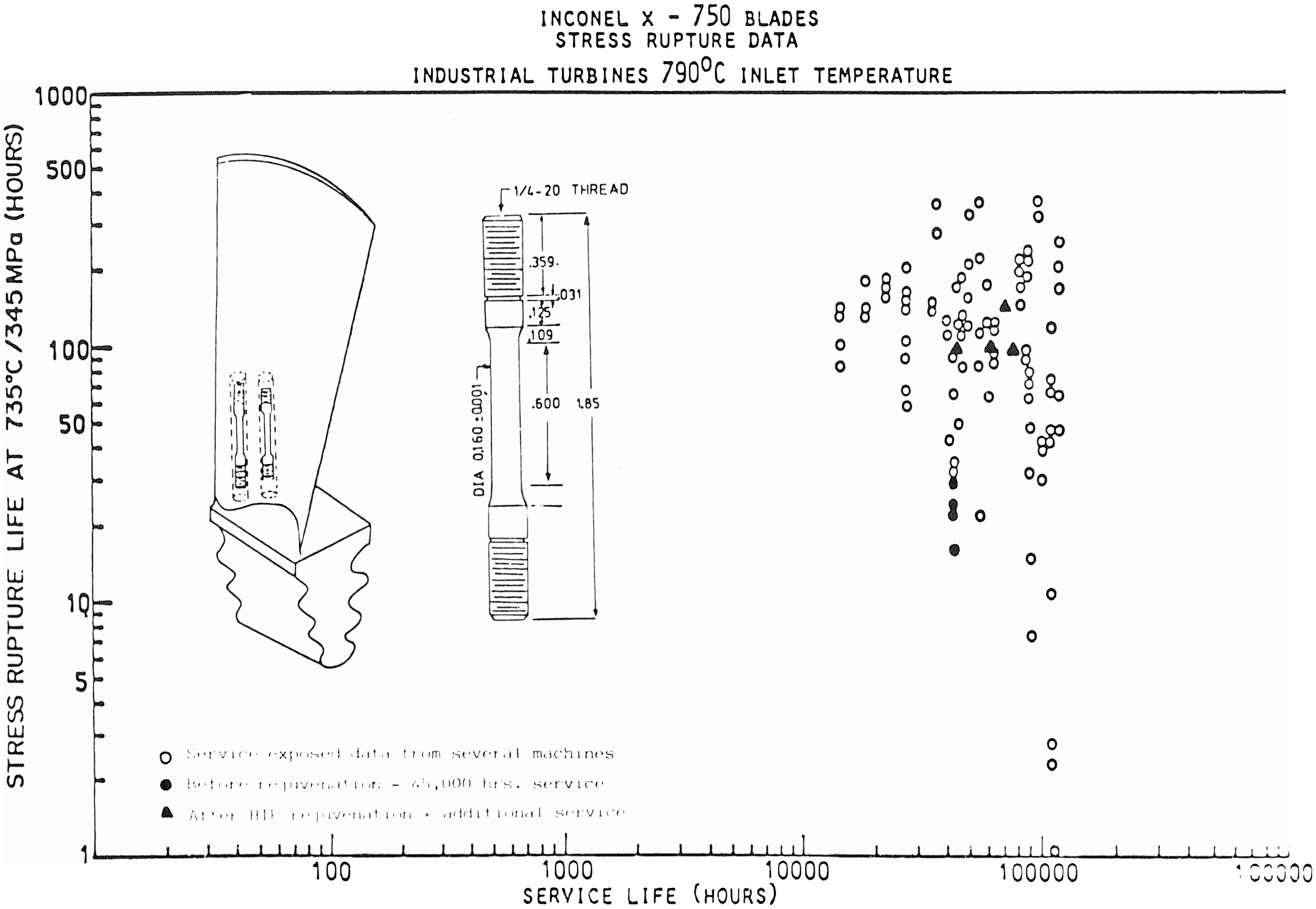

Figure 2. Life Trend Curve for Inconel X-750 Blades, Highlighting the Properties Exhibited by the W62 Row 3 Blades Before and After Rejuvenation.

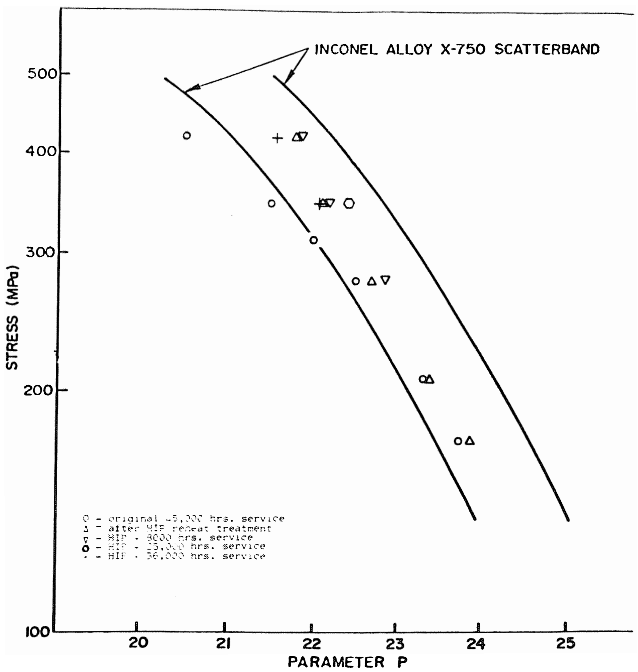

Figure 3. Larson-Miller Plot ($P = T \times 10^{-3} (20 + \log t)$, T in °K, t in Hours) Showing Original Service Exposed and HIP Processed Blade Stress Rupture Properties. After HIP the Blades Were Returned to Service and Monitored Periodically for Remaining Life.

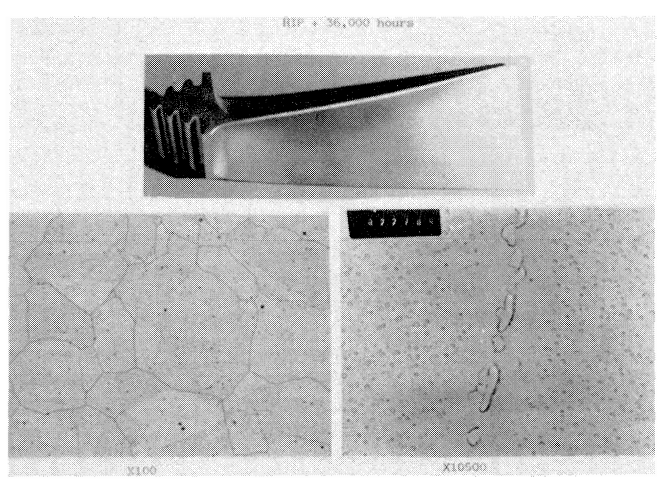

Figure 4. Photographs of the HIP Reheat Treated Inconel X-750 Blade After an Additional 36,000 Hours' Service. The Microstructure Is Virtually Unchanged, With Only Slight Grain Boundary Carbide Coarsening Evident.

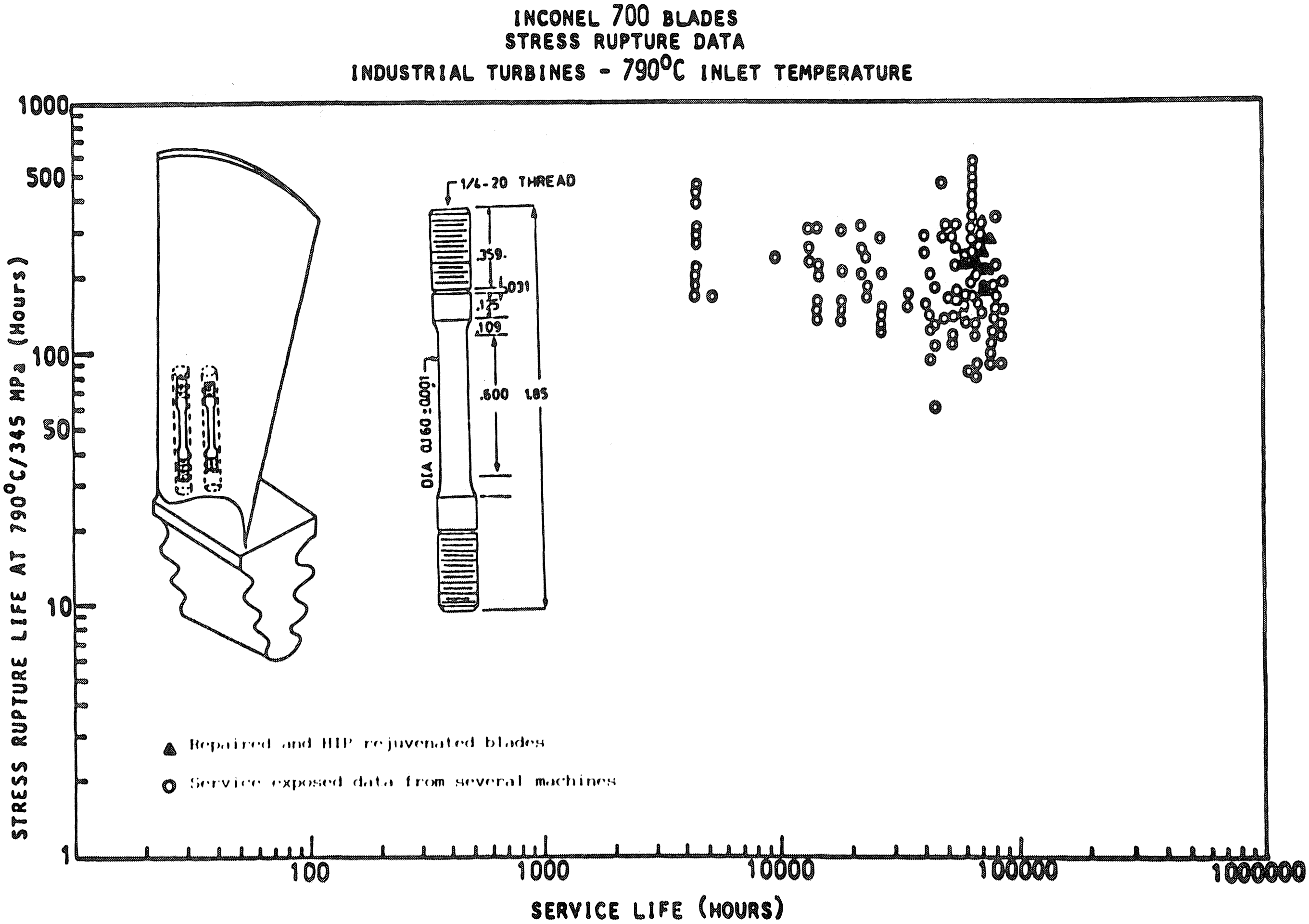

Figure 5. Life Trend Curve for Inconel 700 Blades, Showing the Effectiveness of the HIP Reheat Treatment Process on Repaired Blades.

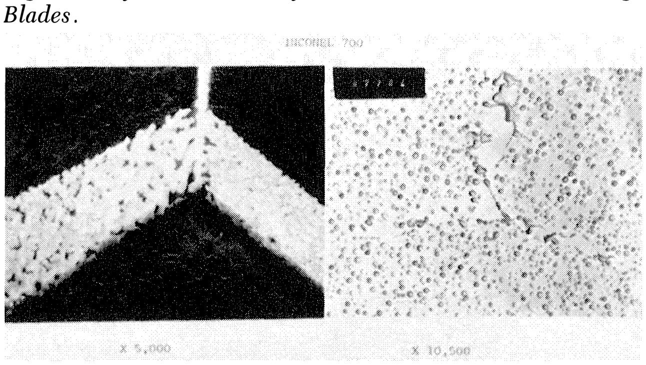

Figure 6. Photographs Illustrating the Structure of the Inconel 700 Blades After HIP Reheat Treatment. The Photograph on the Left Shows the Grain Boundary Carbide Network, While the Replica on the Right Shows the Strengthening Gamma Prime Particles.

should improve the integrity of the repaired part and provide a greater degree of reliability to the turbine user.

EXTENDING BLADE REPAIR LIMITS

General

The extent of weld repair in turbine blades is governed by the stress pattern in the airfoil, the location of the repair and the strength and quality of the weld. Assuming that good quality control is maintained and reinforced with creep rupture and metallographic testing, the primary consideration from a design point of view is the strength of the filler material used in the weld.

Typically, the lower strength weld metals are relatively easy to weld, while the high strength materials used in current turbine blades are much more difficult to weld without flaws. For this reason, conventional weld repair using low strength filler wire has generally been limited to low stress regions of the airfoil.

We are now making an effort to extend the repair limits for turbine blades both by applying an improved knowledge of local stress in the airfoil, and by developing improved high strength filler metals and processes. This combined metallurgical/mechanical design approach to repairs should result in a better understanding of repairs, as well as improve reliability.

The tool we are using for evaluation of the stress patterns in repaired turbine blades is finite element analysis. Using this technique, a mathematical model is created using small elements of finite size to approximate the continuous geometry and stiffness of the structure. When boundary conditions are input, the loads, deflections and stresses at points throughout the structure are calculated. The resulting stresses and strains can be compared to the strength of the base metal and weld metals being considered in the repair. Using advanced computer programs, the effects of different weld metal strength, creep strain, elastic modulus and thermal expansion characteristics can be included in the stress calculations.

Current Weld Repair Limits

As indicated previously, the majority of the repairs performed to date have been accomplished using weaker weld filler materials such as Inconel 625 and, therefore, limited to the lower stressed portions of the airfoil. An analysis of a typical stress pattern for a free-standing blade, as shown in Figure 7, indicates that the margin of allowable stress over actual net section stress is greatest at the tip. This feature permits the use of lower strength welding materials close to the blade tip and accounts for the relative success enjoyed by such repairs. For example, Figure 8 shows a typical tip repair on an Inconel 700 blade using Inconel 625 weld metal.

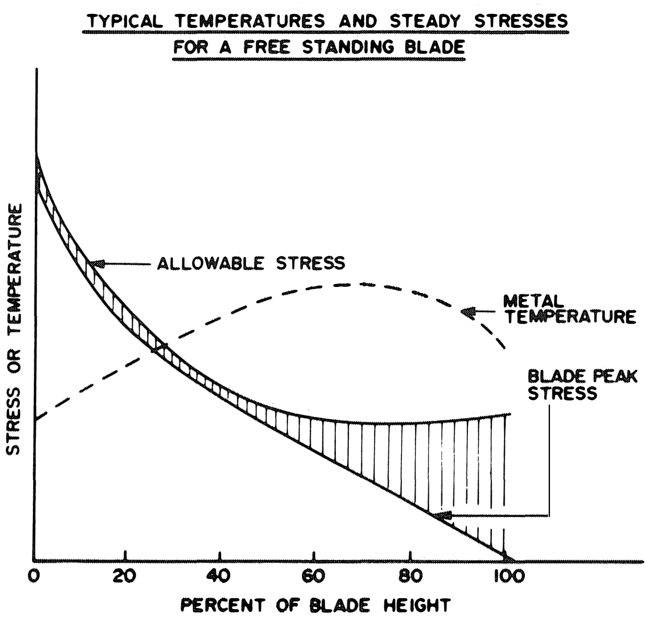

Figure 7. Diagram Illustrating the Net Section Stress Profile Along the Airfoil of a Free Standing (Unshrouded) Blade. The Band or Spread Between the Allowable and the Actual Blade Stress Determines the Average Strength Margin Available at Various Heights.

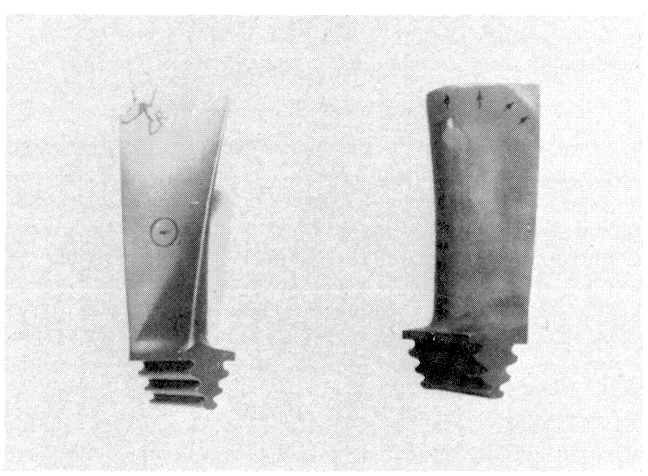

Figure 8. Photographs of a Service Damaged Inconel 700 Turbine Blade Before and After Weld Repair. Inconel 625 Filler Metal Was Used for Repairs Close to the Blade Tip Where the Stresses Are Low. Note That the Trailing Edge Repair Is Opened to the Tip to Minimize the Effect of Thermal Strains Resulting from the Different Coefficients of Expansion.

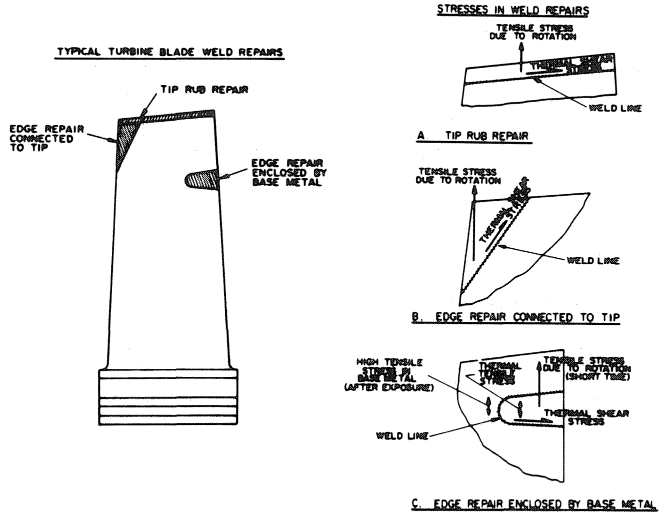

Figure 9. Diagrams Illustrating the Geometry of Typical Airfoil Weld Repairs, Along With a Summary of the Principal Stresses Due to Centrifugal Loading and Thermal Strains. In the Case of the Enclosed Notch, Differences in Coefficient of Expansion Will Result in Additive Tensile Stresses at the Tip of the Notch. Also, With Time, the Weaker Filler Metal Will Creep or Relax and Lose Its Load Carrying Ability.

In addition to the overall stress distribution, one must also consider the stress patterns associated with the various geometries or weld preparations used. The diagrams shown in Figure 9 illustrate the principal stresses along the weld interface arising from both centrifugal loading and differences in thermal expansion characteristics. The analysis indicates that, for tip- and edge-connected welds, the thermal shear stresses can be accommodated along the weld interface. However, care must be exercised when the weld repair geometry approximates a notch in the edge of the airfoil.

The notch repair can cause local high stresses due to material property differences between the weld and base metals. For instance, if the weld metal has a lower coefficient of thermal expansion than the base metal, the weld will be loaded in tension when the blade temperature rises during operation. Also, as the weld metal generally will have lower creep strength than the base metal, it will relax in service, and most of the load on the section will be transferred to the base material. The net effect can be that the weld metal carries almost no load and the repaired notch acts as a stress concentration.

Stress Analysis

In order to establish more accurate limits regarding the extent of allowable repairs using dissimilar filler metals, improved knowledge of the local and net section stresses in the airfoil is required. This can be best accomplished by using finite element analysis to model the geometry and material properties of the turbine blade, as well as the filler material used in local repairs.

A finite element model of a Frame 5 second stage turbine blade is shown in Figure 10. Twenty-node quadratic brick elements were used to accurately model the curved surfaces of the airfoil. The blade model was subjected to centrifugal and thermal loads, and the displacements, strains and stresses were calculated using the finite element computer program ANSYS (7).

In the first case, repairs to the blade tip were considered. The material properties of a typical weld metal were used for

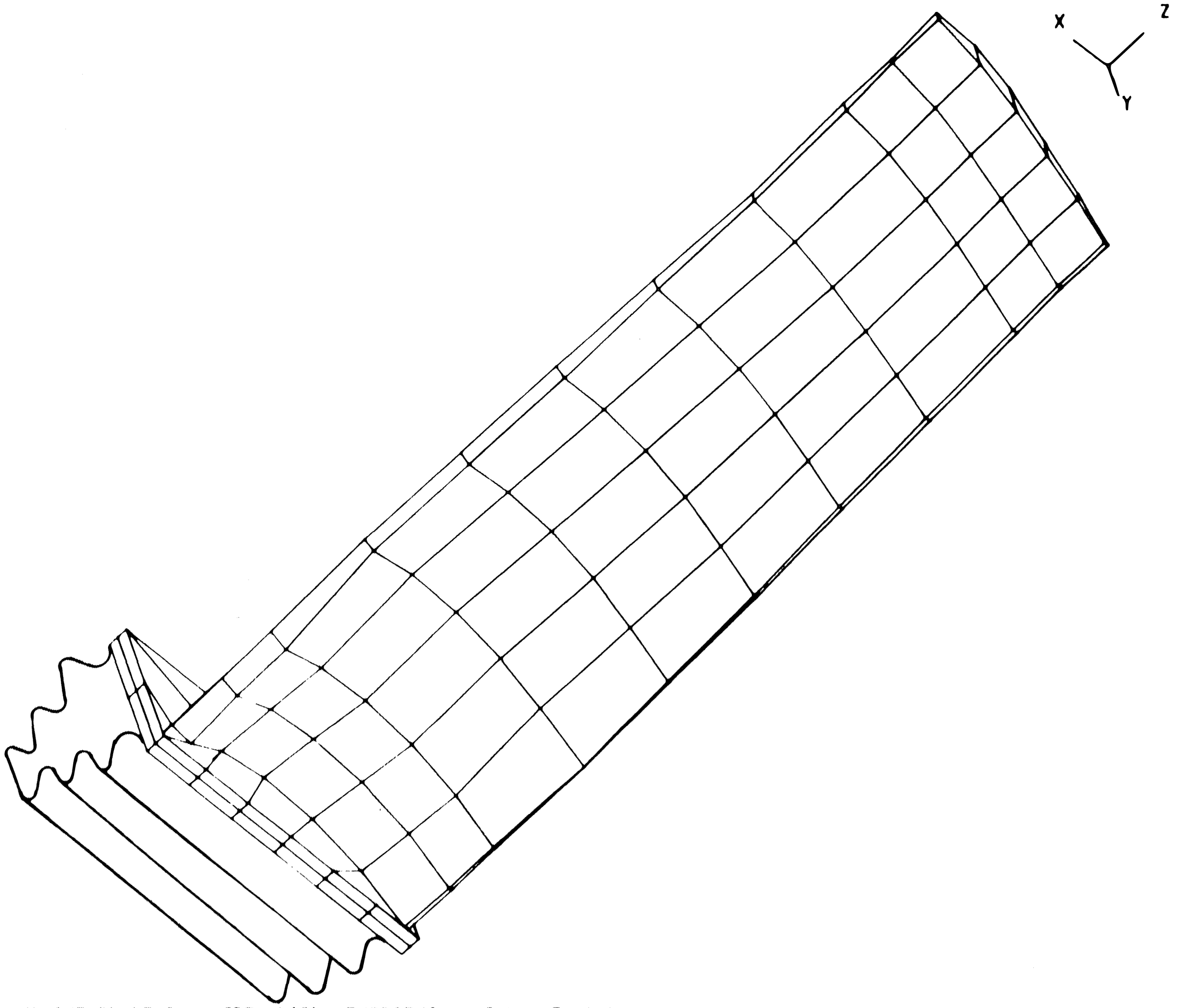

Figure 10. Computer Plot of a Finite Element Mesh of a Free Standing Turbine Blade (Frame 5, Second Stage Bucket). The Curved Surfaces of the Airfoil Are Accurately Modelled by the Use of the Quadratic Element Formulation. The Blade Root Was Drawn In for Clarity.

the row of elements at the tip of the airfoil, and a comparison was obtained between the stress in the original blade and that in the tip repaired blade. The results, presented in Table 1, indicate that although the life, based on creep rupture, is reduced in the weld repaired area of the blade, it still exceeds the required overall airfoil life, and, therefore, the repair is considered satisfactory.

Table 1. Comparison of Creep Rupture Life for Tip Welded Blades.

	Maximum Principal Stress at Tip (ksi)	Creep Rupture Life at Tip (hrs)
Original tip configuration	2400	5×10^7
Welded tip configuration	6300	1×10^6

The same technique can be used to evaluate proposed weld repairs at any location. Naturally, the model may have to be modified and the mesh refined in areas of high stress or severe discontinuity. Also, other loads may have to be considered, such as nonuniform temperatures, gas loading and stresses due to blade vibration. Nonlinear effects such as yielding and creep relaxation must also be modelled. All of these effects can be analysed using modern computer codes.

Weld Metal Selection

Extensive weld repair can be accomplished if the strength, physical properties and quality of the weld metal are properly matched to the base material. Ideally, the weld metal composition should match the base metal, and the weld should be defect-free. Unfortunately, most modern turbine blade alloys are extremely difficult to weld using conventional techniques, and the availability of suitable weld filler metals is quite limited.

High strength filler metals generally have lower ductility, higher rupture strength and less creep relaxation than commonly used lower strength weld metals such as Inconel 625. The rupture strength and creep rate are closer to those of the blade material, which means that they carry closer to their share of the section load. They can, therefore, be used for repairs closer to the base of the airfoil, as well as in notches and holes in the airfoil. Because of their low ductility, they must be closely matched to the base metal in thermal expansion, to avoid large thermal strains which could cause cracking or high local stresses.

An example of the application of high strength welding is shown in Figure 11. These Nimonic 80 turbine blades had suffered extensive foreign object damage, which extended into the highly stressed areas of the leading edge and required the use of a matching filler metal. Inconel X-750 welding wire was chosen because of its availability and close match to the base material chemistry. The blades were HIP reheat treated after welding and tested for stress rupture properties. Favourable results, exceeding the new material requirements, were obtained from both the weld metal and the base material.

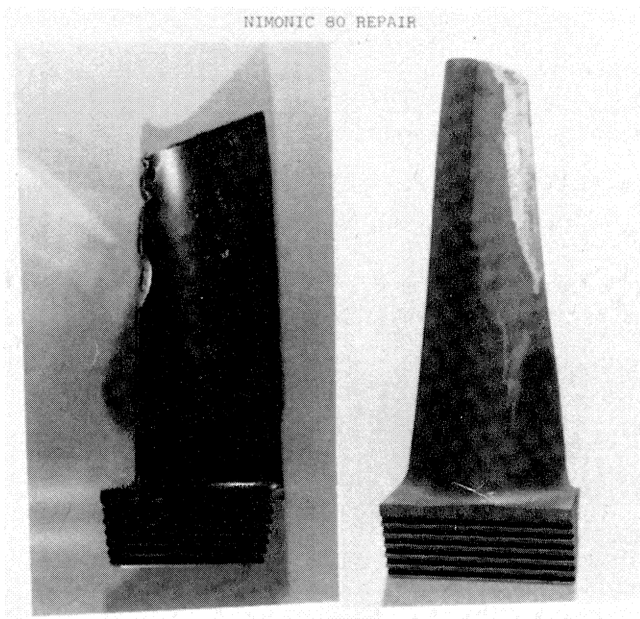

Figure 11. Photographs of a Nimonic 80 Service Damaged Blade Before and After High Strength Weld Repair. The Damage Extended into Highly Stressed Areas of the Leading Edge, and a Stronger Load Carrying Weld Material, Such as Inconel X-750, Was Required.

Lashing Wire Hole Repair

Another critical area which requires special attention is the repair of a blade lashing wire hole. Lashing wires are used on turbine stages to modify blade frequencies and to provide damping in order to avoid fatigue failures (Figure 12). The use of lashing wires creates a unique problem because the presence of the hole in the airfoil, combined with the centrifugal load of the wire, produces high local stresses. Premature creep rupture damage can occur near the hole, and corrosion and wear can make a repair necessary.

A common repair technique is to braze a bushing into the oversize hole. However, an evaluation of the strength of the braze repair, as shown in Figure 13, indicates that the interface does not have the necessary creep strength. Stress rupture samples taken through the brazed plug failed prematurely on loading along the weak braze interface.

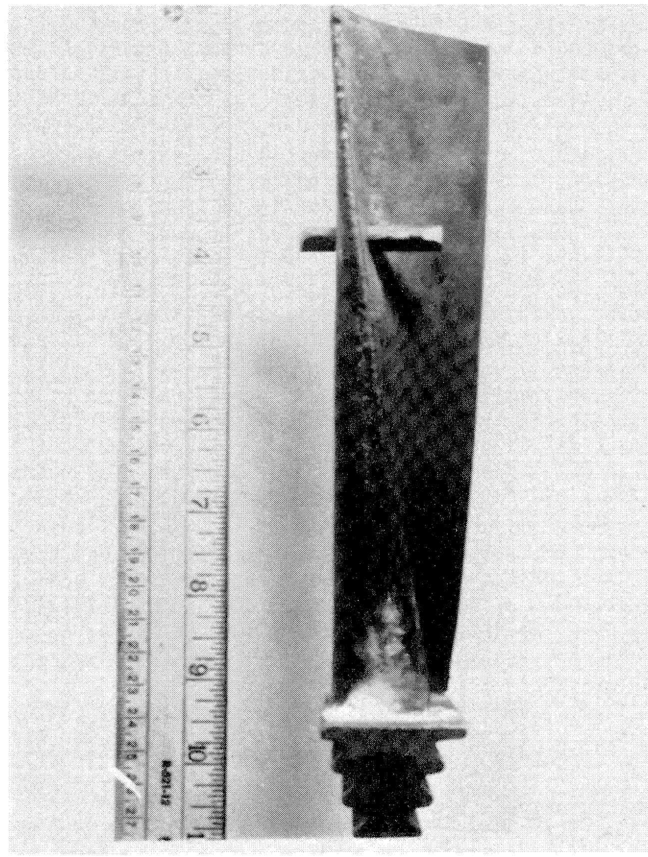

Figure 12. Photograph Showing an A286 Turbine Blade With Lashing Wire Still in Place. Lashing Wires Cause High Local Stresses in the Airfoil at the Hole, and Their Repair Requires Special Attention.

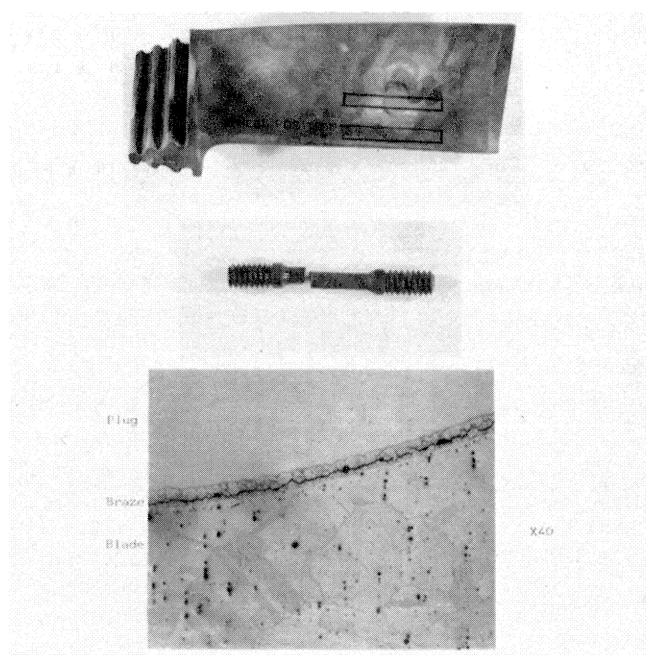

Figure 13. Photographs of the Failed Stress Rupture Sample Taken Through the Brazed Plug, Illustrating the Intergranular Failure Through the Braze Metal. The Braze Showed Much Lower Strength Than the Base Metal and Therefore Would Not Be Able to Adequately Transmit Load Across the Interface.

A two dimensional finite element model was therefore produced to evaluate the local stress field around the hole. Eight-node quadratic solid elements were used. The blade section was assumed to be of uniform thickness and to be symmetrical about the hole axes, so that only one quadrant was modelled (Figure 14). Uniform pressures were applied to simulate centrifugal loads due to the airfoil and the lashing wire. A uniform temperature was applied to all elements.

A plot of equivalent stress in the structure is shown in Figure 15. The analysis indicates that the peak stress is at the edge of the hole and is five times higher than the average section stress. This implies that optimum material properties are required at the surface of the hole to withstand the high local stresses.

Next, we considered the case of possible repairs to the hole using dissimilar weld metals or braze. The material properties of the row of elements closest to the hole were changed to model the effect of a mismatched weld metal repair. The results, illustrated in Figure 16, indicate that even higher local stresses are induced by this geometry. The reduction in creep rupture life caused by this type of repair was then calculated, and the results are summarized in Table 2. Obviously, this is a critical area of the blade, and any repair procedure should approach the strength of the original blade alloy.

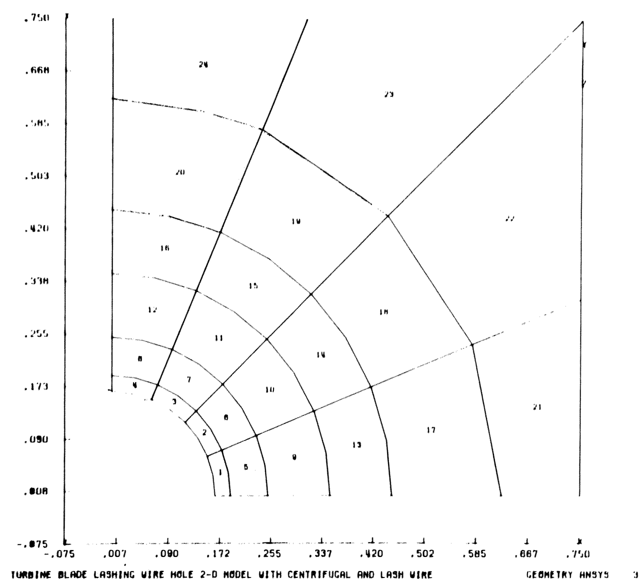

Figure 14. Computer Plot of a Turbine Blade Lashing Wire Hole, Modelled Using Finite Elements. The Model Is Constrained Along the Left and Lower Edges, and the Loads Are Applied in the Hole and Along the Upper Edge.

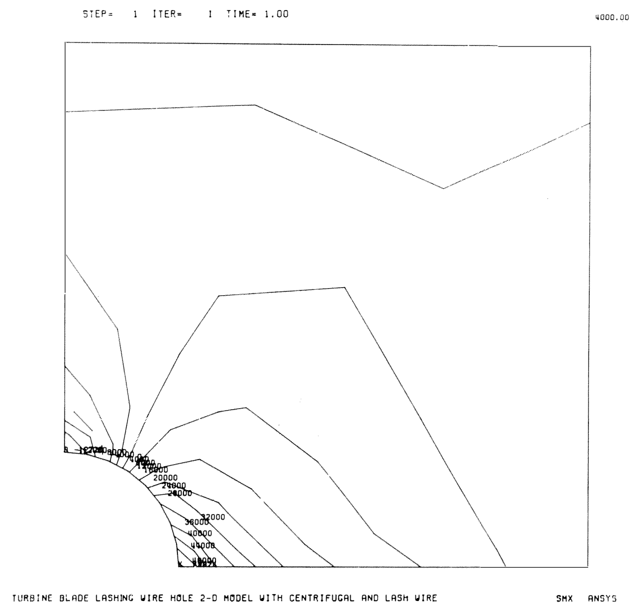

Figure 15. Computer Plot of Principal Stress at the Lashing Wire Hole With Uniform Material Properties.

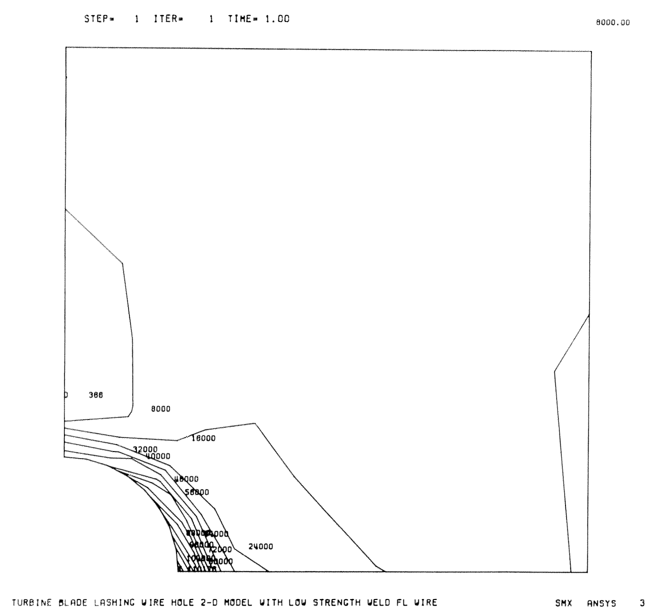

Figure 16. Computer Plot of Principal Stress at the Lashing Wire Hole Using Unmatched Weld Metal Properties Near the Hole. The Isostress Lines Show a Peak Stress of 110,000 psi in the Weld Metal at the Edge of the Hole.

Table 2. Comparison of Creep Rupture Life for Lashing Wire Hole Repair.

	Maximum Principal Stress (ksi)	Average Section Stress (ksi)	Life Based on Maximum Stress (%)	Life Based on Average Section Stress (%)
Original hole configuration	49,000	10,000	100	100
Repair with mismatched metal at hole surface	110,000	16,000	0.10	3.25

NOTE: The actual life will lie between the two calculated lives, due to local creep relaxation around the hole.

CONCLUSIONS

Our analysis indicates that the technology is now available to safely rejuvenate and repair turbine blades. HIP processing, combined with optimized reheat treatments, has been demonstrated to be both effective and stable in the rejuvenation of creep damage. The process can also be beneficial when used in conjunction with weld repairs to improve the soundness of the repair.

The application of finite element stress analysis provides a more accurate method of examining the types and extent of repairs permissible. The effects of material property differences can be analysed and combined with stress rupture testing and microstructural analysis to provide reliable repairs. It has been shown that highly stressed areas, such as notches and lashing wire holes, should not be repaired using weaker, dissimilar materials, because these can result in a serious reduction in creep life.

In the future, there is a need to develop improved high strength welding processes capable of providing mechanical properties compatible with the blade material. This will enable repairability limits to be extended into the highly stressed areas of severely damaged components.

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