APPLICATION OF Ti-6Al-4V AS STEAM TURBINE BLADING MATERIAL

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Introduction

Low pressure steam turbine blade failures comprise the largest single source of forced outage in fossil fueled power generation turbines, amounting to an estimated 20-25% of all turbine outages. About one-third of these involve corrosion as a contributing factor. The chief location of blade failures is the next-to-last rotating stage (L-1 row) as illustrated in Figure 1 [1].

The L-1 row is where the initial condensation from the superheated steam occurs. The initial condensation contains most of the impurities in the steam. Blades that operate in dry steam are not subject to corrosion, while blades that operate in wet steam are less susceptible to corrosion because of washing effects. The initial condensates are of highest concentration, and are subject to alternate wetting and drying as the turbine load changes between full load and partial load. Thus, the deposits at the L-1 row become concentrated to the point of saturation and even may be solid. The composition of the deposits depends on the specific impurities in the steam and their solubility-temperature relationships. From the point of view of corrosion, the most important impurities in fossil turbines are alkali chlorides and sulfates. In fossil turbines, the pH of the wet deposit varies from alkaline to acid as the steam expands from the high pressure through the low pressure turbine. Corrosion is worse under conditions of low pH and when oxygen is dissolved in the salt solutions. During turbine operation oxygen is low, but may become high during periods of standstill.

Sodium hydroxide also can occur in steam turbines as a result of improper water treatment. Existing data suggest substantial corrosive effects at high concentration (high pH) and high temperature [4]. Such conditions occur only rarely in fossil turbines. Hence, the matter is not of major concern to the application discussed in this paper.

Common blading steels generally are of the martensitic chromium type characterized by Fe-13 Cr. The presence of the corrosive chloride and sulfate deposits results in pitting on the surface of the blades, in crevices between the blade roots and steeples, or at shrouds and tie wires. An example of a
heavily pitted L-1 row that was exposed to corrosion during standstill is shown in Figure 2. The pits form sites for corrosion fatigue crack initiation. The fatigue cracks nucleate and grow as a result of the alternating stresses which are superimposed on the steady centrifugal and bending stresses on the blades. The steady stresses typically are about 175 MPa whereas the alternating stresses can approach about 35-70 MPa. The corrosive environment, characterized by saturated salt solutions, has a drastic detrimental effect on the fatigue strength of 13 Cr steel, particularly at low pH and in the presence of dissolved oxygen, as is illustrated in Figure 3 [2].

The work to be described will present a solution to this problem in turbine reliability through the substitution of titanium blades for steel blades in the moisture transition region of LP turbines. Also, the titanium blade substitution is of interest for last stage blading. Here the steam contains sufficient moisture to not be corrosive, except in double reheat turbines where the moisture transition can occur at the last row.

The last stage blades in LP turbines are the longest blades in the turbine. The maximum length of last stage blades limits the maximum size of steam turbines, since blading steels operate at the limit of their fatigue strength capabilities. The permissible length of 13 Cr steel blades corresponds to about 850 mm for a 3600 RPM machine and 1320 mm for a 1800 RPM machine. Another threat to reliability of last stage blades is erosion from water droplets that impinge on the leading edge at supersonic speeds in the largest turbines. It is necessary to protect the steel from water droplet erosion by erosion resistant shields made of stellite, or by hardening heat treatments of the leading edge region. Titanium last stage blades probably would not require erosion resistant shields, since the erosion resistance of Ti-6Al-4V titanium alloy is substantially better than that of the 12 Cr steel, as shown in Figure 4 [3]. Another limitation to the length of last stage blades is the ability of the blade root attachment to operate at safe stress levels. With an equal volume substitution of titanium for steel, the attachment stress would be reduced to about 60% of the steel value, which would permit the steel-to-blade attachment to be heat-treated to lower strength levels where susceptibility to stress corrosion cracking would be less. With an equal weight substitution, longer blades could be used without increasing the stress on the blade root connection.

**Design Criteria for Titanium Blades**

The important design criteria for blades is fatigue crack nucleation rather than fatigue crack propagation. The number of load cycles on a blade is extremely high, estimated to be $10^9-10^{12}$ cycles, depending on the mode of vibration and source of excitation. Thus, a crack of significant size cannot be tolerated because it would soon propagate to critical size. Titanium alloys have better fatigue endurance properties than steels without taking into consideration their superior corrosion resistance. This is shown in Figure 5, where the fatigue strength of Ti-6Al-4V in air is seen to be about 30% higher than that of 13 Cr steel [1]. However, the fatigue strength in the presence of corrosive environments is the most significant factor in the substitution of titanium for steel in the transition row. The fatigue strength of 13 Cr steel is reduced to about one-fifth to one-third of that in air in the presence of NaCl solutions, whereas the fatigue strength of the titanium alloy is relatively unaffected.

The superior corrosion resistance of titanium under conditions in the L-1 row of steam turbines results from its chemical stability in aqueous solutions over a wide range of pH-values, as illustrated in Figure 6 [4]. The L-1
Figure 1. Forced outage rate due to blades 1966–1977 [1].

Figure 2. Example of heavy pitting of an L-1 row of 13 Cr steel blades after service.

Figure 3. Effect of pH and oxygen content in water and saturated NaCl on the 10^7 cycles fatigue strength of 13 Cr steel at 80°C [2].

Figure 4. Comparison of typical erosion resistance of Ti-6Al-4V, 12% chromium steel blade material and STELLITE 6B erosion shield material [3].

Figure 5. Fatigue properties (R = -1) of 13 Cr steel and Ti-6Al-4V [1].

Figure 6. Temperature and pH effects on corrosion of titanium in saturated brine.
row generally operates below 80°C, where titanium is unaffected, even under crevice conditions from pH2 to pH14. The potential of titanium in NaCl solutions corresponds to TiO2 stability over the entire range of pH anticipated in the moisture transition row.

If one wishes to take advantage of the better strength-to-weight ratio of titanium compared to steel, the length of the last stage blades can be increased by at least 40% more than that for steel blades. The increased blade length would permit an improvement in turbine efficiency of as much as 1% in fossil turbines. In a nuclear turbine, which generally operates at a lower overall thermal efficiency, the improvement in turbine efficiency should be even higher, about 2% [8] for the 40% increase.

Most of the titanium applications in blading have involved direct geometry substitutions for steel, where the full weight saving is realized. In making a geometric substitution of titanium for steel, advantage can be taken of the fact that the vibrational frequencies of titanium and steel blades of the same geometry are approximately the same. The frequency of vibration varies as \((E/P)^{1/2}\) where \(E\) is the modulus of elasticity and \(P\) is the density. In blades it is essential to avoid resonant frequencies occurring in the lower modes of vibration during running speeds. A Campbell diagram is illustrated in Figure 7 where titanium and steel blades over the first three modes of vibration are illustrated for a 585 mm blade which was used in a turbine test [3]. Resonance of the modes would occur if at running speed (3600 RPM) the blading natural frequency would coincide with a multiple of the running speed. In design the blading frequencies are constrained to fall between multiples of running speed at the synchronous speed. This design procedure is known as tuning. A problem that might be encountered with titanium blades would be variation in modulus of elasticity as a result of variable texture from one blade to the next, which could cause resonance in some blades. The modulus normal to the basal plane can be considerably higher than that transverse to the basal plane, affecting blading frequency due to detuning.

Another potential problem is the low damping capacity of titanium relative to that of steel. Figure 8 shows the damping of 12 Cr steel is about 15 times higher than Ti-6Al-4V. With a superimposed mean stress of 140 MPa the ratio is reduced to three times. Damping acts to limit the magnitude of vibratory stress in blading by energy dissipation. Titanium lacks the magnetomechanical contribution to damping found in the steels used in stream turbines. However, material damping is only a fraction of the total system damping in long blade designs. Mechanical damping and aerodynamic damping are major contributors to total system damping. Limited blade testing indicates that material damping is a sufficiently small portion of total system damping as to be of no consequence. Westinghouse experience with a row of 585 mm titanium blades bears this out [3].

System damping in steam turbine blading consists of mechanical and aerodynamic damping in addition to materials damping. Telemetry tests have shown that materials damping is about 25% or less that of system damping. Thus, even if materials damping in titanium is negligible, there would be sufficient system damping to make the system operate without the danger of excessive stresses in the lower, tuned modes. Mechanical damping is the result of small relative motions between contacting members such as the blade root in the disc, the rivet tenon in the shroud, and the loose lashing wires which pass through the blade foil. In free-standing blades, the only source of mechanical damping occurs in the blade root connection, but this turns out to be an effective means of damping, about as high as in shrouded blades. Thus, the low mechanical damping characteristics of titanium are not anticipated to be a future problem in the blade application.
Experience and Manufacture with Titanium Blades

Although the application of titanium blading in steam turbines has become of recent major interest, titanium has been considered for this application already for about twenty years. A survey conducted for EPRI by Battelle indicated that titanium blades, particularly for the long last stage application, have been evaluated by steam turbine makers all over the world [5]. The application appears to be furthest along in the Soviet Union, where titanium blades are used in serial production for steam turbines 800 MW or larger. Development also is well along in Germany, Switzerland, and the United States. A complete last stage row of 585 mm Ti-6Al-4V steam turbine blades, in operation for over 5 years, is shown in Figure 9 [3]. Test blades have been run in partial rows of operating turbines for 15-20 years without reports of failures. The application of titanium in the moisture transition rows, where corrosion resistance is of interest, has become important only in the past several years.

Because of the promising characteristics of the Ti-6Al-4V alloy as a substitute for the common blading steels, the Electric Power Research Institute and the Westinghouse Electric Corporation have instituted a project to install a row of titanium Ti-6Al-4V alloy blades in a Westinghouse 725 mm low pressure turbine. The original L-1 blade was 405 mm long, 100 mm wide at the base, with a tip shroud that grouped the blades by threes. This blade operated in the low moisture region where highly concentrated salt solutions deposit on the blades. The presence of chlorides and sulfates in the deposits results in localized pitting, which becomes the point of origin for corrosion fatigue cracks. The corrosion pitting/fatigue of blades at the moisture transition region of fossil turbines is characteristic of an industry-wide problem. In the retrofit, it was decided to redesign the shrouded blades to be freestanding with the same configuration. A freestanding L-1 row of steel blades also was fabricated and will be installed at the opposite end of the two-flow L.P. turbine. Rotating tests have been conducted on both freestanding rows to ensure proper tuning through the first four modes of vibration. Telemetry tests to be conducted in 1980 will establish operating characteristics.

Titanium blades have been manufactured for many years for aircraft gas turbines. The last stage and L-1 blades in steam turbines are large, similar to the front fan blades used in aircraft gas turbines. Generally, Ti-6Al-4V for blade applications is fabricated in the alpha-beta phase field and mill annealed, which generally gives a duplex-type microstructure with a relatively large primary alpha grain size of about 20 µm. The main problem in producing titanium blades with high fatigue strength is obtaining the initial barstock with fine alpha grain size and maintaining the fine grain size during processing. To achieve this goal, it is necessary to first beta-quench and then forge at relatively rapid strain rates and cool rapidly from the alpha-beta working temperature [6]. In general, this has not been done in commercial practice. The fabrication and heat treatment approach described later in the section on improved properties would be applicable here.

Titanium blades generally are produced in two stages, with an initial preform to the rough blade shape, allowing a relatively large section for fabrication of the root sections of the blade. Finish forging using protective glass coatings is done in closed dies in one or two blows with a high-capacity rapid acting press or hammer. The forging temperature is high in the alpha-beta field, about 900°-930°C, where about 30-50% beta is present.
Processing must be controlled to avoid variation in texture. After cooling to room temperature, generally in air, the forged blades are mill annealed for about two hours at 700°C and air cooled.

Finishing of titanium blades is critical. It is essential to eliminate surface contamination and imperfections. Machining is done using sulfurized, halogen-free oil to avoid stress corrosion cracking. Finishing is done by abrasive polishing, taking care to avoid surface heating. After final polishing, the titanium blades generally are put into service in the shot peened condition, using dry glass beads, to an intensity of 0.004-0.006 A. This puts the surface layer in compression to a depth of about 100 µm.

Compared to steel, the manufacture of titanium blades requires higher capacity presses because of lower forging temperatures. Less straightening of titanium blades is required, but there is greater springback because of the lower modulus of elasticity. Also, glass lubricants are needed in forging, and more care is needed to remove surface contamination. However, in general, the same facilities can be used to manufacture titanium blades.

It is important also to review the cost aspects of the substitution of titanium alloy for steel blades. This is difficult, because of rapidly changing prices for both titanium and steel. However, if the cost of the original titanium barstock is taken to be about 5 to 6 times that of steel barstock, some reasonable cost estimates may be made. Taking the weight of the titanium starting barstock at 60% of the weight of steel, the cost ratio becomes about 3 to 4 times. The completed titanium blade cost is about 2-3 times higher than a steel blade of the same size.

Properties of Mill Annealed Ti-6Al-4V

Ti-6Al-4V is a good titanium alloy for use in steam turbines because of its combination of strength, ductility, and corrosion resistance, and because of the extensive experience with this alloy as aircraft gas turbine compressor blading. Most of the Ti-6Al-4V used in blading has been fabricated in the alpha-beta field about 25-50°C below the beta transus, air cooled to room temperature, and finished by mill annealing for several hours at about 700°C and air cooled. The mill annealing treatment effectively stabilizes the alloy against property changes during service at lower temperatures. A typical microstructure of alpha-beta processed and stress relieved Ti-6Al-4V barstock used in steam turbine blading is shown in Figure 10. It consists of primary alpha and lamellar alpha-beta colonies produced during cooling from the working temperature.

The tensile properties of the initial 76 mm diameter Ti-6Al-4V barstock and 405 mm free-standing blades fabricated therefrom are shown in Table 1.

Table 1. Tensile Properties of Mill-Annealed Ti-6Al-4V

<table>
<thead>
<tr>
<th>Condition</th>
<th>Modulus of Elasticity, GPA</th>
<th>0.2% Offset Yield Strength, MPa</th>
<th>Ultimate Strength, MPa</th>
<th>Elongation Reduction in 50 mm, %</th>
<th>Elongation Reduction in Area, %</th>
</tr>
</thead>
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<tr>
<td>76 mm D Barstock</td>
<td>110</td>
<td>1000</td>
<td>1090</td>
<td>12</td>
<td>37</td>
</tr>
<tr>
<td>Blade Foil (long.)</td>
<td>-</td>
<td>965</td>
<td>1035</td>
<td>18</td>
<td>51</td>
</tr>
<tr>
<td>Blade Root (long.)</td>
<td>-</td>
<td>925</td>
<td>1000</td>
<td>17</td>
<td>47</td>
</tr>
</tbody>
</table>
Figure 7. Campbell diagram for 585 mm blades [3].

Figure 8. Fixed-fixed beam damping comparison of Ti-6Al-4V with 13 Cr steel.

Figure 9. Hammond 1 low pressure turbine rotor showing the last row Ti-6Al-4V blades to the left [3].

Figure 10. Light micrograph alpha-beta processed and mill-annealed Ti-6Al-4V bar stock.

Figure 11. Fatigue properties of mill-annealed Ti-6Al-4V bar stock.
The strength values of the blades are seen to be approximately the same as those of the original barstock, but the tensile ductility is higher because of the additional reduction in working.

The fatigue properties of mill-annealed Ti-6Al-4V barstock in air at room temperature and 100°C and in 22% NaCl solution at 100°C are shown in Figure 11. The temperature of 100°C approximates the temperature of the L-1 blade and the 22% NaCl saturated solution is taken as representative of the salt solution deposited on the L-1 blades. It is seen that the room temperature fatigue strength of 500 MPa is lowered to 430 MPa at 100°C. The corrosive environment further lowers the strength only to 390 MPa, indicative of the excellent corrosion resistance of the titanium alloy in chlorides. This high fatigue strength in saturated salt solution contrasts to a fatigue strength of only 100 MPa for the 13 Cr blading steel under the same conditions.

**Improvement in Properties of Ti-6Al-4V**

It is possible to significantly improve the mechanical properties of the Ti-6Al-4V alloy over the mill-annealed condition through the use of recrystallization treatments that produce ultra fine alpha grain size [6], since the alpha grain size controls crack initiation. It is essential to start with initial quenching from the beta field to produce a fine lamellar structure. The alloy then is worked in the alpha-beta field to a minimum reduction in area of about 60% and quenched to room temperature to avoid recovery or recrystallization during cooling. The structure is now essentially cold worked. Recrystallization can occur on subsequent heating at elevated temperature for times that decrease as the temperature increases. Thus, 2-6 hours at 800°C, depending upon the prior degree of reduction, or 0.5-1 hour at 955°C is sufficient for recrystallization. 800°C recrystallization results in a fine equiaxed microstructure with an alpha grain of 2-6 µm and about 15% of intergranular beta located primarily at the grain boundary triple points. An example of this microstructure is shown in Figure 12 [6]. The 955°C recrystallization treatment takes place about 30°C below the beta transus, and consists of about 50% alpha grains of about 6 µm size and the balance beta phase which transforms to martensite upon quenching. Subsequent annealing at 800°C produces lamellar alpha-beta structure in the transformed beta regions. An example of this bimodal structure is shown in Figure 13 [6]. Transmission electron micrographs clearly show that the alpha phase is recrystallized and free of dislocations. For steam turbine blading, the alloy is usually stabilization annealed for several hours at about 650°C, and air cooled to room temperature. Alternatively, the alloy may be quenched from 800°C and aged at 500°C for 24 hours followed by air cooling. This produces precipitates of Ti₃Al in the alpha phase and fine alpha in the beta phase, which results in maximum tensile and fatigue strength.

The tensile properties of Ti-6Al-4V with these two structures are given in Tables 2 and 3. The tensile yield strength of the alloy after solution treating and aging at 500°C is about 80 MPa higher than in the stabilized condition. A further decrease in strength of about 50 MPa of the stabilized alloy results from testing at 80°C, which corresponds to the service temperature. The highest strength is found with the fine-grained equiaxed alpha structure, with the bimodal and lamellar structures intermediate, and the coarse grained equiaxed lowest in strength. There is a significant loss in tensile ductility in the fully lamellar structure, but the bimodal structure exhibits tensile ductilities as high as the equiaxed structure.
Texture has an important effect on the mechanical properties of Ti-6Al-4V, particularly on modulus of elasticity. Three basic textures can be developed depending on fabrication temperature and process, and are illustrated by the basal plane pole figures in Figure 14 [6]. The variation in modulus parallel and transverse to the rolling direction is also shown. The highest modulus of 123-126 GPa is obtained when the stress axis is normal to the basal planes, whereas the low value of 107-113 GPa is obtained when the stress axis is parallel to the basal plane. Use of a consistent fabrication procedure is important to control texture and modulus of elasticity. A set of 10 blades manufactured by the same procedure resulted in a variation from 109.6 to 111.7 GPa. In contrast, the modulus of elasticity of five different barstocks varied from 109.6 to 122.0 GPa, depending on the diameter and processing history.

Fatigue properties at room temperature in 3.5% NaCl solution of the aged Ti-6Al-4V alloy in the equiaxed and bimodal conditions are shown in Figure 15 [7]. Corresponding tests in air were similar, but about 25-50 MPa higher, and are not shown for purposes of clarity. The highest fatigue strength is found for Ti-6Al-4V in the bimodal condition, despite the fact that the alpha grain size was 6 µm compared with 2 µm for the fine equiaxed condition. The slightly lower strength in the fine equiaxed condition probably results from its strong texture and congruent alpha grain boundaries. This results in an effective slip length somewhat larger than the actual alpha
Figure 12. Fine grained equiaxed Ti-6Al-4V [5].

Figure 13. Bi-modal Ti-6Al-4V [6].

Figure 14. Basic textures and modulus of elasticity in Ti-6Al-4V. (Basal plane pole figures, schematically). [5]

Figure 15. Smooth bar fatigue life ($R = -1$) in 3.5% NaCl solution of Ti-6Al-4V microstructures aged at 500°C [7].

Figure 16. Comparison of plain and notch bar fatigue properties of Ti-6Al-4V at 80°C in deionized water.

Figure 17. Fatigue crack propagation ($R = 0.2$) in 3.5% NaCl solution of Ti-6Al-4V microstructures aged at 500°C [7].
grain size. In contrast, the alpha grains in the bimodal condition are surrounded by lamellar structure, essentially free of texture, and the fatigue strength reflects the actual grain size. The lowest fatigue strength is found with the coarse-grained alpha structure, about equal to the fatigue strength in the mill-annealed structure, taking into account the difference between room temperature and 100°C testing.

Notched fatigue properties are important in the blade application, because of the serrations in the blade root area, which anchor the blades to the steeple. Typical notched fatigue properties, for stabilized equiaxed Ti-6Al-4V with 4 μm grain size at 80°C in deionized water are presented in Figure 16. The notch with a stress concentration factor K_c = 2.48 results in a decrease in the fatigue strength from 450 MPa to 260 MPa. Crack propagation at high ΔK values is not an important design criterion for blades, because of the large number of service cycles involved. However, knowledge of the threshold ΔK_th may be important, because of minor defects and notches. The fatigue crack propagation characteristics of aged Ti-6Al-4V in the equiaxed and bimodal conditions in 3.5% NaCl at room temperature are shown in Figure 17 [7]. The bimodal structure exhibits the lowest propagation rates because of its lamellar matrix. Fatigue crack propagation rates in NaCl are somewhat higher than in air for all microstructural conditions, as illustrated for the bimodal condition in Figure 17.

In fabricating the blades for the test row starting with the 76 mm barstock, it would have been difficult to produce the recrystallized structures discussed in this paper, particularly in the root section because of insufficient reduction for future application. We therefore decided to produce experimentally the recrystallization bimodal structure in the 76 mm barstock itself. With the kind cooperation of RMI, Inc., we started with a 228 mm billet that was beta quenched. This is being reduced to 76 mm barstock using GFM forging in two steps with an intermediate recrystallization treatment at 140°C. This treatment should yield the fine recrystallized structures in the starting barstock which will then be carried through to the final blade forging.

Future Prospects

In the immediate future, prospects look promising for the use of titanium in retrofit blade applications where corrosion has been shown to be a problem. In the long term, titanium may be most useful for long last stage blade applications where its high strength to weight ratio will permit increased power capacity and increased efficiency.

Acknowledgement

The authors would like to thank their colleagues at EPRI, Ruhr-University Bochum, and Westinghouse for their contributions to the work presented. In particular, they would like to thank David Poole of EPRI, Manfred Peters of Ruhr-University Bochum, Albrecht Gysler of DFVLR, Cologne, and Robert Bates of Westinghouse R&D Center in Pittsburgh for their particular contributions. The work reported was supported by the Electric Power Research Institute, Palo Alto, California 94303, under Contracts RP912, RP1264-1, and RP1266-1.
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