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Status of Titanium Blading for Low-Pressure Steam Turbines

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Final Report
February 1977

Prepared by
Battelle, Columbus Laboratories
Columbus, Ohio

ELECTRIC POWER RESEARCH INSTITUTE

STATUS OF TITANIUM BLADING FOR LOW-PRESSURE STEAM TURBINES

EPRI AF-445
(Technical Planning Study 76-641)

Final Report

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FOREWORD

This report was prepared by Battelle's Columbus Laboratories, Columbus, Ohio, as a Technical Planning Study (TPS) for the Electric Power Research Institute (EPRI). The work was initiated under EPRI Agreement No. TPS 76-641, "Status of Titanium Blading for Low Pressure Steam Turbines", in support of the Thermal Mechanical Conversion and Storage program area in the Fossil Fuel and Advanced Systems Division. Dr. R. I. Jaffee, of this Division, was the project officer and participated in a major portion of the research effort. Mr. R. A. Wood of Battelle was the principal investigator. Dr. J. C. Williams of Carnegie-Mellon University, Pittsburgh, Pennsylvania, was consultant on titanium processing and microstructure.

The research was conducted from May, 1976, to December, 1976, and included field survey information collection and interviews with foreign and domestic steam turbine manufacturers and titanium-oriented companies and individuals. Letters of inquiry, telephone survey efforts, computer based and manual reference searches were used in collecting information. The final report was submitted in January, 1977.

The cooperation and contributions from the numerous participating companies and individuals are gratefully acknowledged. As can be readily appreciated, the assistance of the turbine manufacturers in contributing information was requisite for a report of this type. Companies and organizations contacted are listed in the Introductory Section of the report.

ABSTRACT

Titanium is of interest for blading the last stages of low-pressure steam turbines. It is stronger, lighter and more corrosion and erosion resistant than the standard 12Cr steel which has been used for blading for many years. A possible disadvantage of titanium blading is its low damping capacity, which requires careful design to tune out resonant vibrations that might be encountered in service, and the use of mechanical damping using shrouds and lashing wires. The lower density of titanium permits longer blades to be used for last stage rows, which would be useful in very large units. The lower density of titanium also results in lower stresses on the attachment to discs or shafts, reducing their susceptibility to stress corrosion cracking.

Because of the above attributes of titanium, a survey was conducted by Battelle Columbus to summarize the worldwide status of titanium blading in the low pressure steam turbine. This report shows that steam turbine makers all over the world are considering the use of titanium blades, particularly for larger turbines, but also for present size turbines because of better corrosion resistance. Titanium blading appears close to being introduced into production steam turbines, particularly in Western Europe, and are in standard production in the Soviet Union. In the United States, titanium blades are being evaluated for last stage and next-to-last stage rows on a limited basis, and are routinely used for closing blade applications. EPRI is using this information as guidance for R&D on titanium blading. A current project, RP912 with Westinghouse, is evaluating the corrosion fatigue resistance of Ti-6Al-4V alloy in steam.

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EXECUTIVE SUMMARY

The survey conducted for the Electric Power Research Institute by Battelle's Columbus Laboratories had the primary objective of determining the status of titanium technology and utilization regarding steam turbine blading. Steam turbine companies and companies with a related interest in titanium were questioned to identify turbine companies having titanium programs or interests, to collect their developmental or operational information, and to solicit their opinions and information regarding the potential payoff for titanium blading in terms of: titanium for longer last-row blades, titanium for more reliable blades, and titanium blades for improving turbine efficiency.

Responses from a representative sample of steam turbine companies from the United States, Europe, and Asia revealed that there is a strong interest in titanium for blading and other components among many companies and several have active development programs. Further, titanium blading has production status for steam turbines of some organizations. Twenty-two cases of titanium turbine blade production, operational test, or development (four, thirteen, and five, respectively) were identified. Production titanium blades are found in small to medium size turbines--test blades are found in the full range of turbine sizes although predominately for the larger machines.

Very long titanium blades (about 50 inches) are being developed in Russia and Switzerland for the last-stage blading of very large turbines (e.g., 1200 MW). However, most companies currently appear to have a reduced interest in long titanium blades because the trend toward increasingly larger turbines has experienced a reversal. Nevertheless, some of these same organizations have active titanium blade test programs. Last-stage titanium alloy blades in the 20 to 30-inch size are in operational testing by several companies. Production blades in this size range were identified for machines manufactured in Russia and for the closing blade application in American machines. American manufacturers of small turbines offer 4 to 15-inch long titanium blades for several production turbine models.

The small-turbine manufacturers substituted titanium blades for steel blades in designs where steel would have been unsatisfactory for operating conditions planned. The titanium blades have exhibited excellent erosion and corrosion resistance -- very few problems with the blades in either small or medium size machines were reported.

The erosion resistance of titanium in wet steam appears better than 12-chromium steel and nearly as good as Stellite shielding in some of the operational testing in progress. The corrosion, corrosion-fatigue, fatigue, modulus, damping, and thermal characteristics of titanium blades appear to afford trouble-free service. However, much of the testing is being done under conditions which are not very demanding. Operational testing of long titanium blades is still in progress. Thus, so far, there is little basis for estimating an improved reliability for titanium blades. It appears that a case for titanium is building, but much more data under the most severe conditions for long blades are needed before a definitive position can be established.

The high cost of titanium blading was frequently cited as one factor against its more prevalent use. A manufacturer of turbine blades estimated that titanium blades would cost from 10 to 25 percent more than Stellite-shielded, 12-chromium steel blades of the same geometry. However, it has been estimated that design and installation costs (e.g., in-situ shroud welding operations) might raise the total cost for titanium blading to about three times the cost for steel blading. This might translate into a 1 percent rise in total turbine costs for a large machine. The cost differential can be viewed as very small in terms of the cost of forced outages (about $10,000 per hour). If titanium blading were only 20 percent effective in reducing forced outage due to blade problems, the benefit would equal the higher titanium cost with the avoidance of only a few outages over the turbine's life.

The potential for titanium last-stage blading in improving the power and efficiency of turbines through optimization of annulus area and hub/tip ratio appears to be an area meriting study. However, it would appear applicable only for areas having adequate cooling water. Studies of this type, continued operational testing, and systematic investigations to generate a data base for optimizing titanium blade designs are needed to develop accurate cost-benefit information. The titanium blading in steam turbine experience revealed by this survey appears sufficiently successful to merit additional study.

Section 1

INTRODUCTION

The steam turbine has been in existence for almost a century, and steam plants for generating electrical power were introduced around the beginning of the twentieth century. Present day turbines are powered by either fossil or nuclear fuels, both old and new machines are usually large and expensive, and the matter of keeping them running on a more or less continuous basis continues to be a concern. There are scheduled downtimes for maintenance purposes to contend with, and there are forced outages (FO) due to malfunctions.

Forced outages of electric power generating plants can be caused by malfunction of any one of the several components of the total system: malfunctions in the boiler and in the steam turbine per se are major causes. All outages are costly: the downtime for a large plant generally equates to a cost for lost power generation of about $10,000 per hour for machines of 200-MW size and larger. Needless to say, there has been a concerted effort through the years to construct highly reliable steam turbines to minimize this source for FO.

Turbine blade failures represent one of the largest sources of FO in both fossil and nuclear fueled steam turbines. Data available from the Edison Electric Institute (EEI) for a 10-year period (1964-1973) indicate that blade failures result in about 15 percent of fossil turbine FO and 17 percent of nuclear turbine FO. In addition, it has been estimated that at least half of the FO caused by the uncontrolled vibration of turbine-generator units has been due to turbine blade malfunction (i.e., additionally about 9 and 12 percent of FO causes for fossil and nuclear machines, respectively). The EEI FO data are given in Table 1-1. These data reveal that the cost of turbine FO is extremely high -- on the order of $61,000,000 per year for FO due to blade failure alone.

Most of the turbine blade failures occur in the larger turbines (200 MW or greater; see Table 1-1), where machines utilize very long blades. Many failures are in the long last-stage blades of the low-pressure (LP) steam turbine

Table 1-1

CAUSES AND HOURS OF FORCED OUTAGES OF FOSSIL AND NUCLEAR FUELED STEAM TURBINES

(1964-1973 Edison Electric Institute Data)

Cause of FO	Fossil Turbines (60 to 600+ MW)			Nuclear Turbines		
	FO Hours	%	Rank	FO Hours	%	Rank
Blade failures	56,593[1]	14.9	2	1,702	17.0	3
Vibration of turbine-generator unit	67,990[2]	17.9	1	2,336	23.3	1
Lubrication system and bearings	37,569	9.9	4	1,756	17.5	2
Control, turbine, and reheat stop valves	28,455	7.5	5	1,120	11.2	4
Shaft	41,170	10.8	3	--	--	--
Shell leaks	--	--	--	890	8.9	5

(1) 36,887 FO hours for machines of 200 MW or greater.

(2) 48,530 FO hours for machines of 200 MW or greater.

Note: (1) value plus 1/2 of (2) value equals 61,152 FO hours or about 6,100 FO hours per year attributable to turbine blade failure (see text).

sections. Last-row LP blades can be up to 50-some inches long in machines where rotation speeds are sufficiently low (e.g., in 1500 RPM European nuclear machines) or 40-some inches long in European fossil fueled machines or in U.S. nuclear machines. More commonly, 30 to 33-inch-long LP blades are used in the large U.S. fossil fueled machines operating at 3600 RPM. Turbine blades of all sizes are subject to steady state loading (mainly due to centrifugal forces), and long LP blades, in particular, are subject to severe vibrational loading. Blades and machines are designed to minimize the risk of resonance at normal speeds and to control amplitudes when resonance occurs during runup or other operational anomalies.

The cause of most blade failures generally is conceded to be high-cycle fatigue aggravated by environmental effects. Examination of failed blades suggests that, in numerous cases, fatigue failure has been accelerated by corrosion processes in the presence of condensed corrodants. The effect of gaseous steam impurities is difficult to estimate, but may be quite important. Other causes for blade failure are known, of course (e.g., blade rubbing due to localized temperature anomalies), but corrosion augmented fatigue is certainly the major problem area.

That a good start had been made toward the development of titanium alloy blading into steam turbines was widely known for several years. Titanium alloys are 40 percent lighter than the 12-chromium steels most commonly used for blading, and equally strong. Thus, titanium blades would be subject to 40 percent lower centrifugal stresses. Also, it is believed that titanium is less sensitive to the environment of steam turbine blading: more corrosion resistant and more resistant to water droplet erosion than annealed 403 stainless. Thus, it appeared that a widespread titanium application to LP steam turbine blading might well eliminate some of the blade failure problems that prevail. This prospect was sufficiently interesting to the Electric Power Research Institute (EPRI) that the subject area, titanium for steam turbine blading, is being evaluated by the present TPS and such as RP 912, which compares the corrosion-fatigue characteristics of 12-chromium steel with Ti-6Al-4V in wet steam.

However, little was known about the status of the development of titanium steam turbine blading. Who was doing what? Was the time for widespread application near at hand or was the R&D in an initial or intermediate stage? EPRI support of R&D might well accelerate the timetable for titanium steam turbine blading and afford a considerable payoff for the utilities in terms of reduced turbine FO. But first, it was apparent that the need to know the status of the development and the problems foreseen in integrating the technology into commercial machines was a prerequisite for funding direct R&D programs. Therefore, a survey phase of the investigation was initiated.

The primary objective of the survey was to determine the status of titanium technology and utilization regarding steam turbine blading. Ancillary objectives included determinations regarding the titanium blading operating experience, identification of those participating in the development effort on a world basis, potential cost-benefits of substitution (or introduction) of titanium for steel blading, and recommendations, if merited, toward an EPRI research and development program on titanium for steam turbine blading.

The survey research was initiated in May of 1976. The report and periodical literature was searched using machine and manual methods. Systems searched included: Chemical Abstracts, Engineering Index, Mechanical Engineering Index, Metals and Ceramics Information Center Data Base and Card Files, Defense Documentation Center Data Base, Battelle's Foreign Science Library, and Metals Abstracts. Generally, holdings only for the last 10 years were requested. Later, the holdings further back in time for some systems were searched. Based on the limited references identified in this search, the activities relative to applying titanium to steam turbines is not well documented.

Survey methods yielding most of the information for this study included written, telephoned, and personal interview requests for information from foreign and domestic steam turbine manufacturers, associated organizations, and from companies well oriented in titanium technology such as aircraft gas turbine engine and airframe companies. Organizations contacted are listed at the end of this introductory section. While questions posed varied with the character of the companies contacted, the principal queries to turbine people related to, "Have you examined titanium for steam turbine blading and what is your assessment?" The companies were asked to speak to the payoff potential for titanium blading in terms of:

- Titanium for longer last-row LP blades
- Titanium for more reliable turbine blades
- Titanium blades for improving turbine efficiency

The cooperation of the participating organizations is gratefully acknowledged. Understandably, some of the detailed information available could not be reported for proprietary reasons. However, sufficient information was released to indicate an active interest in titanium for blading and considerable potential for this relatively new material in this application.

ORGANIZATIONS CONTACTED

Aerojet Liquid Rocket Company	Sacramento, California
Allgemaine Electrizitaets-Gesellschaft AG	German Federal Republic
Allis-Chalmers Corporation, Power Systems Division	Milwaukee, Wisconsin
American MAN Corporation, Steam Turbine Generator Department	New York, New York
Battelle's Columbus Laboratories	Columbus, Ohio
The Boeing Company, Boeing Marine Systems Division	Seattle, Washington
Brown Boveri & Company, Ltd., Research Department	Switzerland
C. A. Parsons & Company, Ltd.	England
Central Electricity Generating Board	England
Cie Electro-Mechanic	France
Contimet GmbH	German Federal Republic
Crucible, Inc., Colt Industries	Pittsburgh, Pennsylvania
Electricite de France	France
English Electric-AEI Machines, Ltd.	England
Escher Wyss GmbH	German Federal Republic
Fuji Electric Company, Ltd.	Japan
G.E.C. Turbine Generators, Ltd.	England
General Electric Company:	
Aircraft Engine Group	Evendale, Ohio
Large Steam Turbine Division	Schenectady, New York
Medium Steam Turbine Department	Lynn, Massachusetts
Imperial Metal Industries, Ltd., New Metals Division	England
Ingersoll-Rand Corporation, Turbo-Products Department	Phillipsburg, New Jersey
Ishikawajima-Harima Heavy Industries, Ltd.	Japan
Kobe Steel, Ltd.:	Japan
Research Department	
Titanium Metals Department	
Kraftwerk Union AG	German Federal Republic

Lawrence Livermore Laboratory (University of California)	Livermore, California
Martin Marietta Aluminum, Titanium Division	Torrence, California
Maschinenfabrik Augsburg-Nurnberg AG	German Federal Republic
Mitsubishi Heavy Industries, Ltd.	Japan
U.S. Navy Sea Systems Command	Washington, D.C.
U.S. Navy Ship Engineering Center	
Philadelphia Division	Philadelphia, Pennsylvania
Headquarters	Washington, D.C.
Oregon Metallurgical Corporation	Albany, Oregon
Peter Brotherhood, Ltd.	England
Pratt & Whitney Aircraft, Division of United Aircraft Corporation	E. Hartford, Connecticut
RMI Company	Niles, Ohio
Rockwell International, Inc.:	
Columbus Aircraft Division	Columbus, Ohio
Los Angeles Aircraft Division	Los Angeles, California
Rocketdyne Division	Los Angeles, California
Scientific Council for Structural Materials of the USSR Academy of Sciences	Soviet Union
Siemens-Electrogerate GmbH	German Federal Republic
Skoda Works, Turbine Department	Czechoslavakia
Stal Laval Turbin AB	Sweden
Sulzer Brothers, Ltd.	Switzerland
Terry Steam Turbine Company	Windsor, Connecticut
Titanium Fabrication Corporation	Fairfield, New Jersey
Titanium Metals Corporation of America, Timet Division	
Corporate Headquarters	Pittsburgh, Pennsylvania
Henderson Research Laboratory	Henderson, Nevada
Los Angeles District Office	Los Angeles, California
TRW, Inc., Compressor Components Division	Cleveland, Ohio
Westinghouse Electric Corporation	
Research Laboratories	Pittsburgh, Pennsylvania
Steam Turbine Division	Lester, Pennsylvania
W. H. Allen Sons & Company, Ltd.	England
Zaklady Zamech	Poland

Section 2

BACKGROUND INFORMATION

The better part of a century has passed since the conception and demonstration of the modern steam turbine by Charles A. Parsons of Great Britain. An excellent account of the development history and the technical aspects of steam turbines is presented in the April, 1969, issue of Scientific American by Walter Hossli.[2-1] He describes early, fairly small (2,100 HP), turbines for ship propulsion as well as recent, much larger (110,000 HP), turbines for this use. Also, turbines for electric power generation are reviewed, from the first small one of 250 KW (in 1900) to the giants of the 1970's (e.g., 1,300,000 KW).

Further, Hossli describes the principles of steam turbine design and operation. His representation of variations in steam temperature, pressure, and specific volume, as steam passes through a typical system, is shown in Figure 2-1. Figure 2-2 illustrates the arrangement of components in a typical modern cross-compound unit wherein steam passes through double-flow high-pressure and intermediate-pressure sections and finally to double-flow low-pressure sections before entering the condenser and passing back to the boiler.[2-1, 2-2]

The 1000 F steam temperature indicated in Figure 2-1 did not become an operational reality before the mid-1940's, having increased in stages over a 40-year period from the relatively low-temperature steam utilized in the early, small machines.[2-3] The size of turbines also increased continuously during this period. Steam pressures increased too, along with steam temperatures for electric power generating turbines, and by the mid-1950's, a few 1100F, double-reheat, supercritical pressure machines were operating, and later, the 1200F, 5000 psi Eddystone plant of the Philadelphia Electric Company was operated.[2-3,2-4,2-5] However promising these higher temperature, higher pressure steam machines appeared to be, difficulties in their reliable operation were encountered, resulting in a retreat to the more widespread use of 1000F steam units in the 1970's. A few 1100F machines continued in operation: high equipment costs prevented their more common usage.[2-6]

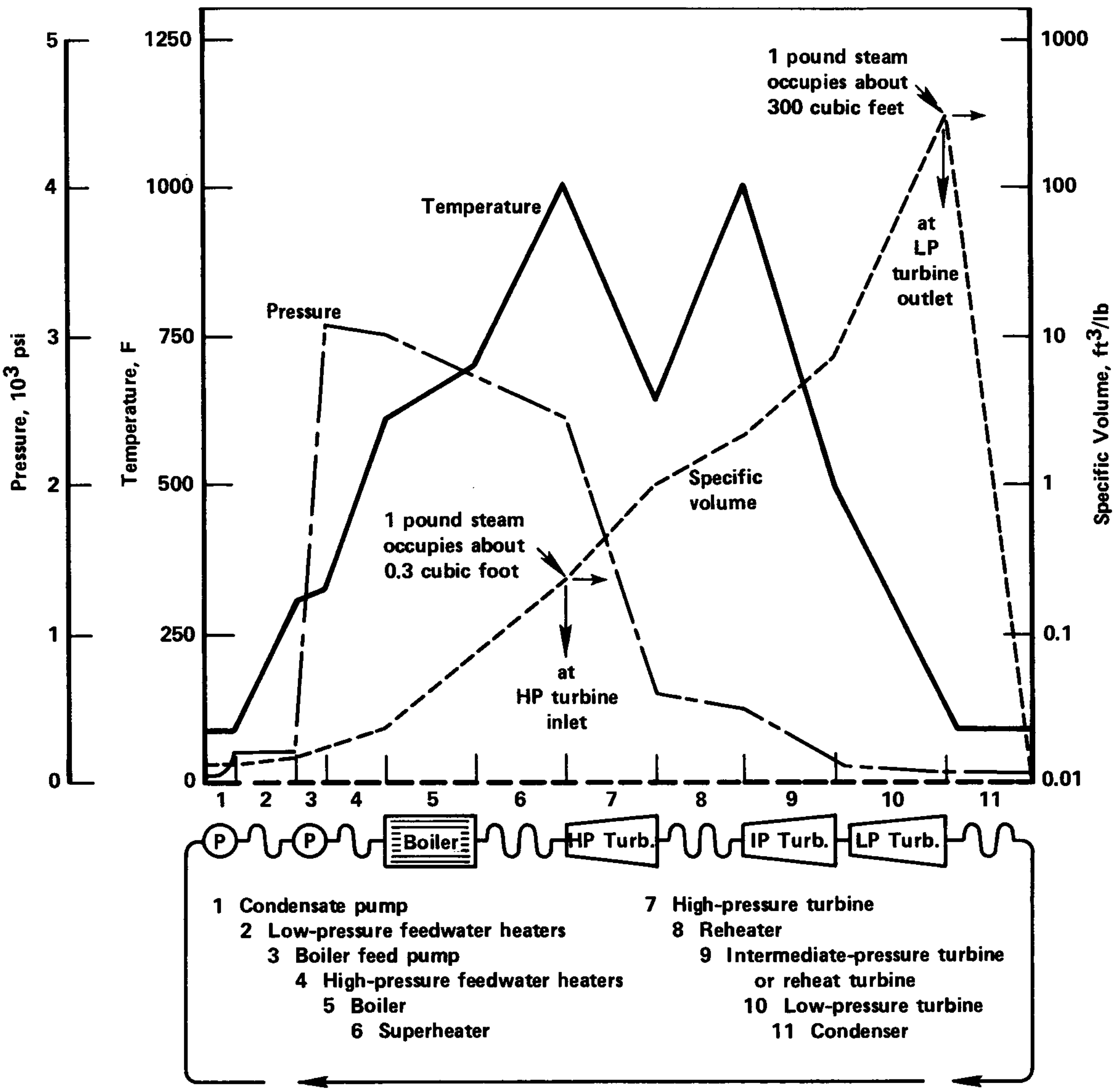
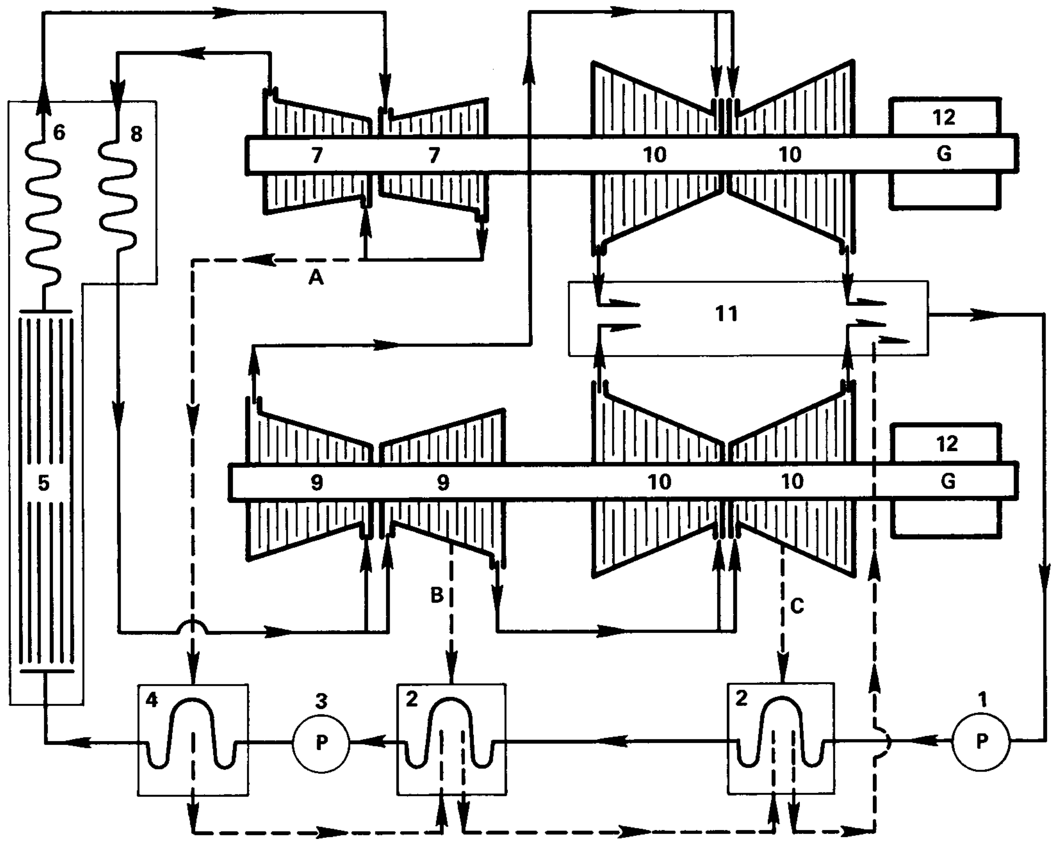


Figure 2-1. Steam Pressure, Temperature, and Specific Volume Relationships in the Various Components of a Large Steam Power Plant[2-1]

The growth of turbine application and size during the twentieth century established trend lines which planners utilized to project the desirability of up to 2000-MW machines before the year 2000 (e.g., Reference 2-1, 1969). The world's turbine makers were largely together in this projection and most had plans for very large turbine generator sets. To say that some of these designs extended the capacity to produce hardware beyond the state of the art is perhaps unfair because materials people had kept pace with designers on a historical basis.



1 Condensate pump
2 Low-pressure feedwater heaters
3 Boiler feed pump
4 High-pressure feedwater heaters
5 Boiler
6 Superheater
7 High-pressure turbine (double flow)
8 Reheater
9 Intermediate-pressure turbine (double flow)
10 Two Low-pressure turbines (each double flow)
11 Condenser
12 Generators
A, B, C Steam extraction points for preheating feedwater.

Figure 2-2. Arrangement of Steam Turbine-Generator Components and Steam/Water Flow Pattern in a Typical Modern Cross-Compound Unit[2-1,2-2]

Nevertheless, some new turbine designs presented significant material challenges. But new and improved materials and technology for processing large components were coming on the scene which permitted designers to consider advances in turbines quite beyond previously established limits. One of these materials was titanium.

Although titanium metal became available shortly after the turn of the century, ductile metal (in small amounts) was not available until the late 1940's.[2-7]

The United States Bureau of Mines successfully developed a pilot-plant operation to produce batch lots of ductile titanium in 1946 by a process devised by Dr. Wilhelm Kroll, a native of Luxembourg, who later worked in the United States. Since the several outstanding properties of titanium metal were known in a general way, U.S. military development support dollars became available in the years following World War II to determine if titanium was the solution to many aircraft and ordnance design needs.[2-7,2-8] In particular, titanium appeared to be an attractive material for utilization in gas turbine engines, then predicted to become the dominant aircraft power plant in military air vehicles.

The important characteristics of titanium, its low density, high strength, and corrosion resistance, were developed and exploited by both military and industrial interests during the late 1940's and 1950's period. England, Japan, and the Soviet Union became titanium metal producers during this time. While numerous development and application programs on a world basis contributed to the advance of titanium as a structural material, the U.S. became the technological leader in titanium. Its development for and utilization in the Pratt & Whitney Aircraft J57 gas turbine aircraft engine dominated -- the program consumed over 50 percent of the total United States production of titanium for a number of years.[2-8]

As might be expected, the titanium alloys initially developed and used, for example the Ti-3Cr-1.5Fe (Ti-150A) and the Ti-2Cr-2Fe-2Mo (Ti-140A) evaluated and tested in the first J57 Models (1952), were replaced by materials having superior characteristics, as for example, the still viable Ti-6Al-4V alloy, developed in the early 1950's.[2-8,2-9] The tensile and fatigue strengths of Ti-6Al-4V and Ti-8Al-1Mo-1V alloys, the latter developed in the late 1950's, are shown in Figures 2-3 and 2-4 in comparison with the strengths of selected steels, on a density-adjusted basis.[2-8]

The Pratt & Whitney Aircraft Company, and later the General Electric Company and other major aircraft gas turbine engine producers, selected, for primary engine use, the Ti-6Al-4V alloy, the Ti-5Al-2.5Sn alloy (excellent weldability), and unalloyed titanium. Foreign titanium producers and users had available other sets of alloys, but the above three were usually available as well. Additional alloys have since been developed and introduced into service by titanium producers and the gas turbine engine manufacturers (e.g., the

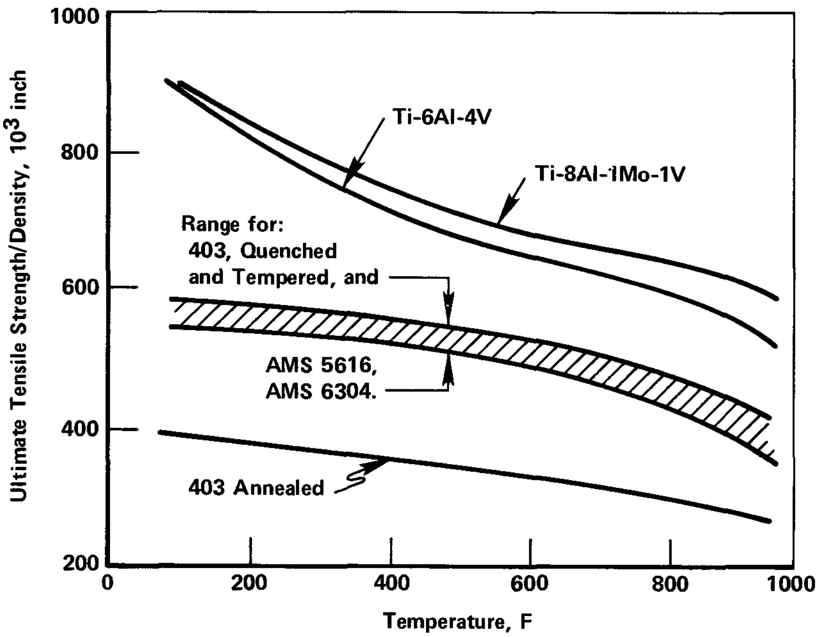


Figure 2-3. Effect of Temperature on the Specific Tensile Strength of Titanium Alloys and Steels[2-8,2-11]

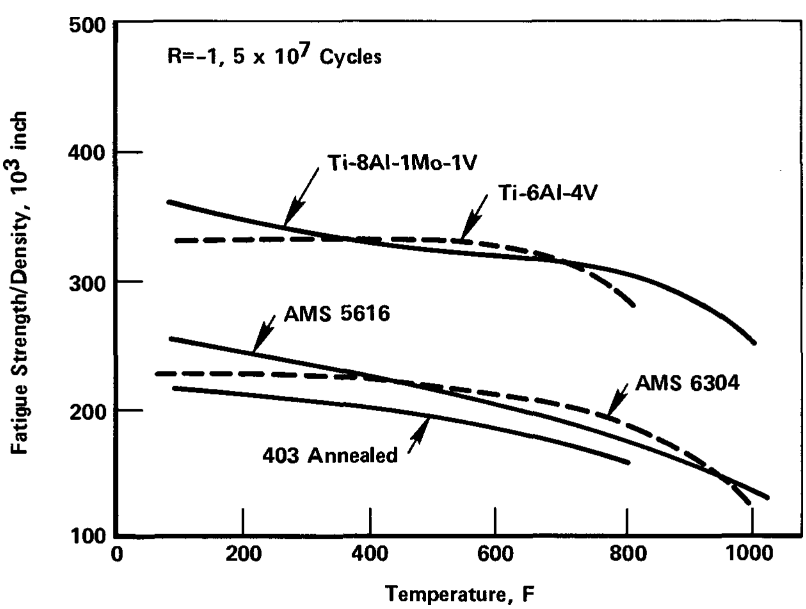


Figure 2-4. Effect of Temperature on the Specific Fatigue Strength of Titanium Alloys and Steels[2-8,2-11]

Ti-5Al-2Sn-2Zr-4Mo-4Cr [called Ti-17 alloy] alloy developed by the General Electric Company, Large Gas Turbine Engine Division, Evendale, Ohio). However, the Ti-6Al-4V alloy continues as the "workhorse" material for engines and many other applications both in this country and abroad. Mechanical and physical properties of currently available titanium alloys are listed in several handbooks; for example, References 2-10 and 2-11. Selected characteristics and properties of Ti-6Al-4V and Ti-5Al-2.5Sn alloys are summarized in Table 2-1.

The post-World War II period thus included industrial requirements for greater electric generating capacity (with the apparent need for larger size turbine-generator sets) and an advanced metallurgical technology base (with the availability of new and improved materials such as titanium). Quite naturally, steam turbine materials and design people began examination and exploitation of titanium. Examination of titanium alloys for use in steam turbines began in the early 1950's. The U.S. Navy R&D people recognized the potential for titanium in this application as early as anyone.[2-12,2-13] Exploitation of the early-available titanium alloys (e.g., Ti-150A) by the Navy in the form of steam turbine blades led to some hardware failures, however, and postponement of vigorous attempts to apply titanium steam turbine blading extensively.[2-14] Elsewhere, industrial steam turbine R&D people were looking at titanium for blading too. For example, by 1959, the Leningrad Metallurgical Plant had manufactured 665-mm ($\sim$ 27-inch) length blades from the Ti-5Al alloy (Soviet designation VT5) for use in a low-pressure steam turbine of 50-MW size.[2-15]

The domestic and foreign steam turbine manufacturers were looking at titanium for two basic reasons: as a material for improving turbine reliability and as a material with characteristics suitable for increasing turbine blade size beyond the limiting size imposed by the characteristics of steel. The excellent corrosion resistance and the good fatigue strength of titanium were characteristics of titanium that appeared attractive relative to turbine blade reliability. The high strength-to-weight ratio of titanium alloys was the characteristic that made it a candidate for very large blades. As turbine size increases, the last-stage blades of the low-pressure section(s) can be advantageously designed to great lengths; to sizes and lengths which, if made from steel, could not be retained by the rotor and blade root hooks due to the centrifugal forces involved. Light weight, high strength, corrosion resistant titanium alloys appeared as a possible solution to the very large size last-stage blade problem for the larger turbines being planned.

Table 2-1

SELECTED CHARACTERISTICS AND PROPERTIES OF THE Ti-6Al-4V AND Ti-5Al-2.5Sn ALLOYS[2-10,2-11] (Annealed Condition, Room Temperature Values)

Characteristics and Properties	Ti-6Al-4V	Ti-5Al-2.5Sn
Alloy type	Near alpha, alpha-beta alloy	All alpha alloy
Annealed microstructure	Equiaxed alpha with 10-15% beta phase intergranularly	Equiaxed alpha with trace of beta phase
Density, lbs/in^3	0.160-0.161	0.162
Mean coefficient of thermal expansion per degree F$\cdot 10^{-6}$	4.9 (32 to 212 F) 5.1 (32 to 600 F)	5.2 (32 to 212 F) 5.3 (32 to 600 F)
Modulus of elasticity, ksi$\cdot 10^3$		
Tension	16.0-16.5	$\sim$16.0
Torsion	$\sim$6.10	$\sim$ 7.0
Typical tensile properties:		
Ultimate strength, ksi	133-143	116-138
0.2% offset yield strength, ksi	123-133	117-129
Elongation, percent	12-15	13-16
Reduction in area, percent	28-45	27-45
Fatigue behavior at R = 0		
10^7 cycle strength (K_t = 1), ksi	$\sim$50	40-60(1)
10^7 cycle strength (K_t = 3), ksi	$\sim$30	$\sim$15
Fracture toughness, K_{IC}, ksi$\sqrt{in}$	55-80(2)	$\sim$70
Typical charpy V-notch impact, ft-lb	21	23
Hardness, Rockwell C scale	36	36
Heat treatability	Can be solution treated and aged to moderately high strength	Not heat treatable
Weldability	Good	Excellent

(1) Highly dependent on surface preparation.

(2) Highly dependent on heat chemistry, processing, and annealing variables.

The very young titanium industry experienced numerous technical and economic problems but continued to grow, at times with setbacks, as illustrated by the titanium mill products shipments data of Figure 2-5. The applications were 90 to 95 percent aerospace applications, and the developing technology was so oriented. The major technical problems of hydrogen embrittlement and alloy segregation were basically solved by utilizing a double vacuum melting procedure with consumable electrodes (a once melted ingot became the electrode for second melting). The role of the interstitial elements, carbon, oxygen, and nitrogen, became better understood, and amounts of interstitials in alloys were better controlled. The high cost of titanium was trending downward (Figure 2-6) and users, particularly aircraft gas turbine engine and airframe manufacturers, were increasingly winning at the game of applying titanium in sophisticated designs at lower costs.

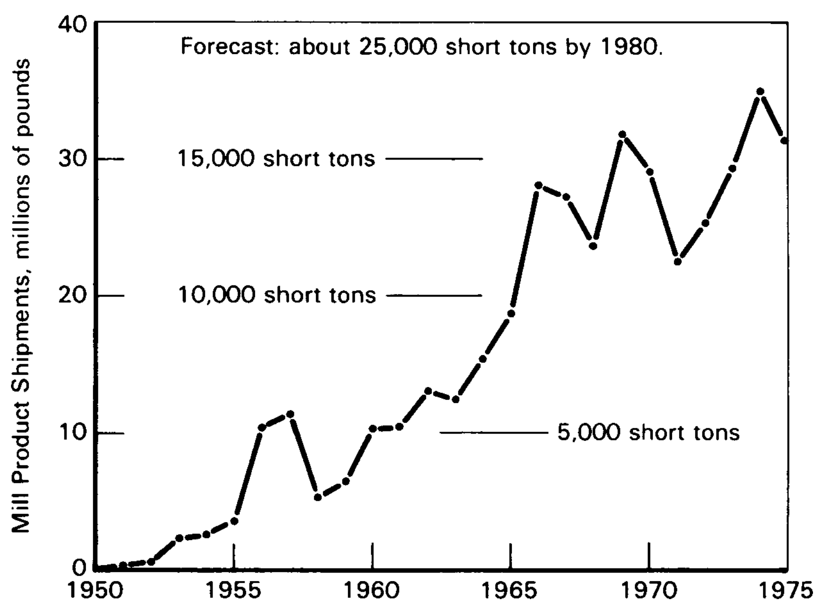


Figure 2-5. The 25-Year Growth of the Titanium Industry in Terms of Mill Product Shipments[2-7]

While much was written and information on the use of titanium in the aerospace role became widely known through various media, information on the application of titanium in steam turbines was not readily available. The titanium efforts

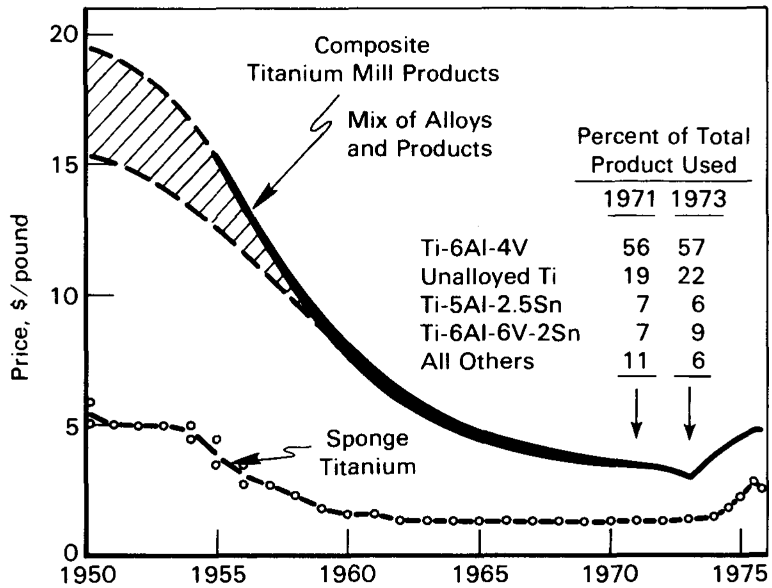


Figure 2-6. Price History of Sponge and Mill Product Titanium[2-7]

by the steam turbine groups were of course quite small in relation to the programs conducted by aerospace groups, very little government funding (U.S.) was applied to the efforts, and since proprietary interests were foremost, successes and failures in the steam turbine application of titanium were not well publicized. The idea of titanium for steam turbine blades was abandoned by some companies as a result of failures experienced with the still developing technology of titanium or as a result of their determining that goals could be achieved by designing with improved steels. Additional steam turbine companies worked intermittently and at low key in applying titanium, while others postponed active programs. Further, the trend toward increasingly larger machines was interrupted. Currently, increased electric generating capacity is being supplied by greater numbers of highly reliable intermediate sized turbines.

The mature steam turbine industry and the youthful titanium industry have had, as briefly described in the above history, an association of 25 years. The Electric Power Research Institute posed the question, "What is the status of titanium for last-stage steam turbine blading after this quarter-century relationship?" The present survey project attempts to answer this query and presents some augmenting information as well.

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Section 3

THE EXAMINATION AND USE OF TITANIUM IN STEAM TURBINES

The steam turbine industry in the United States, Europe, and Asia was surveyed to determine the extent of the manufacturers' interest in titanium for blades. Sampling methodology included field trips and written and telephone communications, as well as literature surveys. In the short time alloted for information collection purposes, it was not possible to obtain a thorough coverage of manufacturers. Further, some companies contacted did not have sufficient time to prepare a contributing response. Nevertheless, it is believed that a representative sample of the total information available was obtained and the results pertaining to the examination and use of titanium for steam-turbine applications are presented in this section of the report. The information is organized by country.

3.1 CZECHOSLOVAKIA

The Skoda Works in Plzen has developed the technology of forging and machining turbine blades from Ti-5Al-2.5Sn alloy.[3-1] Ten experimental blades of this composition were fitted in the last stage of a 55-MW turbine and operated for 40,000 hours prior to examination. Blade properties were found to be unaffected by this use and blade erosion was less than unprotected 13-chromium steel blades (about the same as steel blades having a hardened leading edge). The details of blade design (about 500 mm or 20 inches overall length) and method of shrouding were not revealed in this account. Follow-on studies, connected with the development of another titanium alloy (not identified) blade having an active length of 1200 to 1300 mm (47 to 51 inches) for a 3000-rpm turbine, were reported, but details were not given.

The problems associated with the use of titanium alloys for blades were discussed in two references.[3-2, 3-3] One mentioned was the insufficiency of the aerodynamic design of Ti-5Al-2.5Sn blade profiles for operation at $\sim$ Mach 2 tip speeds. The 47 to 51-inch blades for large-capacity machines operating at 3000 rpm were cited and undoubtedly this was in reference to the previously mentioned development of Reference 3-1. A specific detail of learning how to control the detwisting of long blades over the full operating range of the machine was mentioned. The other problem cited was the need to solve the erosion resistance difficulties associated with peripheral speeds of more than 600 m/s (about 1970 ft/s). Research on the latter problem using hard coatings and brazed-on Stellite shielding was described (see section on Erosion Phenomena).

The use of floating damping wire is cited in Reference 3.1 as the fix mostly used for the minimizing of the lowest mode of tangential blade vibration. Solid damping wires of titanium alloy (not identified) are used for blades having an active length of 840 mm (33 inches). The report also described the price of titanium blades as much higher than the price of steel blades (no elaboration).

3.2 FRANCE

Reportedly, there is some interest but not much activity on titanium for last-stage turbine blading at Electricite de France (EDF).[3-4] On the other hand, EDF is very active in developing the use of titanium tubed condensers for steam turbines and has specified titanium for all new plants utilizing high chloride content cooling water. No information on titanium for turbines was found in the French literature.

3.3 GERMAN FEDERAL REPUBLIC

About 10 years ago, Allgemaine Electrizitaets-Gesellschaft (AEG) in Berlin installed eight moderate-sized blades of titanium (648 mm or 25.5 inches long) without erosion shields in a 100-MW turbine.[3-4] The turbine has been running without any trouble from the titanium blades. Also, about 10 years ago, Contimet GmbH forged Ti-6Al-4V alloy blades for Siemens, who tested six of them in the low-pressure section of a 160-MW turbine and experienced good results, but apparently prefer to continue using 12-chromium steel blades for present-size turbines. Recently, Contimet has supplied Boehler of Germany with 22 tons of titanium (Ti-6Al-4V) to be forged into blades for Brown Boveri Company (BBC) use.

It was reported that Kraftwerk Union AG (KWU), formerly held 50 percent by Siemens and 50 percent by AEG Telefunken -- now 100 percent by Siemens, is not now considering the use of titanium alloy for end blades up to and including the length of 42.5 inches for 3600-rpm machines.[3-4] (It should be noted that this length blade for 3600 rpm operation is considerably greater than the longest blades offered commercially by U.S.-based manufacturers, e.g., 33-inch blades made by the General Electric Company for 3600-rpm machines.) A development program for free-standing steel blades of the above length has been quite successful and the need for titanium regarding an increased blade length does not now exist. Erosion problems are minimized by the use of hollow last-row stationary vanes for taking off water in machines operating with exit steam of greater than 7 to 8 percent water content. The details of a KWU examination of titanium for turbine blading, which occurred several years ago, were not reported, except that the decision against immediately using titanium was made.

There is a large German program on corrosion-fatigue which has been going on for at least 4 years.[3-4] It was organized by an insurance company R and D center (Allianz-Zentrum für Technik GmbH) and involves four producers of steam turbines: BBC, KWU, AEG, and MAN (Maschinenfabrik Augsburg-Nürmberg AG). The German government provides matching funds to that of the five industrial contributors for a total of about 1 million marks per year (about $400,000). The program is chiefly on 12-chromium steel with steam chemistry, temperature, and strength level as chief variables. Titanium materials are not being evaluated. Standard corrosion fatigue tests have been developed, but crack growth tests were to be started later.

No information on titanium application in turbines from Germany was found in the literature.

3.4 JAPAN

While Japan is well known as a producer of titanium metal and the application of titanium in industrial equipment is actively pursued by the metal producers, only a single application of titanium for turbine blades was identified in survey work. Kobe Steel developed and has in operation last-stage Ti-6Al-4V blades in a 50-MW, single-cylinder, axial-flow, condensing turbine manufactured by the Takasago Works of Mitsubishi Heavy Industries, Ltd. and installed at the Kakogawa Works of Kobe.[3-4] The ten titanium blades in the test operation are 23 inches (584 mm) in length and have Ti-15Mo-5Zr alloy overlays on leading edges to improve erosion resistance (see section on Erosion Phenomena). It was reported that each titanium blade weighs 2.0 kg (4.4 pounds) whereas

12-chromium steel blades of the same geometry weigh 3.4 kg (7.48 pounds). Examination of blades after 24-month service in this 3600-rpm machine revealed that only moderate erosion attack was experienced under wet steam conditions (12 percent). No difficulties in titanium blade operation were reported.

Titanium tubing is used in the condensers of steam turbines manufactured by Hitachi, Toshiba, Fuji Electric, Seo, Kawasaki Heavy Industries, and Mitsubishi. However, only Mitsubishi Heavy Industries was identified as having an interest in the titanium blading developed by Kobe Steel. In addition, Ishikawajima-Harima Heavy Industries (IHI) reports that they have not participated in the development or use of titanium-alloy turbine blades.

No information on titanium turbine blading research being conducted in Japan was found in the literature examined.

3.5 POLAND

A single reference to Polish activity in the application of titanium in steam turbines was found in the literature.[3-5] Contact with Zaklady Zamech (Elblag) was attempted but not established. The 1972 article described the use of Ti-5Al-2.5Sn and Ti-5.5Al-2Mo-2Cr-1Fe-0.2Si alloys (the latter is the Soviet alloy designated VT3-1) as lashing rods. Details on the spot welding of Ti-5Al-2.5Sn rods and on hot bending ends of VT3-1 rods to hold them in a fixed position on turbine blades were reported. It was mentioned that stages stabilized with VT3-1 rods were in use.

3.6 RUSSIA

Reportedly, the Russians have a 500-MW turbine-generator in serial production that utilizes titanium in the turbine blades and also in several large parts not identified.[3-4] One plant operating such a unit is Leningrad Electrosila (LMZ). Considerable research work of a general nature is in progress toward applying titanium in turbines, and titanium-application research on actual turbines that are larger than the 500-MW item mentioned above is in the development and test stage. The Russian development cycle includes the building of full-size experimental machines on which they do testing and these are put into trial service prior to production of such models.

An 800-MW turbine-generator set having titanium blades which is in developmental service was reported. Also, a 1200-MW fossil-fueled machine having titanium blades is in the design and construction stage. Their 800-MW set has been in operational test for 1 year and is close to serial production. The design of the 1200-MW set calls for a total of six rows of titanium last-stage buckets in the three low-pressure turbines. The last-stage blades have an active blade length of 1200 mm ($\sim$48 inches) and are made of TS5 alloy (Ti-$\sim$4Al$\sim$2.5Sn$\sim$1.7Zr$\sim$1.7V).[3-6] Reportedly, the 1200-MW turbine-generator set is behind schedule, but one section of the six-flow, low-pressure turbine is being readied for test now with testing of the entire unit perhaps 1 to 2 years away from full test. Although not disclosed in Reference 3-6, it is believed possible that the Russians are blading the entire low-pressure turbine with titanium blades to reduce the loads on the disc and spindle.

The Soviet literature on the subject of applying titanium to steam turbines is fairly extensive and several references are cited in appropriate other sections of this report. In a recent book on the use of titanium,[3-7] several specifics were cited pertaining to the use of titanium in steam turbines. Sections of the book were translated and are included below to indicate the status of titanium for turbines in a general way. Details of applications were sought but not obtained.

Reference 3-7. The Use of Titanium in the National Economy, S. G. Glazunov, et al (A. T. Tumanov, Ed.), Tekhnika, Kiev-1975 (200 pages), Chapter on Titanium in Machine Construction (pages 131-142). Excerpts from pages 140-141:

> "The utilization of titanium alloys in power machinery is quite insignificant, although a number of technical problems are solved very effectively through this use. The expediency of using such alloys in power engineering is determined by economic and technical considerations. In a few cases, titanium alloys with high specific strength must be used because, for the present, no other metals exist - such is the case for the long working vanes of steam turbines [$\sim$40-48 inches ($\sim$1000-1200 mm)]. - - - - "Using these alloys for working vanes less than 40 inches (1000 mm) in length, and made of steel as a rule, results in the load relief of the stressed rotor of the low-pressure cylinder of the turbine and increases the total reliability of construction. The first experiment in using vanes of this kind in turbines gave positive results.

"Vanes ∿27 inches (665 mm) in length and made of titanium alloy VT5 (Ti-5Al), for a low-pressure turbine rated at 50 megawatts, were made by the Leningrad Metallurgical Plant as early as 1959. Later on, the same alloy was used in making vanes of 30 inches (766 mm) and 38 inches (960 mm) in length and installed on turbines of 200 and 300 megawatts, respectively. Up to now, the useful life of the vanes has reached 40,000 to 70,000 hours.

"A prolonged testing of the utilization of titanium vanes in the turbines of the Leningrad Metallurgical Plant revealed the satisfactory efficiency of this material. From the standpoint of corrosion-erosion resistance, the titanium vanes are better than steel vanes under conditions of wet steam production. At the same time, along with the titanium vanes in the steam turbines, one can use with success a titanium wire of the VT5 alloy for the damping connections. At present, series production of turbines having the last stages made of titanium alloys is organized in other turbine construction plants of Soviet Russia.

"In recent years, along with organization work conducted under the guidance of the Central Scientific Research Boiler and Turbine Institute, a large complex of studies was carried out concerning the selection, investigation, and processing of high-strength titanium alloys for vanes of the last stages of the low-pressure cylinder of a turbine (3000 rpm) with a power of 1200 megawatts. The studies resulted in the fabrication of forged vanes with 54 inches (1350 mm) length of the working part." (Book is in Russian. Translations are by D. K. Dreyer of Battelle-Columbus.)

In addition to the VT5 alloy mentioned in the book (above), other references indicate that the Soviets are examining the TS5, Ti-(3 to 5)Al-(2 to 3)Sn-(1.4 to 2)Zr-(1.4 to 2)V, VT3-1, Ti-5.5Al-2Mo-2Cr-1Fe-0.2Si, and VT8, Ti-6.5Al-3.5Mo-0.25Si, alloys for the blading application.[3-8,3-9,3-10] The use of VT5, Ti-5Al alloy, blading is additionally described.[3-11] The various references found during the survey indicate that the Soviets are conducting a comprehensive total program with regard to investigating the properties and characteristics of titanium alloys relative to the blading application.

3.7 SWEDEN

Stal-Laval Turbin A.B., Finspong, reportedly has a titanium-for-steam-turbines plant program.[3-4] Information on the extent of the program did not become available. However, Imperial Metal Industries, Ltd. of Great Britain reported on the joint development of IMI-680, Ti-2.25Al-11Sn-4Mo-0.2Si blades for a 12-MW company power station turbine manufactured by Stal-Laval.[3-12] The 12-MW, axial-radial flow turbine, originally fitted with 160 steel blades of 216-mm (8.5-inch) length in each exhaust row, was refitted with 200 titanium blades (each end) having 240 mm (9.5-inch) length. Two steel lacing wires for each row of titanium blades were used for damping (no covers). The last row overall diameter was maintained--the disc diameter was reduced. The refitted turbine could develop 13.5 MW at peak load and is further discussed in the report section on improved power and efficiency (see page 5-64). Examination of the titanium blades after a period of operation revealed the absence of blade erosion (1510 ft/sec tip speed running at a mean wetness of 9 percent). The titanium alloy blade profiles were machined by Stal-Laval from fully heat-treated, IMI-680, rectangular bars. The hardness of the alloy in this condition is about 380 HV_{30} (Vickers hardness, 30 kg load) and the tensile strength is typically about 190 ksi (85 t/in^2).

3.8 SWITZERLAND

The Brown Boveri Company, Baden, has been active in the development of titanium last-stage turbine blades since 1962, and has operated titanium blades in turbines of up to 600 MW.[3-4] The evaluation is continuing with plans for the installation of two full stages of titanium blades in a large 3000-rpm low-pressure, turbine section. The blades will be 48 inches (1200 mm) in length and will be made of Ti-6Al-4V alloy supplied by Contimet and forged by Boehler of West Germany.

The IMI-680 titanium alloy also has been examined for the turbine blades of BBC machines. A number of blades of this alloy and 867-mm (34-inch) length were installed in the last row of a 300-MW turbine interspersed with conventional steel blades of the same geometry.[3-12] The blades appear to be freestanding in the photograph accompanying the article. No erosion was observed on the titanium blades in the relatively dry steam conditions after a period of operation. BBC also examined IMI-680 blades in test rigs where they were subjected to cyclical bending loads far in excess of those encountered in service without evidence of crack initiation or propagation (test details not given).[3-13]

A considerable increase in power of a steam turbine can be obtained by adding additional stages to the low-pressure turbine section(s). Longer length blades for such sections could only be from a higher specific strength material such as titanium or fiber composites in selected designs. Long blades from these materials would be needed in machines of up to 2000-MW size. Titanium blades would not be substituted generally for 12-chromium steel blades in present-size machines because BBC is comfortable with the steel blade service experience. Steel blades have to be replaced occasionally before 20-year service, but generally the performance in present-size turbines is satisfactory. Where possible, shrouds or erosion shields are not used with steel blades, and also would be avoided in the case of titanium.

A surface treatment, which appears to be heat treating the leading edge of steel blades to the high-strength condition, leaving the remainder of the blade in the fully tempered condition, provides good erosion resistance and good corrosion fatigue strength in BBC practice. The BBC experience has indicated that titanium blades can be used without erosion shielding as a result of its naturally high erosion resistance in combination with BBC blade and machine design features.

The attachment of titanium blading to steel discs (3 percent Ni steel) is done through the usual fir tree arrangement, the same as with 12-chromium steel blades, without any problems encountered with clearance, galling, load imbalance on hooks due to elastic modulus mismatch, or corrosion due to galvanic coupling. Tests on a range of IMI titanium alloys have shown an absence of stress corrosion, pitting, or crevice corrosion when the materials are in contact with 13-chromium steel at temperatures up to 350 C (660 F) in environments containing a mixture of NaCl and NaOH deposits.[3-13] Also, operating temperatures in the last stages of BBC low-pressure turbines are sufficiently low so that no problems have been experienced due to the difference in thermal expansion between titanium alloy and steel. This might not be the case if the entire low-pressure turbine were bladed with titanium.

The relatively low elastic modulus of titanium alloys (16 to 17 million psi for titanium compared with 30 million psi for steel) and the low damping capacity of titanium have not been a major concern of BBC in their development of last-stage blades. In summary, BBC has not encountered any intrinsic technical difficulties in applying titanium alloys to their needs. They do admit to a reservation in connection with the relatively high cost of titanium blading, however, which is discussed in the Cost Information section of the report.

3.9 UNITED KINGDOM

Reportedly, the Central Electricity Generating Board (CEGB) management people were interested in the low-pressure blade application for titanium several years ago when they were encouraging the development of a 1300-MW turbine.[3-4] However, since their 1300-MW turbine plans have been dropped in favor of continued 660-MW turbines, they have also dropped their interest in developing titanium for the low-pressure blade application. One aspect of their past research was aimed at improving the damping capacity of titanium alloys. They found that this could be done by heat treatment. This brought the damping capacity up to about that of 12-chromium steel, but left the titanium alloys in an unstable condition. The CEGB research on the Ti-6Al-4V (IMI-318), Ti-4Al-4Sn-4Mo-0.5Si (IMI-551), and Ti-2.25Al-11Sn-4Mo-0.25Si (IMI-680) alloys is summarized in the section on Damping Phenomena.

The application experience of CEGB was limited to the installation of relatively short titanium blades in its station at Little Barford. These blades were kept in service only a short time because of cracks originating from residual stresses associated with the welded attachment of erosion shields.

No information was made available from several other English turbine companies such as C. A. Parsons & Company, G.E.C. Turbine Generators, and Peter Brotherhood, although information from Imperial Metals Industries, Ltd., New Metals Division, suggests that titanium is being widely examined for turbine applications.[3-12,3-13] For example, the IMI references state that

> "Several fully heat treated IMI Titanium 680 intermediate pressure blades have been in service for a number of years. Because of their low density, they were selected as closing blades and balancing blades in specific cases where steel imposed too high a stress on the root fixings."

Further, the references cite the routine use of Ti-6Al-4V lacing wire, of 16-mm (0.63-inch) diameter, for the last two rows of low-pressure blades in steam turbines of up to 660 MW manufactured by English Electric-AEI Turbine Generators, Ltd. The use of the same alloy for shroud bands riveted to steel blades in certain types of radial flow turbines also was cited. While specific cases were not described, it was stated that Ti-6Al-4V and Ti-2.25Al-11Sn-4Mo-0.25Si blades have demonstrated their mechanical reliability and erosion resistance in a number of trial installations.

3.10 UNITED STATES[3-4]

The high specific strength of titanium alloys has undoubtedly been attractive to U.S. steam turbine manufacturers since their inaugural use in gas turbines in the early 1950's. Accordingly, two American manufacturers of large steam turbines, Westinghouse Electric Corporation and General Electric Company, have conducted programs to investigate the use of titanium for blading over a multi-year period. Some of the makers of smaller steam turbines, such as the Terry Corporation and Ingersoll-Rand Corporation, also have studied and now use titanium alloy blading. Since Allis-Chalmers Power Systems, Inc. uses turbine designs by Kraftwerk Union AG of West Germany, it does not utilize titanium blades although the company has examined the potential of titanium for its machines (see section on Germany). No information was obtained from the American MAN Corporation. The information obtained during survey work is presented under the following company headings:

- 3.10.1 General Electric Company
- 3.10.2 Ingersoll-Rand Corporation
- 3.10.3 Terry Corporation
- 3.10.4 Westinghouse Electric Corporation.

3.10.1 General Electric Company, Large Steam Turbine Generator Operations*

The General Electric Company (GE) experiments and experience with titanium alloys for steam turbines goes back many years. Initially, the interest was in the general evaluation of a new material as well as in a potential association of this new material for last-stage blading in increasingly larger turbines.

*The Intermediate and Small Steam Turbines Department of General Electric does not use titanium in turbines.

The early material of interest was the Ti-5Al-2.5Sn alloy. Later work and operating experience included the Ti-6Al-4V alloy. Mechanical property evaluations, including fatigue behavior characterization, physical property determinations, and corrosion, stress-corrosion, and erosion testing were conducted.

The GE work on the fatigue behavior of Ti-5Al-2.5Sn alloy showed that this material was quite fatigue sensitive to various surface preparations. That is, the alloy showed mean stress sensitivity in a Goodman type, Constant Lifetime Diagram (as opposed to the behavior shown by 403 steel). The GE work also resulted in the conclusion that titanium alloy for blades might require Stellite shielding. Tests indicated that titanium alloy did erode in wet steam although not as badly as steel. Hardness was found to not fully correlate with erosion resistance. Attempts at applying Stellite shielding to titanium alloy blades (e.g., by brazing) were considered less than satisfactory for commercial application.

Culminating the early GE test program, Ti-5Al-2.5Sn blades were introduced in the last stages of three operating turbines receiving steam from fossil-fueled boilers. A few 26-inch blades were interspersed with and tie-wired to adjacent steel blades of the same geometry in the turbines of 150 to 200-MW size. No problems have been experienced to date in more or less continuous operation. A nominal amount of blade erosion is observed--about the same as on adjacent steel blades. However, operating conditions in these machines do not represent severe erosion conditions.

Titanium alloy also was introduced in the closing-blade application in steam-turbine low-pressure sections. By the end of 1976, there were approximately 400 turbines of various sizes, all of the fossil-fueled reheat type, with titanium L-1 and L-2 closing blades. As applied, the Ti-5Al-2.5Sn and Ti-6Al-4V blades have only about half the vibrational stresses of steel blades since the strains are the same. The L-1 stages are operated at about 150 F. No problems have been experienced with this application.

Another application for titanium by GE has been blade covers. Titanium covers were installed on several machines in their intermediate pressure sections where covers experience temperatures up to 650 F. In two installations of this type, covers were found to be missing after a period of service. Recovery of a few pieces of covers and subsequent analyses revealed a high hydrogen content in the material. A reaction with steam, possibly augmented by caustic, was indicated. The reaction is further discussed in the section on Corrosion Phenomena. All other covers in other machines are performing satisfactorily.

A turbine related application for titanium also was described by GE. Hydraulic fluids used in the electrohydraulic control system experience high temperatures and must be cooled. Water contamination of the fluids can cause metal corrosion and fouling of the fluid in the heat exchanger. Thus, titanium tubes are being introduced because of the good corrosion resistance of titanium in the media. General Electric is just beginning to build up service experience in this area.

In GE's experience, steel turbine blade failures have not often been found to be due to a corrosion-fatigue mechanism, per se. Instead, GE has found stress-corrosion plus fatigue-crack-propagation (crack initiation at pits) mechanisms accounting for many of the failures experienced. A few blade failures have been found to stem from chloride pitting. High-cycle fatigue failures without indications of corrosion or stress-corrosion phenomena also have been experienced. Similarly, stress corrosion per se appears to have been the predominant cause for some blade failures.

Many of the blade problems found are related to an improper steam chemistry which can be particularly aggressive when not under control. Steam chemistry can be variable from one time to another within single machines and from turbine to turbine. Localized residuals from steam also are variable in concentration from one location to another within turbines. GE believes that there is a strong need to investigate the full range of steam chemistry variables that constitute the steam-turbine materials environment and to determine precise effects of such environments on materials.

The data that GE has accumulated do not indicate either a reliability advantage or disadvantage for titanium blades. GE believes that, on balance, titanium blading would not be beneficial to the power industry, particularly during a learning curve period. The cost for titanium blades per se is possibly not a deterrent to use because material cost differences between 403 steel and titanium are not so great on a volume basis. However, there are other costs in introducing a new material. To consider titanium for a new last-stage blade development for a larger machine is a multimillion-dollar program with inherent uncertainties and not merited under current conditions or perceived objectives of the electric utility industry. The General Electric Company has not found an industry interest to go to machines larger than those which are presently available using established technology.

3.10.2 Ingersoll Rand Corporation, Turbo-Products Department

The Ingersoll-Rand Corporation uses Ti-6Al-4V alloy blading in one of their axial flow steam turbine models. The unit is rated at 35,000 hp and utilizes last-stage blades having an active length of 12 inches (305 mm). The total blade length is 15 inches (380 mm) which includes a fir-tree, three-hook root for attachment to discs in axial alignment. Root hooks are shot peened for better fretting fatigue resistance.

The titanium blades are produced by forging and machining and used in the annealed condition. The blade tips move at a speed of 1375 ft/s ($\sim$420 m/s) in continuous operation in wet steam (8 to 10 percent moisture). Examination of blades after extended operation has revealed the good erosion resistance of Ti-6Al-4V. Ingersoll-Rand rates the erosion resistance of 12-chromium steel as inferior to that of titanium in their operations. They also state that, while titanium blade costs are higher than steel blade costs by about a factor of three, the titanium blading permits a design flexibility wherein the high cost of titanium blades can be recouped in the manufacture of simpler machines. For example, a single flow exhaust with long titanium blades might be utilized instead of a double-flow machine having 403-steel end blading.

Ingersoll-Rand also utilizes Ti-6Al-4V alloy as blade end-cover strips in several turbine models. Strips are peened onto tenons of last-stage L-1 and L-2 stage blades. The same as with titanium blades, Ingersoll-Rand has obtained good performance of titanium alloy covers in these areas.

3.10.3 Terry Corporation

The Terry Corporation has utilized titanium alloy for several years in the last-stage blades of small multistage axial-flow steam turbines serving various industries. Small 4-inch (100-mm) long titanium blades having a single-hook, root-attachment design were used originally and continue to be used in some machines. Later, an 8-inch (200-mm) tapered and twisted titanium blade was designed for use in larger machines. This blade has a three-hook, fir-tree root and provision for two damping wires, one straight and one zigzag, as illustrated in Figure 3-1. Additional damping of blades is provided by three damping wires in the blade roots. The blades are suitable for use in turbines of up to 25,000 hp, although they are more commonly used in machines of 10,000 hp and under.

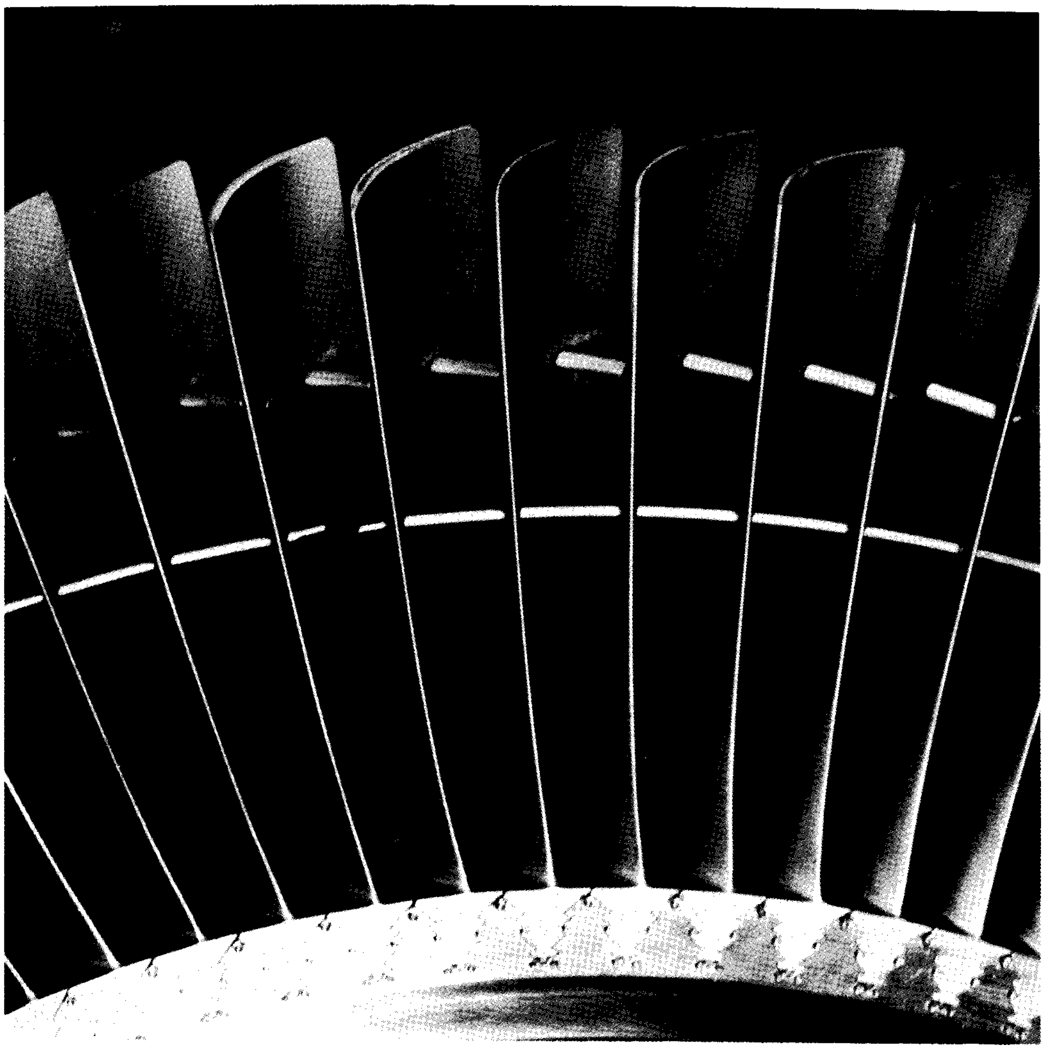

Figure 3.1. Ti-6Al-4V Last-Stage Blades of 8-inch Length With Two Damping Wires in the Blade and Three in the Fir-Tree Root

(Photograph Courtesy of the Terry Corporation)

The blades are manufactured of Ti-6Al-4V alloy by precision forging and machining and used in the annealed condition. The blades are designed to operate between 150 and 200 F in condensing turbines, but routinely experience excursions to between 400 and 500 F for short times during start-ups (low-speed and consequently low-stress conditions). The maximum design stress for blades is about 40 ksi, steady state, and 10 ksi, vibratory.

No difficulties have been experienced with titanium blades in about 12 years of operations. However, Terry reports that the information feedback from turbine users is not effective; perhaps that fact in itself is indicative of trouble-free operation. Inspection of operational turbines reveals minimal erosion damage and no cases of fretting fatigue damage in root (shot peened) or tie-wire areas. The Terry experience with the Ti-6Al-4V blades has established their confident belief that titanium is more erosion resistant than 403 steel in wet steam. Further, they have found superior corrosion resistance for titanium, and the high specific strength of titanium alloy permits the design of very high performance end stages.

Since the Terry Corporation uses the same blade design in both Ti-6Al-4V and 403 steel materials, a direct cost comparison should be possible. However, due to differences in size of orders and point-in-time of orders, several ratios are available. A 2.2 to 1 titanium to steel blade cost ratio is reasonably correct for recent purchases.

The Terry Corporation also uses titanium blade covers on some stages of some turbines. These are usually made of unalloyed titanium, machined and polished to fit over blade tenons, and welded into place.

The now famous Terry solid-wheel radial turbine was first marketed shortly after the turn of the twentieth century. The same basic turbine design is still produced using all steel components. However, the U.S. Navy selected a small turbine of this type (25 hp at 5600 rpm) for use in a side-by-side comparison test between a titanium turbine and one of steel in contaminated steam. [3-14] The objectives were to determine the feasibility of constructing a small turbine from titanium and, if possible, to determine any erosion-corrosion superiority for titanium components in contaminated wet steam.

The Ti-6Al-4V alloy was selected for the rotor and blades (integral construction), casing, nozzle, the nozzle valve, and other components, while unalloyed titanium was used for fasteners and fittings. The parts were used in the annealed condition. Steam containing phosphates, sulphites, and chlorides was supplied to both turbines from a single boiler. A total test time just short of 14,000 hours was used. Examination of components from both turbines at the end of the test period indicated a definite superiority of titanium alloy in erosion-corrosion resistance. Titanium components were clean and bright in comparison with eroded and corroded steel components.

3.10.4 Westinghouse Electric Corporation Power Systems, Large Turbine Division

The early interest of the Westinghouse Electric Corporation (W) in titanium was in response to the trend toward increasingly larger 3600 rpm fossil-fueled turbines. Very large diameter last stages in the low-pressure sections were considered, and high-strength, low-density titanium alloy capable of meeting the higher centrifugal force requirements on longer last-stage blades was studied. Initial evaluation of titanium for blading included studies on formability, design, erosion, corrosion-fatigue, mechanical properties, physical properties including damping characteristics, and cost.

The formability of titanium for blades did not prove to be a problem--blades could be made of titanium alloy in the sizes and sophisticated forms required. Erosion studies indicated that titanium alloys were quite resistant to water droplet impingement damage (see reference to W paper in Erosion Section). The strengths available in the different titanium alloys being considered were found to be adequate for requirements. The low damping characteristics of titanium were identified as a major problem area for the blading application. An alloy development program for high-damping characteristics was initiated and several candidate materials were developed (not identified). No resolution of the damping problem was immediately apparent via the alloy development. Mechanical damping, via shrouds and ties, and blade design refinements appeared as at least a temporary solution to resonance problems in longer blades.

The higher cost of titanium alloy blades compared with the cost of steel blades was an important factor in the W consideration of the titanium blading of turbines. While it was estimated that titanium alloy blades might cost about three times more than steel blades, the titanium blading of the last row in low-pressure turbine sections might increase the total cost of a large turbine by only about 1 percent. However, owing to competitive pressures, this small higher cost for a turbine (and consequently higher price) might make it very difficult to sell customers. A potentially improved turbine reliability via the use of titanium blading might be justification for higher turbine cost if a strong case for titanium could be developed.

The W research work on titanium for blading culminated in a decision to obtain an operational experience with moderately sized blades. Therefore, design and fabrication developments were commenced to equip one end of a double-flow, low-pressure turbine section with 23-inch (584-mm) long Ti-6Al-4V blades. A major development effort was completed to learn how to adequately join blade ties by fusion welding in an out-of-chamber operation. This done, W completed an installation of 120 last-stage blades in one end of a 100-MW, two-flow machine operating at 3600 rpm. The other end of the low-pressure section was equipped with Stellite-shielded 12-chromium steel blades. Thus, the effects of directly comparable operating conditions on shielded steel and unshielded titanium blades would be experienced.

A group of the Ti-6Al-4V blades, revealed for inspection purposes after 45 months of service in an estimated steam wetness of about 8 percent, are shown in Figure 3-2. This photograph reveals the robust section of the blades and the welded shrouds (lashing wires) that tie the blades in groups of five. The blades were fabricated by forging and machining and are in use in the annealed condition. The shroud projections were integral to the forgings and their joining by fusion welding was accomplished after blade placement in the rotor.

Blades are attached to the rotor by the usual three-hook, fir-tree arrangement. The root hooks are straight and axially aligned. It was stated by W that no difficulties have been experienced in the attachment of the titanium blades to the steel rotor. The three-hook configuration of the W Ti-6Al-4V blades accommodates the distribution of stresses to the three holding points very well owing to the low modulus, stress-strain characteristics of titanium.

Examination of the exhaust stage blades after extended service revealed that the titanium blades were only slightly more eroded than the Stellite shields on the steel blades (see Figure 3-2). Neither blade type was considered to have undergone extensive erosion. The tip speed of the blades in the 92-inch-diameter stages is about 1445 ft/s (440 m/s) and represents a fairly mild erosion exposure in comparison with the exposure expected for much longer blades in much larger fossil-fueled machines. Nevertheless, the performance of the Ti-6Al-4V blades in this operating experience appears encouraging.

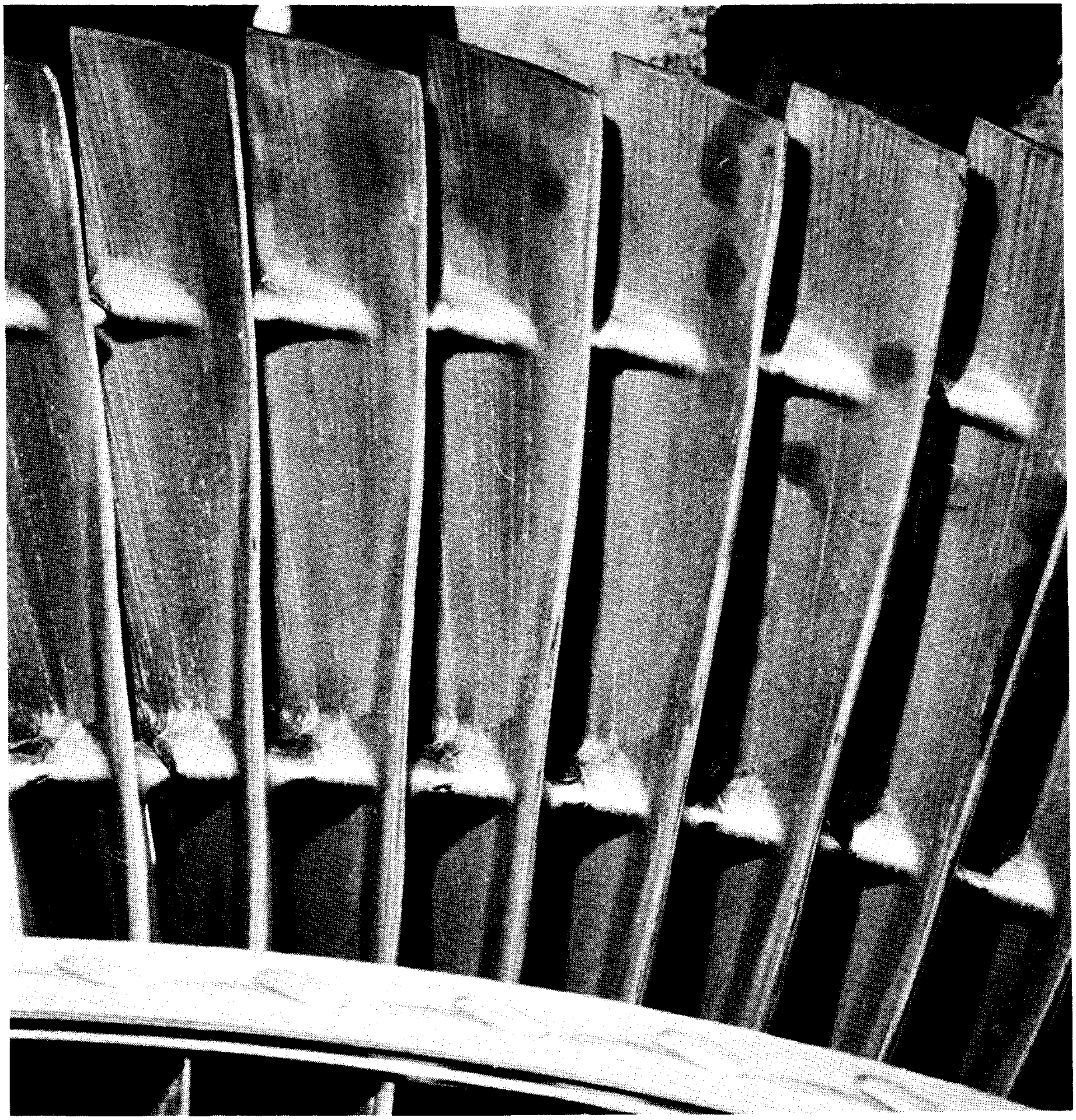

Figure 3-2. Ti-6Al-4V Last-Stage Blades of 23-inch Length With Two Shroud Bands Connecting Blade Groups of Five by Weld Joints

(Photograph Courtesy of the Westinghouse Electric Corporation)

The demand for increasingly larger fossil-fueled steam turbines is currently not as strong as it was when turbine manufacturers started examining titanium for blading. The lack of need for increasing machine size obviates the immediate requirement for last-stage blades longer than obtainable with steel technology. Therefore, the present need for long titanium blades is not urgent and W continues titanium blade development and evaluation work for different reasons. Westinghouse recognizes the desirability of building up an experience and a data base on titanium in preparation of taking advantage of whatever opportunities for titanium might develop.

While the W titanium blades have exhibited satisfactory performance in a relatively undemanding operating turbine, there is really no basis to suggest a need, or to merit a more extensive trial, of titanium blade substitution for steel blades for solution of blade problems. There is considerably more confidence in changing blade design to eliminate trouble than in changing blade material. The necessary design data for titanium to be used with confidence as a blade material are simply not available. The operating experience that exists for titanium blades under real turbine conditions has not, and will never, yield the design data required. Therefore, Westinghouse believes in the necessity to develop the titanium data base required for its more extensive use in blades via comprehensive and systematic research programs. Further, in order to better understand the opportunities for the use of titanium blading, it would appear expedient to conduct studies on the possible advantages of titanium relative to improved blade reliability and in conjunction with the redesign of last stages of existing turbines for improved power and efficiency ratings.

3.11 UTILIZATION SUMMARY

Much of the detailed information sought on the developmental and operational use of titanium in steam-turbine blading (and other components) was not made available for a number of reasons, including proprietary ones. Further, as previously mentioned, some companies did not have sufficient time to prepare contributing responses. Thus, while there is evidence that a great deal of activity in the development of titanium for turbine blading is in progress or has taken place, the survey has collected only a modest number of utilization facts. Those facts collected are summarized in Table 3-1, including information contained in a recently received reference from Japan.[3-15] Additional details are given in the preceding sections.

Table 3-1

SUMMARY OF TITANIUM UTILIZATION IN STEAM TURBINES

Country, Organization	Machine Type, Information	Titanium Component	Material Description	Pertinent Dimensions and Information	Operational Description and Remarks
Czechoslovakia Skoda Works	55 MW Large General	LS Blades LS Blades Damping Wire (LS=Last Stage)	Ti-5Al-2.5Sn Ti-5Al-2.5Sn (?) NG (NG=Not Given)	∿20 in. length 47-51 in. length NG	Development test 40,000 hr of operation Developmental study Operational with 33 in. length blades
Germany AEG Siemens	 100 MW 160 MW	 LS Blades LS Blades	 NG Ti-6Al-4V	 25.5 in. length 26.5 in. length	 Operational test (8 blades) Operational test (6 blades) 88,000 hr of operation
Japan Kobe Steel/ Mitsubishi(1)	 50 MW Same Machine	 LS Blades Blade Shields	 Ti-6Al-4V Ti-5Zr-15Mo	 23 in. length --	 Operational test (10 blades) Weld overlay on blade edges 18,700 hr of operation
Poland Zaklady Zamech	NG	Damping Wire	Ti-5Al-2.5Sn WT3-1(2)	Research Research	Secure by welding Secure by bending
Russia LMZ and others unidentified (Continued)	50 MW 200 MW 300 MW	LS Blades LS Blades LS Blades	Ti-5Al Ti-5Al Ti-5Al	27 in. length 30 in. length 38 in. length	Operational test 70,000 hr of operation Operational test 40,000 hr of operation Operational test

Table 3-1
(Continued)

Country, Organization	Machine Type, Information	Titanium Component	Material Description	Pertinent Dimensions and Information	Operational Description and Remarks
Russia LMZ and others unidentified	500 MW	Blades[3] and other	NG[4]	NG	Serial Production
	800 MW	Blades[3]	NG[4]	NG	Operational test 8760 hr. of operation
	1200 MW	Blades[3]	NG[4]	54 in. length	In development
	General	Damping Wire	Ti-5Al	NG	Operational
Sweden Stal-Laval/ IMI of the UK[6]	12 MW (13.5 MW)	LS Blades	IMI-680[5]	9.5 in. length	Operational uprated machine via titanium blades (200 blades each end)
Switzerland BCC	300 MW	LS Blades	IMI-680[5]	34 in. length free standing	Operational test
	600 MW	LS Blades	NG	NG	Operational test
	Large	LS Blades	Ti-6Al-4V	48 in. length	In development (two full stages)
United Kingdom CEGB	NG	LS Blades	NG	Relatively short	Short-time test (cracks in shield weldment)
--	NG	Closing Blades	IMI-680[5]	NG	Unknown status (Intermediate pressure section)
--	NG	LS Blades	Ti-6Al-4V	NG	Unknown status
			IMI-680[5]	NG	Unknown status
--	NG	Shroud Bands	Ti-6Al-4V	NG	Riveted to steel blades
English Electric	NG	Damping Wire	Ti-6Al-4V	0.63 in. diameter	Operational (lacing)
GEC Turbine Generators	NG	Blades	Ti-5Al-2.5Sn and IMI-680[5]	5 to 11 in. length	Operational tests in four units, 40,000 hrs. of operation
(Continued)					

Table 3-1
(Continued)

Country, Organization	Machine Type, Information	Titanium Component	Material Description	Dimensions and Information	Operational Description and Remarks
United Kingdom GEC Turbine Generators	NG	Damping Wire	Ti-4Al-4Mn, Ti-5Al-2.5Sn, Ti-6Al-4V	0.3125 to 0.4375 in. diameter	Operational 78,000 hrs. of operation
United States GE	150-200 MW	LS Blades	Ti-5Al-2.5Sn	26 in. length	Operational test (six blades in each of three units)
	Various sizes	L-1 and L-2 Closing Blades	Ti-5Al-2.5Sn and Ti-6Al-4V	Various sizes	Operational in about 400 units, some with 10 years service
	NG	Blade Covers	NG	NG	Operational in 11 units
	NG	Hydraulic system	NG	NG	Developmental tubing
United States Ingersoll-Rand	35,000 hp	LS Blades	Ti-6Al-4V	15 in. length	Operational
	Various sizes	Blade Covers	Ti-6Al-4V	NG	Operational (peened onto tenons)
Unites States Terry	Up to 10,000 hp	LS Blades	Ti-6Al-4V	4 in. length, also 8 in. length	Operational, many hr of operation (many units)
	Up to 10,000 hp	Blade Covers	Unalloyed Ti	NG	Operational (many units)
	25 hp	Many Components	Ti-6Al-4V	NG	Research test turbine
Unites States Westinghouse	100 MW	LS Blades	Ti-6Al-4V	23 in. length	Operational test of full stage. 33,000 hr of operation

(1) Kobe Steel blade development in Mitsubishi turbine.
(2) Same as Soviet VT3-1 alloy, Ti-5.5Al-2Mo-2Cr-1Fe-0.25Si.
(3) May be last-stage blades and blades of other stages.
(4) Alloys for blades include VT5, VT3-1, TS5, and VT8.
(5) IMI-680 alloy is Ti-2.25Al-11Sn-4Mo-0.2Si.
(6) Stal-Laval/IMI joint development.

A perusal of the information given in the previous sections and summarized in Table 3-1 shows that there is worldwide interest in applying titanium in steam turbines, particularly blading. As might be expected, the attempts to apply titanium in turbines is concentrated in the last-stage blade application. A range of titanium alloys is being examined. Unexpectedly, perhaps, titanium blades have been applied to, or are being developed for, a wide range of turbine sizes. The commercial application of titanium blades to small industrial turbines is an established operational fact. The operational testing of titanium blades in medium to moderately large turbines appears to be proceeding on a wide front, perhaps as the litmus test of several developmental programs. The development program for very large titanium blades in very large steam turbines is continuing in two countries, Russia and Switzerland, and it would appear that the development will soon enter the operational test stage.

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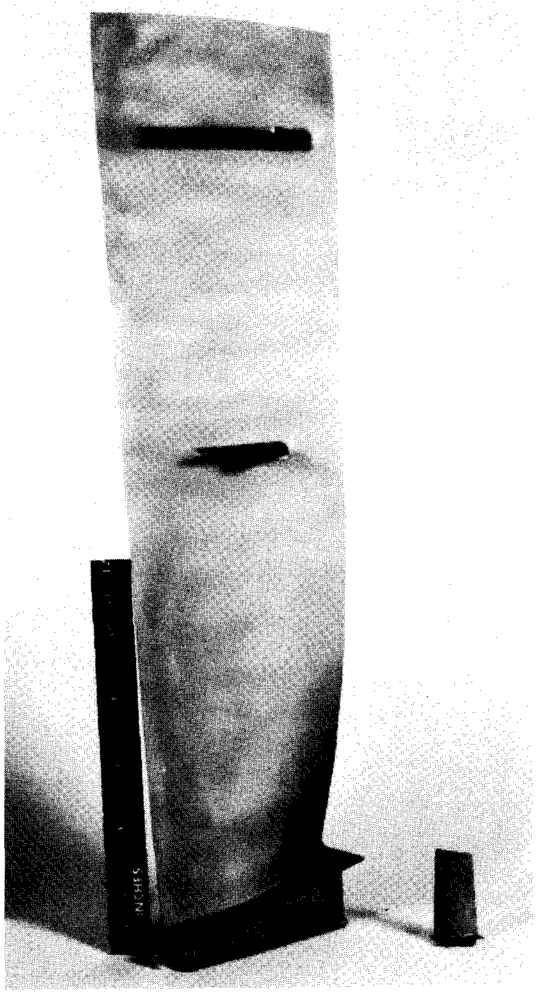
Section 4

RELATED OR PERTINENT TITANIUM UTILIZATION

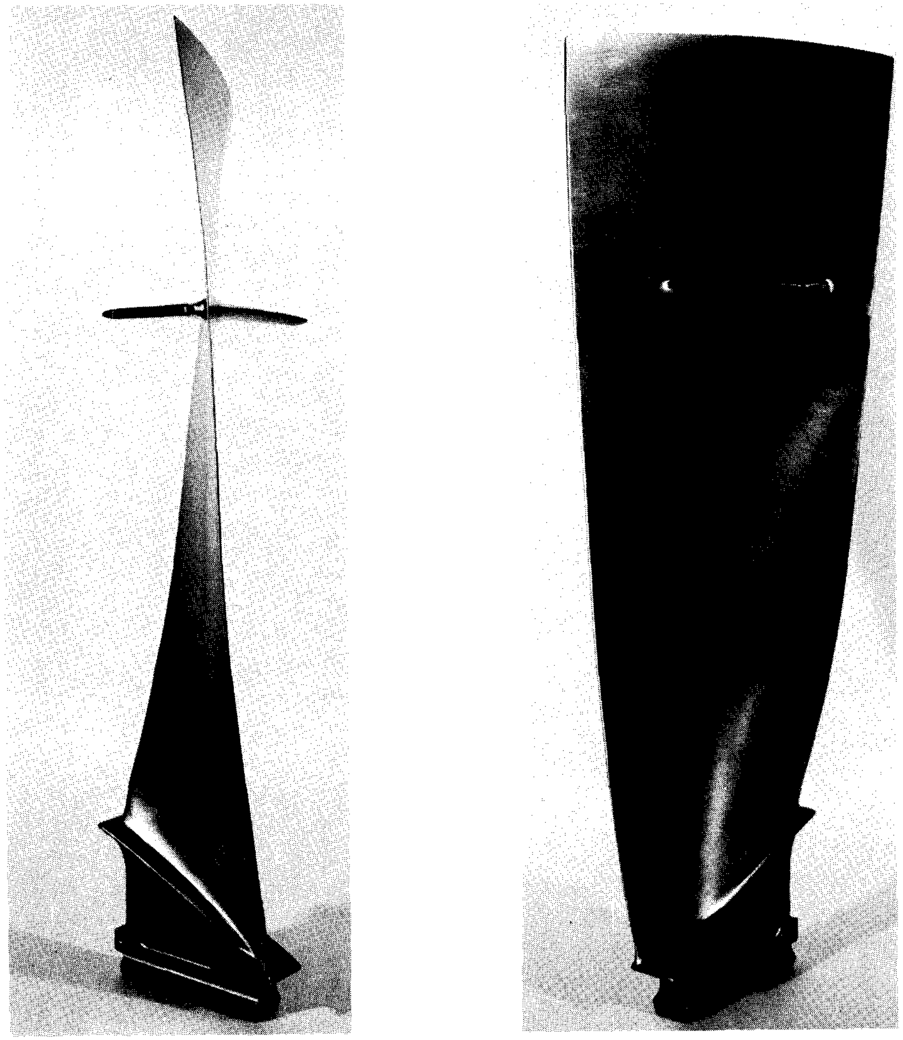
The application of titanium alloys to aerospace requirements, since the early 1950's, has been advanced to a high level of sophistication for both gas-turbine-engine and airframe duty. The use of titanium alloys for fan and compressor blades is particularly noteworthy. As blade sizes have increased with the advent of larger engines, the application becomes increasingly similar to blades for steam turbines in many respects. Fan blades for some of the larger aircraft gas-turbine engines are produced by forging and machining, used in the annealed condition, have overall dimensions with sophisticated taper and twist in the design, and are highly stressed due to centrifugal, bending, and vibratory loading in ways which are similar to those for steam-turbine blading. A few details for the fan blades of the Pratt & Whitney Aircraft Co. JT9D engine and the General Electric Company CF6-50 engine will be presented to illustrate the differences and similarities.

The fan blades for CF6-50 and JT9D engines are shown in the photographs of Figures 4-1a and 4-1b. Gross fan blade dimensions and some operational details are given in Table 4-1 for these blades in a side-by-side comparison with a hypothetical steam turbine blade of about the same overall length in both Ti-6Al-4V and 403 steel materials. The dimensions for the latter were estimated by interpolating and extrapolating information from several survey sources.

The differences between fan blades and turbine blades are of interest. Fan blades have a length/width ratio of about 3.4 to 4.0 (active blade length/average width) while turbine blades have a ratio of about 6. A large portion of the turbine-blade mass and overall length are in the root attachment area. Crush loads on the single hook of a fan blade are probably much higher than on the firtree hooks of a turbine blade and, since aircraft engines are operated on a start-stop basis compared with the relatively continuous operation of a steam turbine, low-cycle fatigue is important in fan-blade design while high-cycle fatigue dominates turbine-blade design.



(a)



(b)

Figure 4-1. Aircraft Gas-Turbine-Engine Front-Fan Blades (a) JT9D Blade Photograph Courtesy Pratt & Whitney Aircraft Co. and (b) CF6-50 Blade Photographs Courtesy General Electric Company

Table 4-1

COMPARISON OF JT9D AND CF6-50 FAN BLADES WITH STEAM TURBINE BLADES OF SAME LENGTH[4-1]

Comparative Feature	JT9D Fan Blade	CF6-50 Fan Blade	Turbine Blade[(1)] Ti	Turbine Blade[(1)] Steel
Blade material	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V	403
Condition	Annealed	Annealed	Annealed	
Overall length, in	29	28	28	
Active length, in	26.5 (avg)	∿25.5 (avg)	23	
Width at tip, in	7.7	∿9	3.1	
Width at root, in	5.6	∿6	4.5	
Max. thickness, tip, in	0.2	∿0.25	0.28	
Max. thickness, root, in	0.4	∿0.6	0.9	
Root type[(2)]	Single hook	Single hook	Three-hook firtree	
Stiffener shrouds, No.	2	1	1[(3)]	
(Distance from tip, in)	(∿4, ∿14)	(∿7)	(∿6.5)	
Shroud face coating	WC	WC	--	
Weight, lb	9.5	∿10	14	22.5
No. of blades in stage	46	38	120	
Stage diameter, in	92	86.4	96 to 102[(4)]	
Stage rpm	∿3600	3800 max.[(5)]	3600	
Blade tip speed, ft/s	1445	1433	1500 to 1600	
Blade max. stress (root area), ksi	70	90 (local)	--	
Max. vibratory stress, ksi	10	8	--	

(1) Composite of information from several sources: interpolations and extrapolations

(2) Straight hook parallel to machine axis

(3) Shroud projection or hole for tie wire

(4) Estimated range

(5) Normally about 3600 rpm

The high-time fan blades, in service for several years, have on the order of 10,000 hours at operational speed and only small amounts of time while operating in a water-droplet environment. Thus, there have been no erosion problems with fan blades; in fact, no leading edge changes, apart from foreign-object damage, can be detected. This is in contrast to the constant water-droplet exposure over many thousands of hours, and consequent erosion, of blades in some steam turbines. Similarly, possibly because of a combination of design and operating conditions, titanium fan blades have not experienced any vibrational fatigue problems, while failure problems in steel turbine blades due to this cause are not uncommon. No corrosion problems have been experienced with JT9D or CF6 fan blades and none are expected since their operating environment is not reactive with titanium.

There are very many aerospace applications which might be pointed out as having some area of relevance to the steam turbine-blade application. While none fit the case for turbine blading exactly, the fan blades previously described approximate the application as well as any. The case for titanium application in helicopters also needs to be called out. Helicopters have sometimes been called flying fatigue test machines. The use of titanium in the main rotor blade of the new UTTAS helicopter is described in a recent paper and an account is given of how titanium's high bending strain allowable and torsional stiffness are utilized.[4-2] Steam-turbine-blade designers might find this article of interest in its discussion of the interrelationships between blade twist, torsional stiffness, and vibratory loading.

Titanium-alloy compressor blading is used in marine gas-turbine engines as well as in aircraft engines. Several marine gas turbines are aircraft-derivative engines and retain the use of various quantities of titanium, particularly in the compressor section, to minimize seawater (saturated air) corrosion which has been the cause of problems with steel compressor blades.[4-3] Examples of marine gas turbines with titanium compressors include Olympus TM3B, GE LM-2500 (derivative of CF6), and P&W FT-4A12. The latter is a derivative of the Pratt & Whitney JT4 (military J-75) aircraft gas turbine engine and has Ti-6Al-4V blades in all 11 compressor stages (eleventh stage operates at 700 F).[4-1] Corrosion and stress-corrosion failures of titanium blades have not been experienced in the high-chloride-content environment of these marine engines.

Titanium has been successfully utilized in a number of seawater environment applications. One which may have some pertinence to the steam turbine blading application is the use of titanium in components of seawater jet pumps. Pumps of this type are used in the propulsion systems of high-performance water craft in sizes of up to 18,000 hp (and development up to 40,000 hp).[4-1] The Aerojet Liquid Rocket Company utilizes unalloyed titanium, Ti-6Al-4V alloy, and 17-4 PH steel for components of one of their two-stage water jets which pumps at the rate of 90,000 gallons per minute.

The first stage of the above pump has a Ti-6Al-4V housing around the 17-4PH inducer (large swept blades) and an integral housing-vane stator section of unalloyed titanium. The separately shafted second stage also uses a Ti-6Al-4V housing around 17-4PH impeller blades and an integral housing-vane stator section of unalloyed titanium. The exit nozzle also is in unalloyed titanium. The components are exposed to seawater flow at up to 190 ft/s and ingested debris. Titanium components have exhibited a "frosted" surface appearance after extended operating experience whereas 17-4PH steel blades have shown cavitation damage. It is recognized that the titanium and 17-4PH parts "see" different impingement angles, pressures, and velocities to account for differences in metal degradation. Nevertheless, titanium is recognized as a superior material for this application and its wider use in such pumps is being considered.

The use of titanium alloy in pumps for other purposes also is reported.[4-4,4-5] The development of pumps for geothermal circulation systems includes surface and down-hole pumps with Ti-6Al-4V alloy components. In the system described, as illustrated in Figure 4-2, one surface pump is used as a primer for a down-hole, turbine-driven pump capable of operating at depths to 10,000 feet in brines at temperatures to 650 F. The second surface pump is used to reinject the brine as it leaves the power take-off heat exchanger. Titanium components of pumps include casing, impeller, inducer, and renewable case-wear rings. The pumps are expected to find additional application in the chemical-processing industry and have been field evaluated by oil companies.

In the petroleum industry, titanium has been found to be an excellent material for water flood pumps used in secondary recovery programs.[4-6] Unalloyed titanium fluid cylinders for pumps have been tested at pressures to 5200 psi (584,000,000 cycles) without failure. The Ti-6Al-4V alloy was recommended for pumps operating at pressures above 5000 psi in environments leading to corrosion problems in otherwise competitive materials.

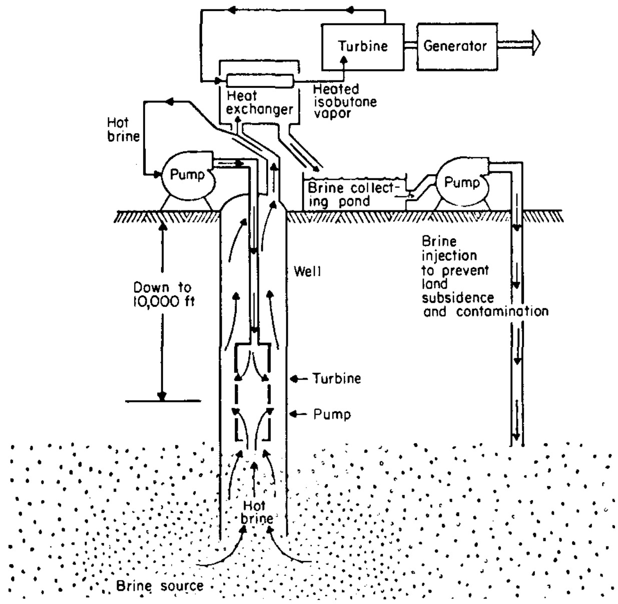


Figure 4-2. Binary Geothermal System Utilizing Titanium Component Pumps[4-5]

A wide variety of reactants hostile to materials used in components of equipment and structures are found in flue gases of refuse incinerators; bulk ingredients of water vapor, carbon dioxide, nitrogen, and oxygen are mixed and contaminated with smaller quantities of acid gases such as hydrogen chloride and active gases such as the oxides of sulfur. The corrosion of wet scrubbing system equipment being employed to reduce pollutants from such mixtures has been a problem. Material testing has been conducted to determine which materials resist corrosive attack in such environments.

The good corrosion resistance of titanium in gas scrubbing components is described in several publications.[4-7 to 4-10] Components of a flue-stack scrubber are shown in Figure 4-3, along with zone locations where titanium and other materials were tested.[4-7] Titanium's resistance to corrosion was rated topmost in zones 1, 5, and 6, and near the top (third ranked) in zones 2, 3, and 4, in one extensive program. One of the authors points out that economically titanium is best suited for use in the components at each end of a system where equipment malfunctions might prove to be very costly.[4-8] Cheaper materials can be used elsewhere, but titanium can withstand the transient conditions of a water outage or a temperature flare at the inlet side of a scrubber and the high stresses and other hostile conditions in the rotating parts of the exhaust fan. Results from one set of corrosion tests conducted in the Zone 6 location are given in Table 4.2.

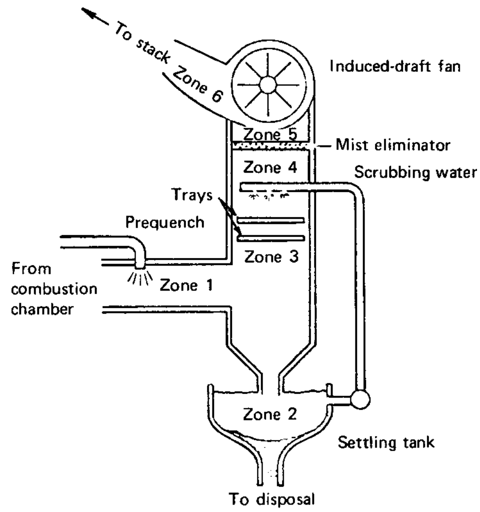


Figure 4-3. Components of a Typical Gas-Scrubbing System[4-7]

Table 4-2

Results of Corrosion Tests in Zone 6 of a Stack-Gas(1) Wet Scrubber Using Salt Water for Scrubbing (90-Day Exposures)[4-7]

Material	Average Corrosion Rate, mpy	Surface Pitting
Titanium	0.5	No
Hastelloy alloy C	1.1	Yes
Inconel alloy 625	1.2	Yes
Inconel alloy 825	7.8	Yes
Type 317 steel	8.8(2)	Yes
Type 316 steel	11.0(2)	Yes
Hastelloy alloy B	8.5	Yes
Carpenter 20 Cb3	12.0	Yes
Carpenter 7-Mo	12.0	Yes
Incoloy alloy 800	14.0	Yes
Monel alloy 400	16.0	No

(1) About 18% H_2O, 8% CO_2, 65% N_2, 8% O_2, 0.25% HCl, plus traces of fluorides, phosphates, and organic acids

(2) Stress corrosion cracking observed.

There are additional titanium applications where a trouble-free, long-time service record indicates that this material is very durable in various hostile environments. The conditions of such cases and those previously described only approximate those prevailing in low-pressure, steam-turbine sections, and usually not all parameters are found in a single case. Nevertheless, the circumstantial evidence from such cases that indicate the ability of titanium to perform successfully over long periods of time in the turbine blading role is abundantly available.

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4-8 Feige, N. G., "Corrosion Service Experience and Economics of Titanium's Usage in Gas Scrubbing Equipment for Refuse Incinerators", Titanium Fabrication Corporation, Fairfield, N.J., paper presented at the 1974 annual meeting of the National Association of Corrosion Engineers, Chicago, Illinois, March 7, 1974

4-9 Tice, E. A., "Corrosion Tests in Flue Gas Desulfurization Processes", Materials Performance, Vol. 13, No. 4, April 1974, pp. 26-33

4-10 Feige, N. G., "Titanium for Incinerator Gas Scrubbing Equipment", ibid., pp. 17-20

Section 5

TECHNICAL AND ECONOMIC CONSIDERATIONS RE TITANIUM BLADING

5.1 EROSION PHENOMENA

The erosion of low-pressure steam turbine blading by the water in wet steam is a commonly observed phenomenon in medium and large-sized machines. Turbine blading can become aerodynamically inefficient by the destruction of blade leading edges via water droplet erosion. The damage can be sufficiently severe to lead to the shutdown of a turbine for blade replacement.

For blade destruction by erosion to occur, there are three fundamental requirements: the availability of water, the condition of a high-energy state as in a high-speed blade-water impact, and a relatively long reaction time. Water is present in steam from condensing turbines when the steam expands to a condition beneath saturation, an operational condition common to the last rows of many turbines. This location also meets the requirement of a high-energy state since the row diameters here are large, and the tip speeds of the longer blades can be quite high. The time requirement is easily met since steam turbines are operated for multiyear periods.

The leading edges of blades near the blade tips are the areas commonly eroded. Under severe conditions, erosion can be detrimental after only a few hundred hours operation. However, due to the precautions that are usually taken, erosion can be minimized, even for service lifetimes of several thousand hours (e.g., 20-year service). The factors that determine erosion rates are

- Amount of water available (moisture content of steam in the last rows of LP turbine blading can be on the order of 10 percent)
- Blade tip speed (tip speeds greater than 1000 ft/s [300^{+} m/s] can be damaging)
- Turbine design (for example, the distance between fixed and rotating blades) [5-1]

- Blade geometry (for example, blade profile selection so that water droplets impinge on blades at different angles and areas)[5-2]
- Blade material.

Comprehensive accounts of the blade erosion phenomenon are afforded in References 5-1 and 5-2 as well as in several other publications.[5-3 to 5-7] Briefly, these papers describe the water source, its accumulation, motion, and disposition on stator blades, water-droplet dispersion, impact effects, relative erosion rates, and measures for reducing erosion. For example, Figure 5-1 depicts absolute and relative steam and water velocities in a low-pressure turbine stage (water droplets exiting from stator blades and impinging on rotating blades), and Figure 5-2 shows relative blade erosion rates versus blade tip speed of medium-sized and industrial turbines according to commonly accepted concepts.[5-1,5-2] Another concept is propounded in Reference 5-2 wherein it is described that relative erosion rate is not necessarily increased in machines with higher blade peripheral velocities when designs are optimized. However, all other factors being equal, the general effect of increasing blade tip speed is to increase the erosion rate.

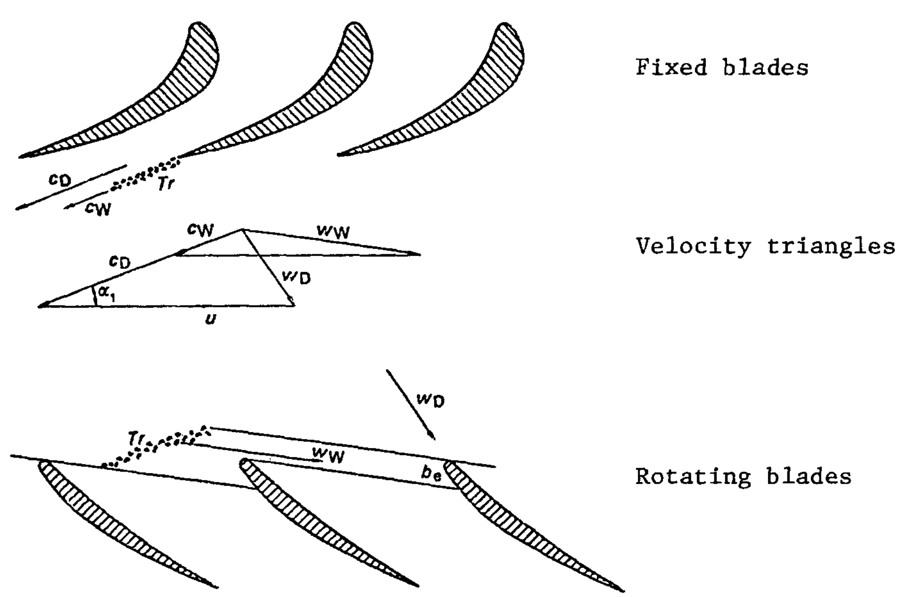


Figure 5-1. Steam and Water Droplet Velocities in a Low-Pressure Turbine Stage[5-1]

c_D = Absolute steam velocity
c_W = Absolute water velocity
w_D = Relative steam velocity
w_W = Relative water velocity
u = Peripheral velocity
b_e = Wetted width = erosion width
Tr = Path of water droplets
$\alpha 1$ = Outlet angle of fixed blades

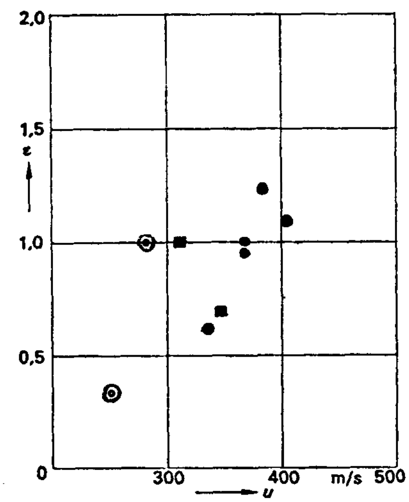


Figure 5-2. Relative Erosion Rates of Steam Turbine Blading (Brown Boveri & Company, Ltd.) [5-1]

ε = Relative erosion rate
u = Peripheral speed of a moving blade

● = 3000 rev/min in service
■ = 3600 rev/min in service
⊙ = 3000 rev/min design

While apparently much can be done to alleviate the blade erosion problem in steam turbines by limiting the steam moisture content (via operational limitations, by providing for water drainage take-off passageways, [5-1,5-8] by controlling the water droplets by turbine and blade design, [5-1,5-2] and by limiting peripheral velocities), the current interest is centered around blade-material behavior. The selection of erosion resistant materials for blades per se or for blade shielding is an effective method of controlling erosion. A specific current interest is how titanium alloy blades have performed under conditions of water droplet erosion and how the erosion resistance of titanium alloy compares with that of steel blade material. In brief, the findings of this survey indicate that titanium alloy blades have performed without erosion problems in operational service and that titanium alloy erosion resistance is equal to or better than conventional steel blade material erosion resistance.

The operational experience reported per the survey included the following blade erosion observations.

Titanium blades of about 20-inch (500-mm) length (alloy not disclosed), and without erosion shields, were installed in a 200 to 300-MW turbine by

Allgemaine Electrizitacts-Gesellschaft AG about 10 years ago and have been operated since without erosion difficulties.[5-9]

The erosion resistance of titanium last-stage blades operating in turbines of up to 600-MW size, and without erosion shields, is rated not worse than the erosion resistance of hardened 12-chromium steel blades operating in the same machines by Brown Boveri & Company (BBC).[5-9]

A specific example cited [5-10] disclosed the lack of erosion in Ti-2.25Al-11Sn-4Mo-0.2Si (IMI-680) fully heat treated blades of 34-inch (867-mm) length, and without erosion shields, operating in a 300-MW turbine having relatively dry steam conditions. Adjacent steel blades in the same row of the BBC machine had shields.

Examination of a relatively small turbine, 13.5 MW after rework by Stal Laval (Sweden), using unshielded IMI-680 fully heat treated blades of 9.48-inch (241-mm) aerofoil length, and operating with a peripheral velocity of 1510 ft/s (460 m/s) in steam with a mean wetness of 9 percent, revealed a complete absence of erosion in the blades.[5-11]

Last-stage Ti-5Al-2.5Sn alloy turbine blades were installed in several GE operating turbines of moderate size many years ago. These blades, without erosion shields, have given problem-free performance; blade erosion is about the same as observed on adjacent steel blades. Operating conditions in these machines do not represent severe erosion conditions.[5-9]

The last-stage row of annealed Ti-6Al-4V blades that Westinghouse installed in an operating turbine of 100-MW size about 4 years ago has not given erosion problems.[5-9] The machine, operating at 3600 RPM, has a two-flow LP turbine section with the titanium blades on one end being subjected to the same wet-steam conditions as the Stellite shielded 12-chromium steel blades on the other end. The 23-inch (584-mm) blades of both steel and titanium have the same geometry. The titanium blades were only slightly more eroded than the Stellite shields of the steel blades in 4 years of operation (another assessment by other Westinghouse personnel claimed that erosion of Stellite shields was equal to that of the titanium blades).

The relatively small blades of titanium alloy used in the small to medium-sized power steam turbines manufactured by the Terry Corporation and Ingersoll-Rand

Corporation, Turbo-Products Department, have not been the subject of erosion problems.[5-9] In general, the experience of these companies has been that titanium alloys are more erosion resistant than the steel blading material more commonly used.

Mitsubishi Heavy Industries, Ltd., manufactured a 50-MW condensing turbine for operation at the Kakogawa plant of Kobe Steel, Ltd. Ti-6Al-4V last-stage blades of 23-inch (584-mm) length were shielded with an overlay deposit of Ti-15Mo-5Zr alloy [5-12] (see U.S. Patent No. 3,802,939, April 9, 1974). The examination of these blades after 2 years revealed that erosion attack was not great.

Specific operational experiences cited for Soviet Union machines utilizing titanium alloy blading do not include direct erosion assessments for the titanium. However, the literature indicates that Stellite shielding is used for titanium blade protection, possibly indicating that unshielded titanium has insufficient erosion resistance for the operating conditions of the machines using titanium.[5-12]

The insufficient erosion resistance of Ti-5Al-2.5Sn blades operating with Mach 2 tip speeds (48 to 52-inch [1220 to 1320 mm] blades in 3000 RPM machines) is cited by Skoda authors (Czechoslovakia).[5-8] The good performance of Ti-5Al-2.5Sn blades in smaller machines (55-MW size utilizing ∿20-inch [∿500 mm] blades) is mentioned also.

The survey revealed that, in many testing programs, titanium alloys have good water droplet erosion resistance in comparison with other metallic materials. For example, tests conducted by one turbine company have shown that the steam moisture content -- blade peripheral velocity limitations imposed on 403-steel blades by operating conditions resulting in blade erosion can be considerably extended with the use of Ti-6Al-4V blades.[5-9] As shown in Figure 5-3, blade peripheral velocity at 10 percent steam moisture content can be increased from about 1450 to 1750 ft/s (440-530 m/s) without erosion problems by substituting Ti-6Al-4V blades for 403-steel blades.

Qualitatively, BBC reports that titanium alloy in tests has better erosion resistance tham tempered 12-chromium steel but less resistance than hardened 12-chromium steel.[5-9] It was pointed out that the erosion performance of

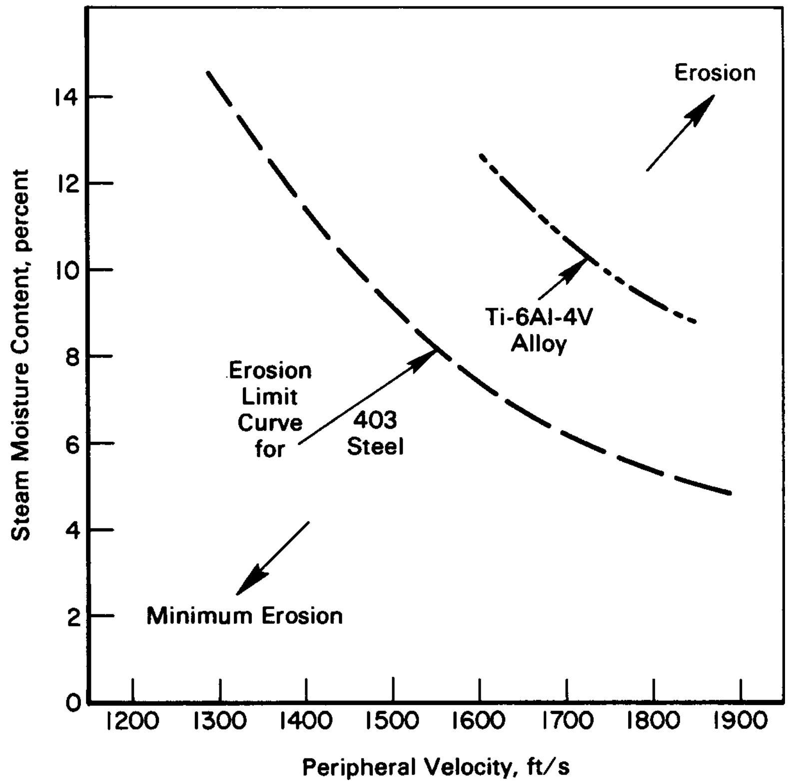


Figure 5-3. Comparison of the Erosion Behavior of Ti-6Al-4V Alloy and 403 Steel Blades in Terms of Steam Moisture Content and Blade Peripheral Velocity (Other test details not given) [5-9]

titanium blades is sometimes observed to be better in actual service than it appears in simulated tests (such as in the rotating blade in a rain chamber).

The Soviets report that two titanium alloys, Ti-5.5Al-2Mo-2Cr-1Fe-0.2Si (VT3-1) and Ti-4Al-2.5Sn-1.7Zr-1.7V (TS5), are definitely more erosion resistant than chromium steel but considerably less resistant than Stellite.[5-14] The VT3-1 alloy is about 1.6 times more erosion resistant than the TS5 alloy according to test results. The results of a water jet impact test on VT3-1 titanium alloy and 2Kh13 steel indicate the approximate equivalency of these materials in resisting erosion under the conditions of a specific impingement (repeated impact of water jet at 150 m/s) [5-7] as shown below.

Material	Maximum Contact Width, mm	Width of Undamaged Strip, mm
VT3-1	0.11	0.25
2Kh13	0.11	0.25

The following test results further indicate the favorable erosion resistant characteristics of titanium.

Erosion damage of materials suitable for use as steam turbine blading was measured after single shot water jet impingement by research workers at Westinghouse.[5-15] Jet diameter and velocity were variables. Damage caused by jet impingement on polished specimens was assessed with the aid of optics. Damage depth and crater volume (μ scale) measurements were taken. Figure 5-4 summarizes selected data for 12-chromium steel, Stellite, and Ti-7Al-4Mo materials. Table 5-1 shows the erosion resistance ranking of materials tested at two jet velocities, 2500 and 3000 ft/s (760 and 914 m/s). The titanium alloys ranked highest (the first five positions) in erosion resistance in this study.

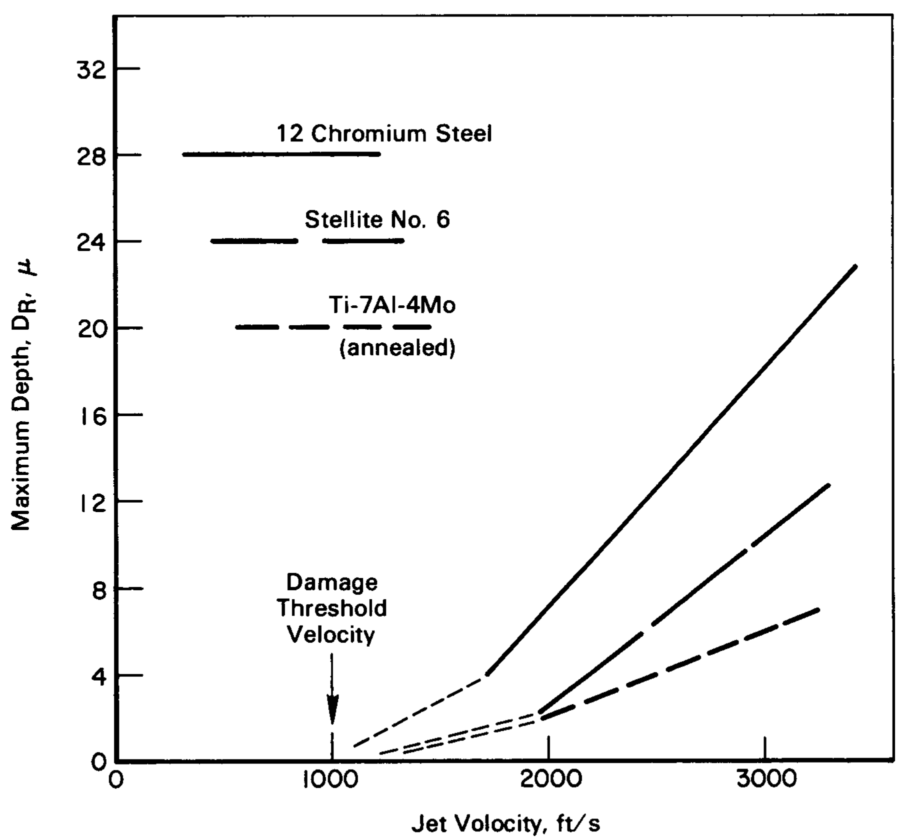


Figure 5-4. Effect of Water-Jet Velocity on the Damage Depth Observed in 12-Chromium Steel, Stellite, and Ti-7Al-4Mo Alloy in Tests Using a 0.06-Inch-Diameter Jet[5-15]

Table 5-1

MATERIAL EROSION RESISTANCE RANKING[5-15]
(Single shot, 60 mil diameter water jet at velocities of 2400 and 3000 ft/s [730 and 910 m/s])

Rank	Material
1	C 130 HT (believed to be Ti-4Al-4Mn as heat treated)
2	RS 140 HT (Ti-5Al-2.75Cr-1.25Fe as heat treated)
3	C 135 (Ti-7Al-4Mo)
4	C 130 (believed to be Ti-4Al-4Mn as annealed)
5	RS 140 (Ti-5Al-2.75Cr-1.25Fe as annealed)
6	Stellite No. 6
7	PDS 2874
8	303 stainless steel

Note: Titanium alloy heat treatment was 2 hours at 1450 F, water quenched, plus 4 hours at 950 F, air-cooled.

Research conducted in relation to the U.S. Navy application of titanium and other materials to hydrofoil craft by the Chance Vought Corporation included water jet erosion-corrosion and cavitation assessments in sea water.[5-16] Figure 5-5 shows selected jet erosion-corrosion data generated on this program while Figure 5-6 shows selected cavitation data. The Ti-6Al-4V and Ti-8Al-2Cb-1Ta alloys were better than any of the other metallic materials tested in the jet erosion-corrosion test; Inconel 718 had the best cavitation resistance.

The New Metals Division, Imperial Metal Industries, Ltd., has provided additional cavitation and erosion resistance data for survey report purposes.[5-10] The cavitation-erosion resistance data for titanium alloys, steels, and Stellite are given in Table 5-2, while erosion characteristics of selected materials, as determined in test rigs (details of test not given), are shown in Figure 5-7. These data suggest that high material hardness is conducive to good erosion resistance. The titanium alloys appear to be more resistant than several steels but less resistant than Stellite in these tests.

The erosion of materials for components of geothermal steam power generating systems is being examined at the Lawrence Livermore Laboratory (LLL) under U.S.

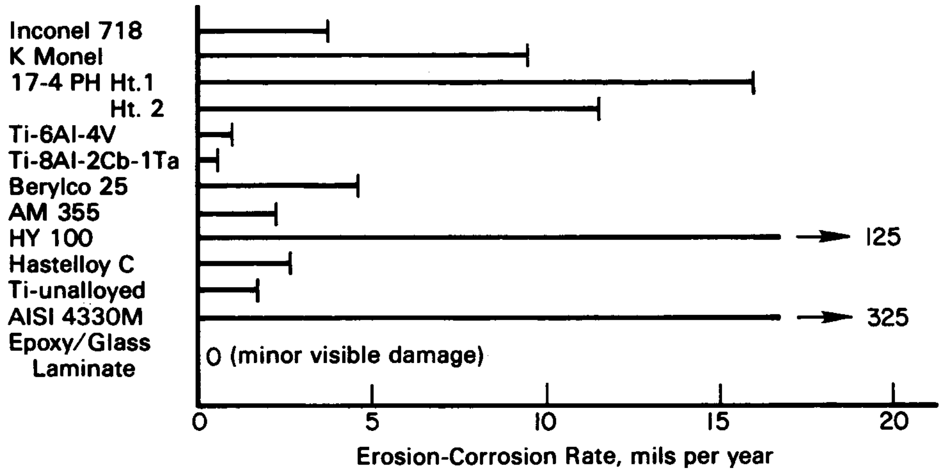


Figure 5-5. Sea Water Jet Erosion-Corrosion Rates for Hydrofoil Material Candidates[5-16]

(30-day exposure at 90 knots, 45-degree impingement angle)

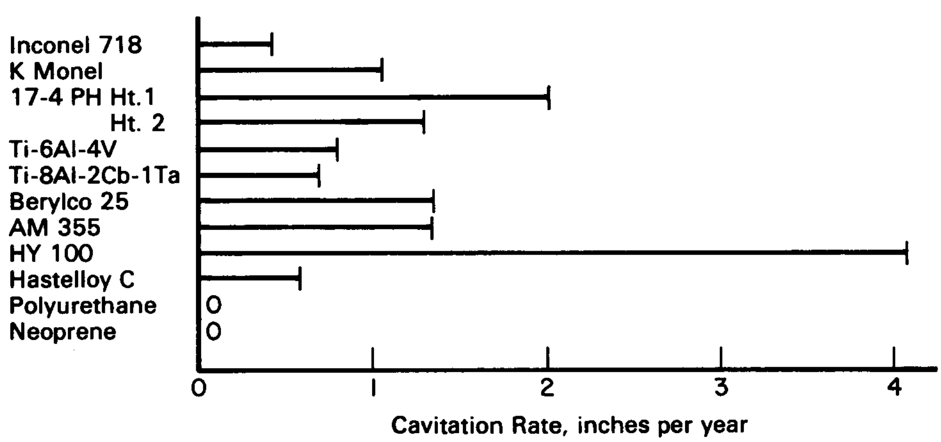


Figure 5-6. Sea Water Cavitation Rates for Hydrofoil Material Candidates[5-16]

(Double amplitude 0.001-inch, 22,000 cycles per second, 8-hour exposures)

Table 5-2

CAVITATION-EROSION RESISTANCE OF TITANIUM ALLOYS, STEELS, AND STELLITE DETERMINED AT ROOM TEMPERATURE IN 10-HOUR EXPOSURES[5-10]
(Peak-to-Peak Amplitude 0.002 Inch, 20,000 Cycles Per Second, Immersion Depth 0.25 Inch, Liquid Depth Under Specimen 3 Inches)

Material Designation (Composition, w/o)	Incubation Period, hrs Pure Water	Weight Loss mg/hr		Volume Loss mm^3/hr	
		Pure Water	3% NaCl	Pure Water	3% NaCl
IMI Ti 314 (Ti-4Al-4Mn)	0.60	3.77	4.21	0.84	0.94
IMI Ti 318 (Ti-6Al-4V)	0.65	4.46	4.90	1.01	1.11
IMI Ti 679 (Ti-2.25Al-11Sn-5Zr-1Mo-0.2Si)	0.75	4.58	5.20	0.95	1.08
IMI Ti 680 (Ti-2.25Al-11Sn-4Mo-0.25Si)	1.40	2.93	3.45	0.60	0.71
IMI Ti Ex 700 (Ti-6Al-5Zr-4Mo-1Cu-0.2Si)	0.95 0.89 0.92		3.1 2.5 2.5		0.68 0.55 0.55
Maraging Steel		3.54		0.46	
FV 520 B Steel		10.0		1.30	
13-Cr Stainless Steel		22.3		2.90	
Annealed Austenitic Stainless Steel		23.6		3.06	
Stellite 6B		1.3		0.16	
Stellite 25		1.5		0.20	

Energy Research & Development Administration funding. Titanium materials, notably Ti-6Al-4V alloy, are included in these studies. While testing is just getting underway, a preliminary result on a carboninitrided Ti-6Al-4V test plate in the fresh water erosion test facility showed that neither the Ti-6Al-4V alloy or boron carbide and zirconium carbide specimens were eroded in a 1600-ft/s (488-m/s) hot-water flow in exposures of up to 9 hours, whereas other metallics (e.g., unalloyed titanium) were eroded in only 3 hours.[5-17]

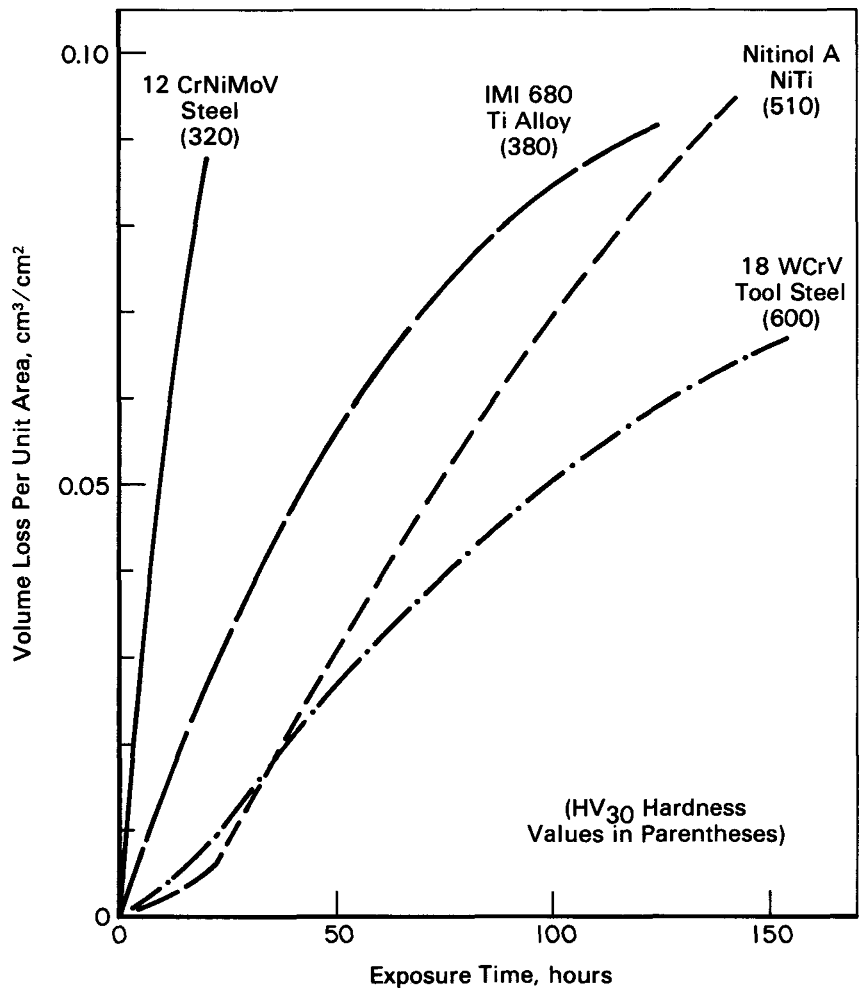


Figure 5-7. Erosion Behavior of Selected Alloys with Increasing Time of Exposure[5-10]

(Details of Erosion Conditions not Given.)

Another indication that the erosion resistance of titanium is good is afforded by the results of various tests conducted in rain (simulated) and dust environments in aerospace oriented programs.[5-18 to 5-20] The data generated in such tests often indicate the superior erosion resistance of titanium; typical rain erosion test data are shown in Figure 5-8 and dust erosion data (as generated in a test compressor) are given in Table 5-3. The extensive effort to find a coating for improving the erosion resistance of various materials to the rain and dust characteristics of the aerospace environment is apparent by the large number of references available on the subject (e.g., [5-21 to 5-23]).

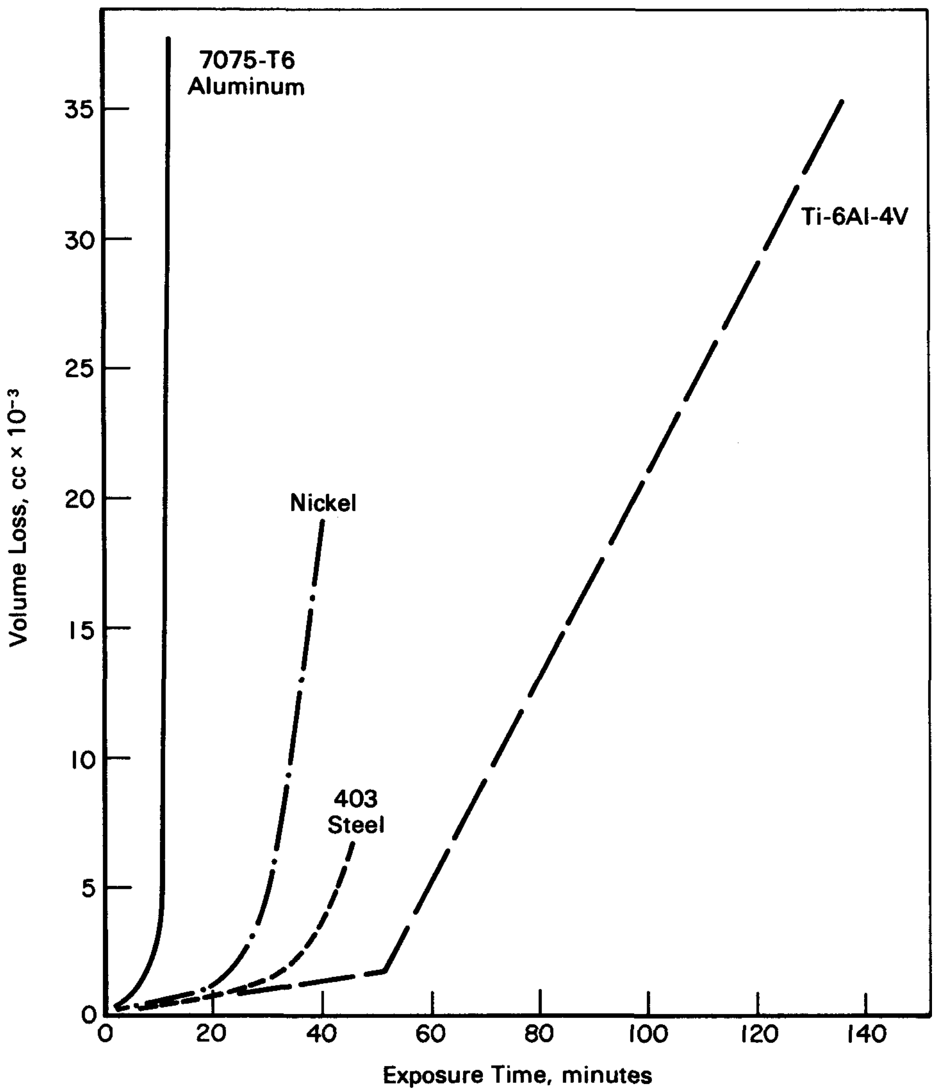


Figure 5-8. Rain Erosion Behavior of Ti-6Al-4V Alloy at 1120 ft/s (341 m/s) Droplet Velocity Compared with Other Ductile Metallics[5-18]

Similarly, there has been a considerable effort over the years to protect steam turbine blades from erosion by applying shields principally, but coatings as well. The following programs aimed at providing erosion protection for blades were identified in survey work.

Early General Electric Company research work on titanium for blades resulted in the conclusion that titanium blades might require Stellite shielding.[5-9] Tests indicated that titanium alloy did erode in wet steam, although not as

Table 5-3

EROSION IN COMPONENTS OF A TEST COMPRESSOR[5-20]
(2400 Grams of 200 μ Quartz Sand for Each Test were Fed into the Compressor Operating at 12,400 RPM. No Other Operating Details or Exposure Times were Given)

Material of Component	Erosion of Compressor Component, mg Loss			
	Inlet Guide Vane	Rotor	Stator	Cumulative Total
2024 Aluminum	2.9 7.9(1)	39.3 32.4(1)	21.2 25.9(1)	130
6Al-4V Titanium	6.1 7.9(1)	26.1 28.0(1)	20.0 20.9(1)	109
310 Stainless Steel	9.8 12.4(1)	40.4 43.8(1)	31.7 32.2(1)	170
410 Stainless Steel	7.1 --(2)	35.2 --(2)	24.0 --(2)	133

(1) Results from a second test (another 2400 g of sand) run on the same once-tested component.

(2) Second test not run. Cumulative total weight loss derived by doubling initial test data.

badly as steel. Hardness was found not to correlate fully with erosion resistance. Attempts at applying Stellite shielding to titanium alloy blades (e.g., by brazing) were considered by GE to be less than satisfactory for commercial application. Details of the assessment were not available.

A technique for the brazing (silver soldering) of shield materials such as Stellite to titanium alloys is reported by the New Metals Division of Imperial Metal Industries.[5-11] A combination of pure silver, overlaid on the titanium, and silver solder, applied first to the shield and then to the joint, is used. A silver layer is deposited on the titanium at about 1830 F by TIG weld technique. Titanium alloys intended for use in the age-hardened condition can be solution heat treated at this point. A layer of silver solder is applied to the shield material at about 1290 F (Stellite is not tempered at this temperature). The coated components are next joined by 1290 F brazing techniques using silver solder for filler if required. Assemblies of this type can be heat treated to age harden the titanium at this point in the procedure if the requirement for hardening the blade exists and if the alloy used is a heat treatable type. Shear strengths of joints produced with the silver, silver-solder method, are on the order of 20 ksi.

Skoda authors also have reported on the application and testing of Stellite shields on titanium blades.[5-24] Two kinds of Stellite, Real 096 (1.3C-2Si-3.5W-5Fe-26Cr-Bal.Co) and ŽAZ 05 Mo (1.3C-2Si-3.5W-5Fe-25Cr-Bal.Co-6Mo), were used as shields for Ti-5Al-2.5Sn alloy blades (designation VT5-1) with joining by silver soldering using three different alloys, with designations B-Ag40CuZnCd, B-Ag45CuZn, and B-Ag50CuZnCd (all are low-melting-temperature silver solders). Brazing was carried out in an argon-filled chamber to minimize oxidation. Jigs were used for clamping shields, brazing foils, and blades together for joining. Evaluation included corrosion tests in boiling distilled water (var, at 212 F) and in steam (para at 390 to 480 F) for long times, and, subsequently, shear-strength tests. The results are shown in Figure 5-9. Additional evaluations of joining technique (e.g., with and without distance-netting for shield-blade joint spacing control) and joining material (the various solders used) by cyclic and static testing were conducted. The highest joint shear stress was obtained without using distance-netting (i.e., use of a small joint gap is beneficial). High values of normal and shear stresses were obtained using Stellite ŽAZ 05 Mo. The higher silver content solders appeared to give the best results. Soviet authors also refer to the use of brazed-on Stellite shields for titanium steam turbine blades, but no details of the joining technique or performance are provided.[5-13]

Skoda authors also briefly describe attempts at improving the erosion resistance of Ti-5Al-2.5Sn alloy by application of hard coatings.[5-8] Hard coatings of (a) 100 percent Cr_3C_2, (b) 60 percent Cr_3C_2 + 40 percent cobalt, and (c) 88 percent WC + 12 percent cobalt were described as being "washed off" blades in 8000 hours of testing, whereas uncoated blades were unaffected. No test details were given. The need for stronger protective coatings was cited.

As previously mentioned, the Kakogawa turbine, manufactured by Mitsubishi and operated by Kobe Steel, uses last-stage Ti-6Al-4V blades protected with an age-hardened overlay of Ti-15Mo-5Zr alloy.[5-9] The Ti-15Mo-5Zr metastable beta

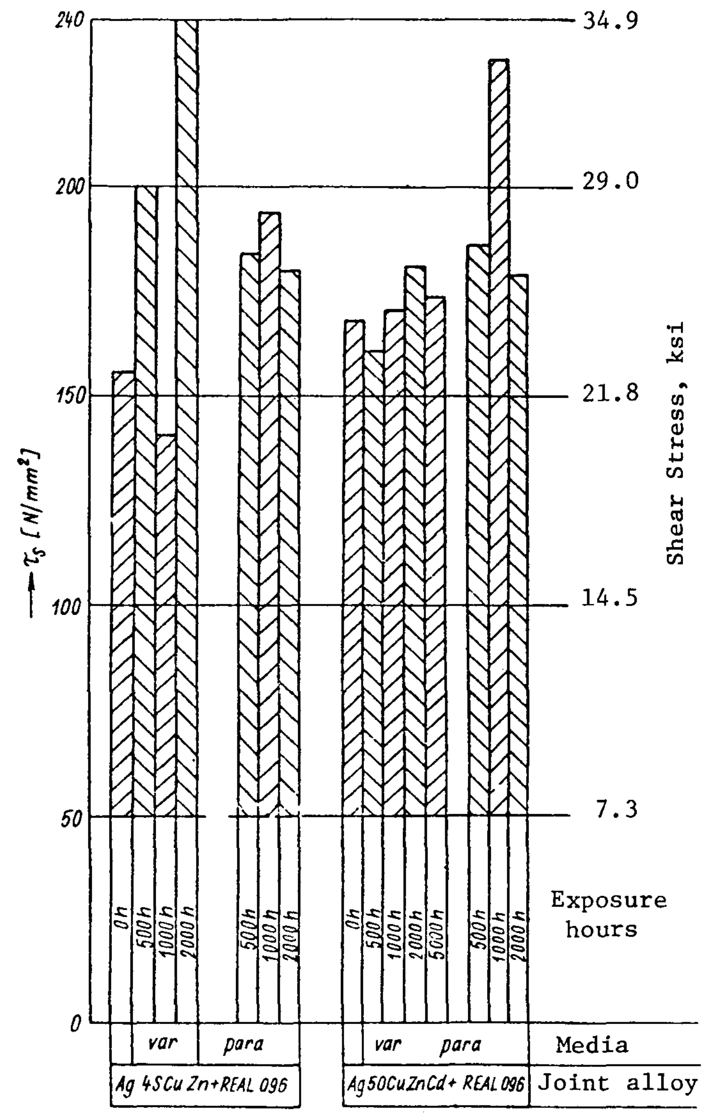


Figure 5-9. Joint Shear Strengths Between Stellite (Real 096) and Ti-5Al-2.5Sn Alloy (VT5-1) Made with the Silver Solder Alloys Indicated. Shear Testing Performed After Corrosion Tests in Water (var) or Steam (para) (para) for Exposure Times Shown[5-24]

alloy layer is deposited by TIG welding technique (the application by diffusion welding or by explosive pressure welding also is cited in the relative patent [5-12]) onto the area of the blade requiring protection. An aging heat treatment of from 5 minutes to 20 hours at 390 to 1110 F, followed by air-cooling, is then given the assembly in order to harden the metastable beta overlay. Figure 5-10 shows the overlay-base metal hardness values achievable with the method. As shown in the figure, a hardened zone of about 0.16-inch (4-mm) depth is formed. Additional information on the heat treatment and properties of the Ti-15Mo-5Zr alloy is presented in Reference 5-25.

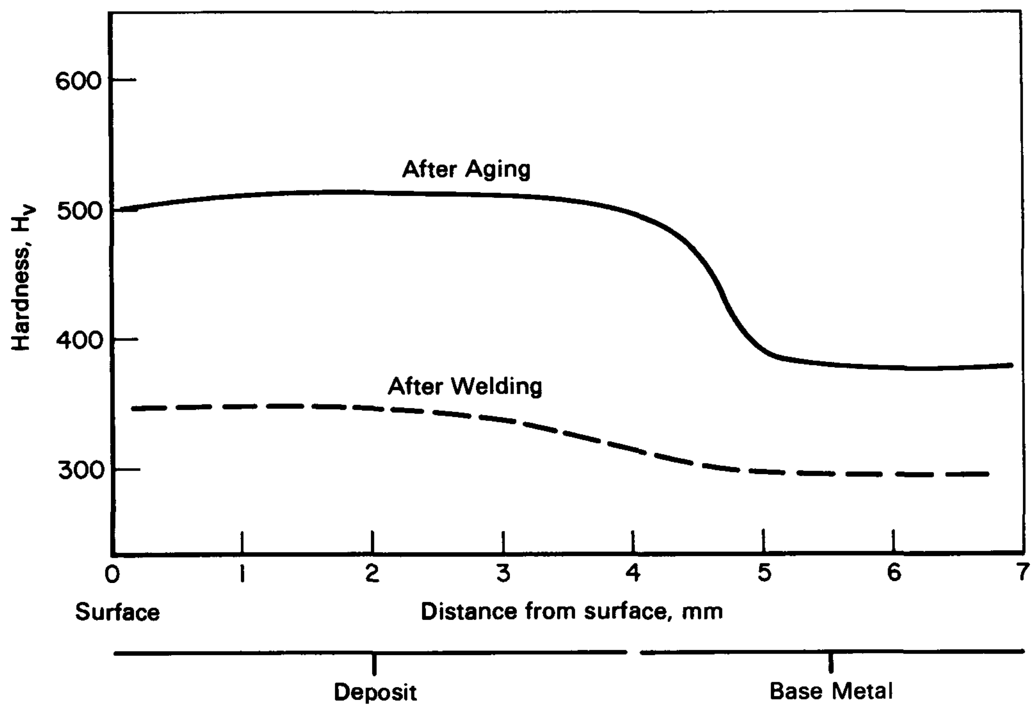


Figure 5-10. Hardnesses of Ti-15Mo-5Zr Overlay Deposit and Base Metal After Welding and After Subsequently Age Hardening[5-12]

5.2 CORROSION PHENOMENA

The estimates made regarding the amount of turbine outages due to blade malfunction range from about 25 percent of all outages (see the Edison Electric Institute data of Table 1) up to about 40 percent.[5-9] Blade failures have been attributed to several mechanisms including corrosion, stress-corrosion, and, in many cases, fatigue mechanisms. Examination of fatigue-failed blades suggests that, in at least 20 percent of the cases, fatigue failure has been accelerated by corrosion processes. The problem is talked about as a corrosion/fatigue problem in general, but very few specific cases of corrosion-fatigue per se have been experienced. Fatigue phenomena augmented by corrosion, for example, corrosion pits as fatigue crack initiation sites, better describes the actual experience.

Corrosion troubles are usually associated with poor water treatment practice.[5-9] For a number of reasons, contaminants such as chlorides, sulfates, carbonates, and commonly hydroxides, become entrained in the steam. The corrosive media is not always identifiable because it may be in a transient form. Contaminants may occur in gaseous, liquid, or solid forms. In some cases, only the reactant residues are available to provide clues to the aggressive species. The steam in turbines, with its additives, can be an aggressive media to some materials even when under control and particularly aggressive when not under control.

Further, the chemistry of the steam in turbines is variable, from one time and place to another time and place, within single machines and from turbine to turbine.[5-9] Localized residuals from the steam also are variable in concentration from one location to another within turbines. One of the examples cited by the General Electric Company was the ability of caustics to condense from steam at high concentrations (30-40 percent not uncommon) over extensive localities within the LP turbine. Thus, the variables of steam chemistry and residuals, as well as material reactions possible in the presence of such media, are of considerable complexity and are not as well known as desired.

The turbine companies believe that there is a strong need to investigate the full range of steam chemistry variables that constitute the turbine environment and to determine precise effects of such environments on component materials.[5-9] In fact, there is a large German program on corrosion fatigue, ongoing for at least 4 years, wherein the German government provides matching funds to those of the industrial contributors (BBC, KWU, MAN, and AEG) for a total of about 1 million marks per year ($400,000). The program is principally concerned with 12-chromium steel behavior with steam chemistry, temperature, and material strength level as chief variables. Standard corrosion fatigue tests have been developed, but crack growth tests have not yet been started. A similar program, and of similar size, is planned for funding by the Electric Power Research Institute. One of the major differences is that the EPRI program will include Ti-6Al-4V alloy as a material for evaluation. The EPRI program is expected to get underway shortly.

The worst corrosion-augmented fatigue problems exist in the largest machines, where blade stresses due to steady and vibrational loadings are highest, and therefore where improper steam chemistry may be highly detrimental to good blade performance.[5-9] The blade failures are found predominantly in the low-pressure sections of turbines, but usually not in the last-row blades. There are two factors leading to the predominance of blade failures in the LP sections of turbines, but in rows of blades in front of the last row. The factors are: (1) steam contaminants tend to precipitate at the point where moisture begins to form and (2) steam velocity changes from subsonic flow to transonic flow. Both phenomena tend to occur in the L-1 or L-2 rows of 3600 RPM fossil-fueled machines.[5-9] Also, it should be noted that steam temperatures are still quite high in the L-1 and L-2 rows (150-200 F), while lower in the last row (85-115 F), suggesting that temperature might be a contributing factor in the higher incidence of corrosion in L-1 and L-2 stages. Figure 5-11 illustrates the extensive damage that can accrue in steel blades in penultimate rows by one form of corrosion encountered, pitting corrosion (contaminant unknown).

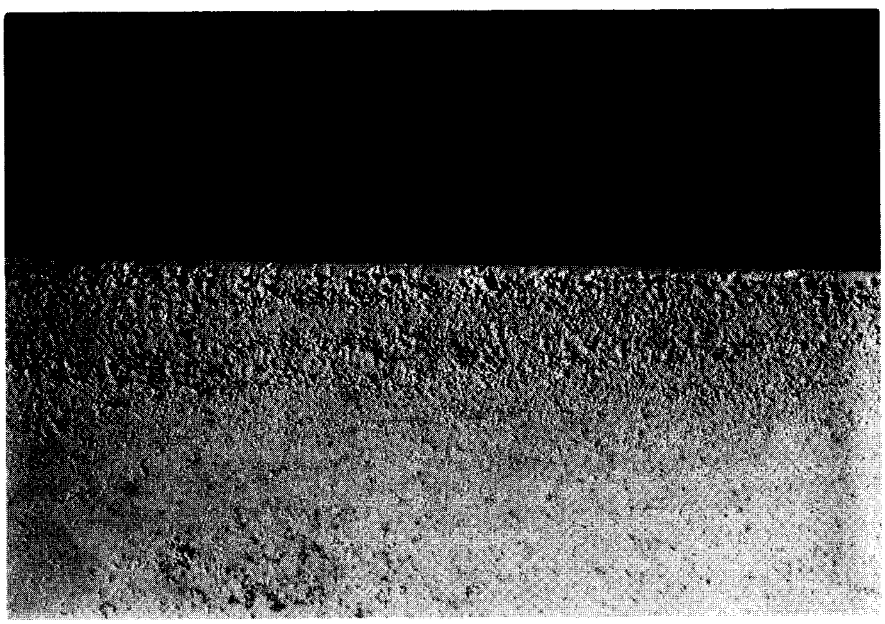


Figure 5-11. Pitting Corrosion Observed in a Steel Blade from a Penultimate Stage, Low-Pressure Section, of a Fossil Fueled Steam Turbine (1X)

Not a single case of a corrosion problem for titanium blades in operating steam turbines was disclosed during the present survey. Admittedly, the experience with titanium blades in service is quite limited compared with steel blades. However, titanium blades have been operated in environments that have been hostile to steel regarding corrosive attack and have remained immune to such attack in some of these same machines.[5-9] The excellent corrosion resistance of titanium to many media (particularly oxidizing and chloride-containing environments) in the temperature range prevailing in low-pressure turbine sections would be expected to produce this result.

While a direct quantitative corrosion assessment of titanium blades operating in steam turbines was not made available through survey efforts, it is possible to indicate the excellent corrosion resistance of titanium by citing the titanium performance record in hostile environments that in some cases might be similar to those prevailing in steam turbines. The following experiences are revealing.

Titanium tubing for steam power plant condensers, in test for over 15 years, and in service for a number of years in several plants, has proven to give excellent performance.[5-26] This application for titanium is particularly suitable for coolant waters having a high chloride content (e.g., brackish cooling water supply). Where chlorides exceed about 250 ppm, the coolant waters can be damaging to stainless steels where mixed in with copper base alloy tubing. In condenser applications, titanium tubes have provided excellent resistance to attack in the area directly under the turbine exhaust where water droplet impingement might combine with corrosion to cause early tube failure. Titanium tubing also has shown an immunity to the most corrosive steam-side area of condensers, in the air removal section where the noncondensable gases (CO_2, NH_3, O_2) concentrate. More than 20 power stations in the United States have condenser units completely tubed with titanium with an additional 15 or so units partially titanium tubed or with test tubes.[5-27] Similarly, the Japanese report 79 titanium tubed installations [5-28] and report specific performance data for the full titanium condenser (tubes and tube sheet) of the 50-MW Kakogawa unit.[5-29]

Titanium heat exchangers to meet several requirements of the petroleum industry also perform well and the use of titanium in this area is growing. Some of the applications, environments, and service records that may be pertinent in showing the excellent corrosion resistance of titanium are summarized in Table 5-4.[5-30]

The immunity of titanium to chloride attack, wet conditions, is a well-known attribute of the metal. The titanium producers, particularly Titanium Metals Corporation of America (TMCA) have been active in developing the chlorine

Table 5-4

EXPERIENCE FOR TITANIUM TUBULAR HEAT EXCHANGERS IN PETROLEUM REFINING APPLICATIONS[5-30]

Processing Unit	Plant Item	Environment: Shell Side	Environment: Tube Side	Service Life, yrs.
Catalytic cracking Turbine compressors	Exhaust steam condensers	Steam 1 atmos. 41 to 235 C (106-455 F)	Salt water 1 atmos. 38 C (100 F)	7.5
Edeleanu Plant	SO_2 drying column reboiler	Steam 1 atmos. 104 C (220 F)	$SO_2 + H_2O$ + oil 1 atmos. 77 C (171 F)	5.0
Hydrorefiner	Trim cooler	Gas oil with H_2 from reactor 1 atmos. 260 C (500 F)	Salt water 1 atmos. 38 C (100 F)	5.5
Crude oil distillation	Overhead condenser	Overhead vapor + desalted crude (pH controlled by NaOH and NH_3) 1 atmos. 116 C (240 F)	Salt water 1 atmos. 27-52 C (81-126 F)	10.0
Crude distillation	Overhead condenser	Overhead vapor + chlorides + water + Process HCl and H_2S 0.3 atmos. 93 C (200 F)	Salt water 4 atmos. 38 C (100 F)	7.5
Crude distillation	Overhead Partial condenser	Overhead vapor + chlorides + water + Process HCl and H_2S 3.5 atmos. 149 C (300 F)	Crude oil 22 atmos. 93 C (200 F)	7.5
Flare gas recovery	LP gas compressor aftercooler	Oil vapors + chlorides + water + Process HCl and H_2S (possibly NH_3) 5 atmos. 180 C (356 F)	Salt water 5 atmos. 71 C (160 F)	8.0

environment, industrial-applications area for titanium. A number of technical data bulletins describing the corrosion resistance and the economics of using titanium in specific conditions and media are available.[5-31 to 5-33] Information on the use of titanium in resisting the corrosive attack of ammonia, as in Solvay ammonia stills, also is available.

In addition to developing a body of corrosion resistance data relating to common industrial uses, tests have been conducted by producers to determine how titanium will perform on a long-term basis in the environments of geothermal power plants.[5-9] It was reported that the geothermal power installation being built in the Imperial Valley (California) by Magma Energy, Inc., San Diego Gas and Electric Company, and C. F. Braun will use titanium components.[5-34] The water/steam mixture from Imperial Valley wells will be pumped at a temperature of about 450 F. The mix is loaded with chlorides (>35 percent) and has a pH of about 5.5. The brine/steam from wells in the Salton Sea geothermal area also is heavily mineralized and, as mentioned previously [5-17], titanium alloys are being intensively tested (preliminary results are encouraging) for applications in equipment to exploit this source of power. The scale-control, erosion, erosion-assisted corrosion, and corrosion tests on a number of materials, including numerous titanium alloys, will provide the basis for field testing a 100-KW brine-tolerant steam turbine in 1977 by LLL.

The reactivity between titanium and hydrogen, while not a corrosion reaction, may lead to the degradation of the metal in cases where the conditions are favorable for its occurrence. The conditions were possibly met in a General Electric Company application of titanium alloy as steel blade covers in the intermediate-pressure section of turbines. Titanium covers were installed on several machines in IP sections which operate at varying temperature and pressure (e.g., inlet, 1000 F, and 500 psi; outlet, 500 F and <200 psi per Figure 1-1). In two of the GE machines, inspection after a period of service revealed that the covers had disintegrated. Recovery of a few pieces of covers and subsequent analyses revealed a high hydrogen content in the titanium alloy. Reaction between the titanium and steam, and possibly augmenting caustic, was speculated.

A postulated mechanism would be the buildup of caustic in such places as the titanium-steel interfaces, general corrosion of the titanium by the hot caustic, and absorption of corrosion-product hydrogen by the titanium to the point where hydride embrittlement resulted in disintegration of covers at prevailing stresses.* Without caustic, one would expect that the titanium covers would not hydride and fail, since the usual temperature for steam dissociation in the titanium/steam reaction is 800-900 F. The other GE machines, wherein titanium covers are apparently giving satisfactory performance, may have some kind of water treatment practice or other conditions not leading to the concentration of caustic.

In the general case for the possible hydrogen contamination of titanium components in a steam environment, it is believed that the service temperatures prevailing in the locations considered for titanium blading are far too low for a favorable hydriding reaction to occur in the absence of a reactant such as caustic. Since turbine service temperatures are much below the temperature required for the thermal decomposition of water (steam), only a titanium-metal-surface/water reaction (reduction or dissociation of water to hydrogen and oxygen) would be expected as the mechanism to provide contaminating hydrogen to the titanium. However, research has indicated that hydrogen contamination of titanium in moist, but otherwise inert, atmospheres was negligible at temperatures below about 1095 F.[5-35] Further, the research indicated that in moist oxidizing atmospheres, the temperature for reaction would be raised. The results suggest that titanium is considerably resistant to hydrogen absorption (even under conditions found in a nuclear steam condenser where appreciable quantities of hydrogen are found in the steam) when moisture or a source of oxygen is present in the system.[5-36] Thus, no problems with the hydriding of low-pressure section titanium blades, particularly in wet rows, would be expected. A research report describing the effect of hydrogen on the properties of Ti-6Al-4V alloy, and suggesting the alloy tolerance for hydrogen levels which do not lead to problems, was prepared by RMI Company authors.[5-37] It was concluded that, for Ti-6Al-4V alloy with acicular microstructures or those with equiaxed alpha-beta microstructures wherein the alpha grain size is smaller than ASTM 8, a hydrogen content of 200 ppm max. appears to be a satisfactory upper limit in the avoidance of problems.

*A parallel situation is used in some laboratories for purposefully hydriding zirconium-base alloy samples. Samples are exposed to 10 percent lithium hydroxide at 650 F, undergo general surface corrosion, and product hydrogen uniformly enters the zirconium samples.

5.3 FATIGUE BEHAVIOR

The most important design criterion for steam turbine blades is high-cycle fatigue crack initiation. The moving blades are subjected to a complexity of cyclic stress patterns generated by aerodynamic and mechanical forces. The large blades in the last rows of low-pressure sections, particularly last-row blading in large turbines, have the highest tip speeds and the most severe vibrational problems. The steady stresses imposed by centrifugal forces and steam bending loads are coupled and additive to the unsteady stresses imposed by the host of vibrational forces operative on the working blades of turbines. While blade designs are optimized to minimize vibrations at resonance frequencies up to third, fourth, fifth, and higher modes of vibration, all possible excitations are not accounted for, and blades must be sufficiently rugged to perform reliably in both known and unknown regimes. Materials which have high fatigue strength must be selected for blade design.

Titanium alloys have become widely accepted in the aerospace industry as materials which possess excellent fatigue characteristics. Numerous airframe and gas turbine engine components of titanium are known for their good service record under cyclic loading. On a more limited basis, titanium alloys also have become known as a steam turbine blading material. Survey work did not reveal instances where titanium blades performed unsatisfactorily with reference to a poor fatigue behavior.* The data available from various testing programs and application experiences are reported in this section to describe the general fatigue behavior of titanium alloys which have been considered for use as steam turbine blading.

The fatigue behavior of titanium alloys is quite dependent on composition, primary and secondary fabrication practices, heat treatment -- in short, the metallurgical condition -- and such other conditions as surface characteristics and the variables of cyclic stress loading. Generally, the high cycle fatigue strength of a titanium alloy might be initially estimated as 50 percent of the ultimate tensile strength. However, as many of the experimental results show, fatigue strengths both higher and lower than 50 percent of the ultimate tensile strengths are possible. An example of the variability observed is shown by the fatigue data of Figure 5-12 for Ti-5Al-2.5Sn alloy in various surface treatment conditions.[5-38] Because the metallurgical and physical conditions of a

*Fatigue-type cracking originating in the joint between the blade and erosion shield was reported.

material is of great importance to the observed fatigue behavior (as well as to other important properties), a background discussion on the metallurgy and microstructure that can be encountered with titanium is provided in Appendix A of this report. Microstructures which afford a fatigue advantage for titanium are described. The appendix provides additional reading on the general metallurgy and the mechanical behavior of titanium for those unfamiliar with the material.

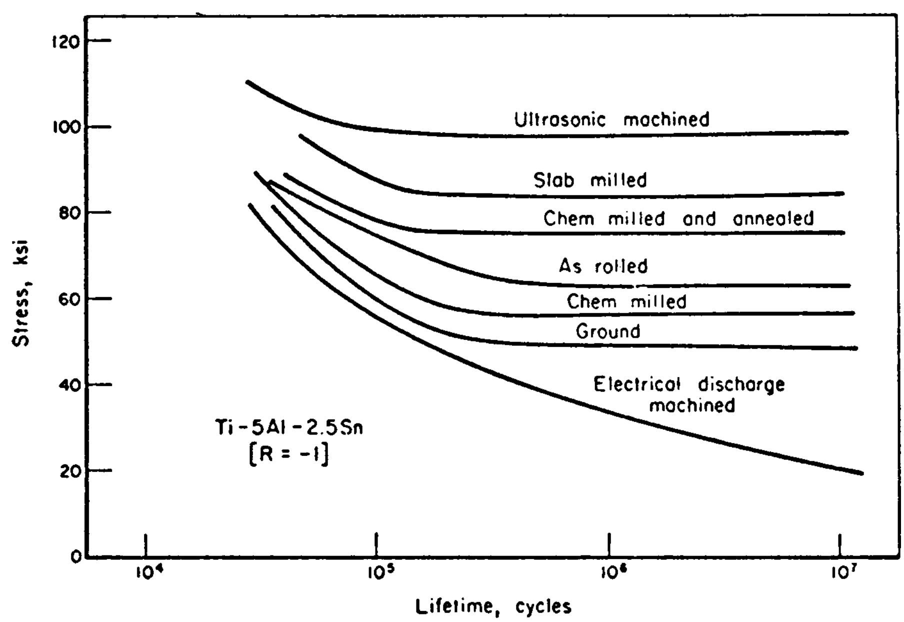


Figure 5-12. The Effect of Various Surface Finishing Processes on the Reversed Bending Fatigue Strength of Ti-5Al-2.5Sn Alloy (0.125-inch sheet thickness; Annealed UTS = 138 ksi, YS = 132 ksi, El = 18 Percent) [5-38]

The Ti-6Al-4V alloy in the annealed, equiaxed alpha-beta microstructural condition has been the "workhorse" titanium material for all applications (see Figure 2-6). The largest use of this material has been in aircraft gas turbine engines, particularly for discs and blades. Not unexpectedly, therefore, several steam turbine manufacturers have examined Ti-6Al-4V alloy for their blading applications and have found it satisfactory in terms of mechanical properties, including fatigue properties. Typical Ti-6Al-4V annealed bar fatigue behavior is presented in the Goodman diagram of Figure 5-13.[5-39] While many variations in fatigue behavior from the above characterization have appeared in the literature, the "typical" behavior of Figure 5-13 could be reasonably

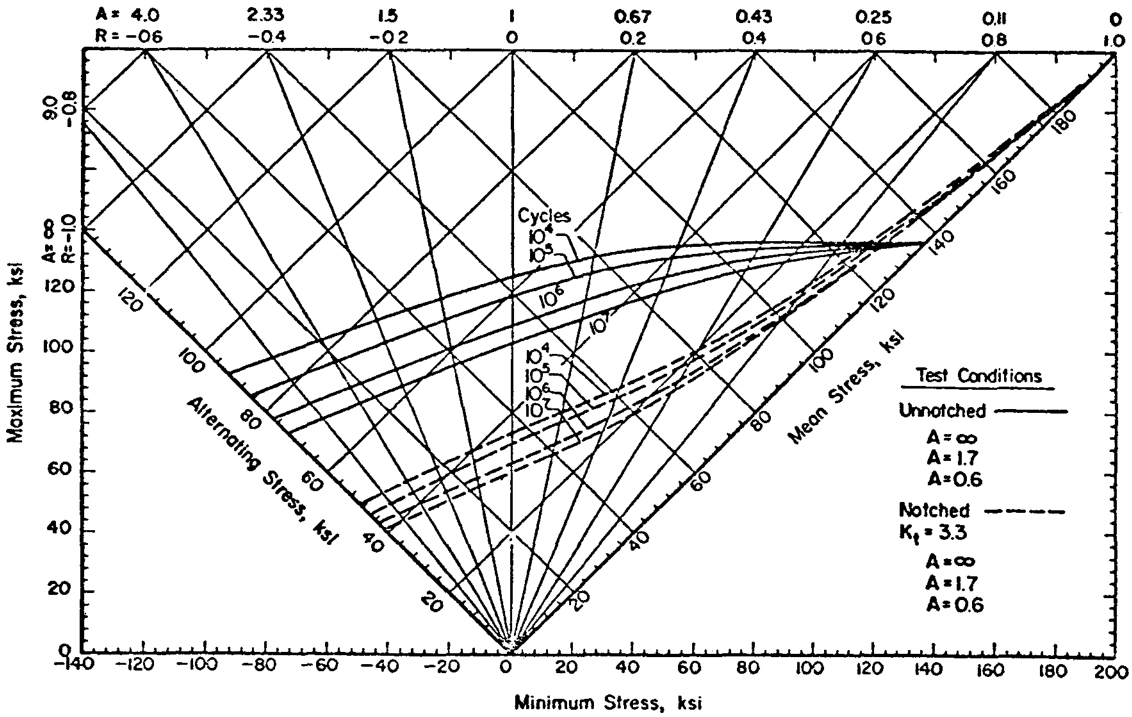


Figure 5-13. Typical Constant-Life Fatigue Diagram for Annealed Ti-6Al-4V Alloy (Bar) at Room Temperature[5-39]

Correlative Information for Figure 5-13

Product Form: Rolled Bar, 1¼-inches diameter

Properties:

TUS, ksi	TYS, ksi	Temp, F
136.5	128.5	RT (Unnotched)
189.0	—	RT (Notched)

Specimen Details:

Unnotched: 0.203-inch diameter

Notched, V-Groove, $K_t = 3.3$:
- 0.331-inch gross diameter
- 0.252-inch net diameter
- 0.010-inch root radius, r
- 60° flank angle, ω

$K_N = 1.74, \rho = 0.044$ inch, where $K_N = 1 + \dfrac{K_t - 1}{1 + \dfrac{\pi}{\pi - \omega}\sqrt{\dfrac{\rho}{r}}}$

Test Parameters:
- Loading - Axial
- Frequency - 1750 cpm
- Temperature - RT
- Atmosphere - Air

Surface Condition: Unnotched: Polished longitudinally with 240, 400 and 600 emery belts.
Notched: Machined V-groove followed by polishing notch root with 600-grit slurry and rotating copper wire.

expected in steam turbine blades made of commonly available grades of Ti-6Al-4V alloy, by fabricators and heat treaters familiar with titanium processing. The data indicate some notch sensitivity for the Ti-6Al-4V alloy, but the experience record has revealed a good tolerance for mechanical stress raisers by this material. Figure 5-14 shows that elevated service temperatures do not seriously degrade the fatigue strength of Ti-6Al-4V alloy, while Figure 5-15 indicates the effect of microstructure on the notched fatigue strength of this material.[5-40,5-41] The potential benefits of microstructural control and a metallurgical discussion on the fatigue behavior of Ti-6Al-4V alloy are given in detail in Appendix A, as previously mentioned.

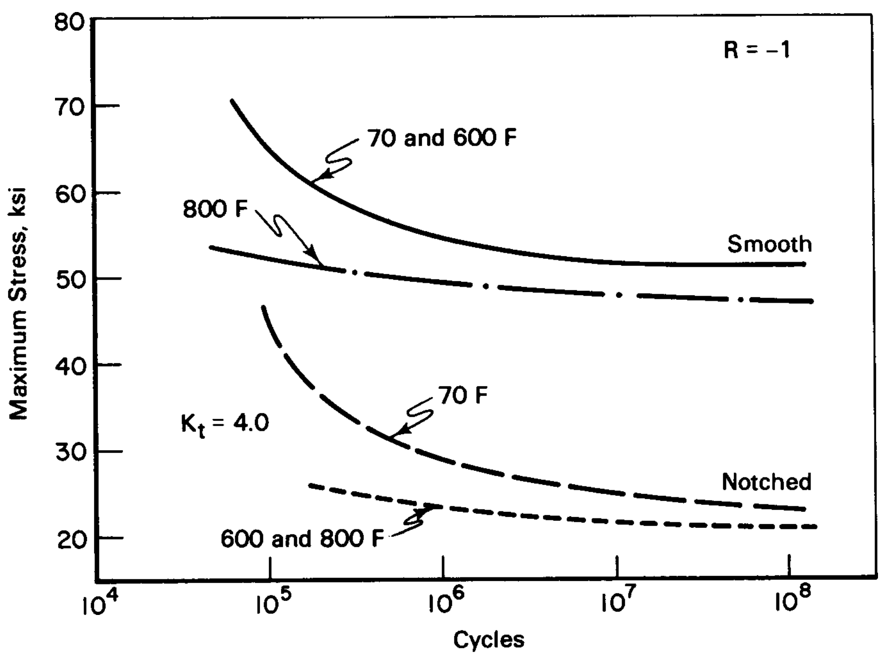


Figure 5-14. Effect of Test Temperature on the Smooth and Notched Fatigue Behavior of Annealed Ti-6Al-4V Forging in Reversed Bending Evaluations (Tensile Yield Strength, 122 ksi)[5-40]

The effects of service temperature, microstructure, and notches on the fatigue behavior of the Ti-5Al-2.5Sn alpha alloy are similar to those described for the Ti-6Al-4V material. Figure 5-16 is a composite drawing illustrating the effect of selected test variables.[5-42]

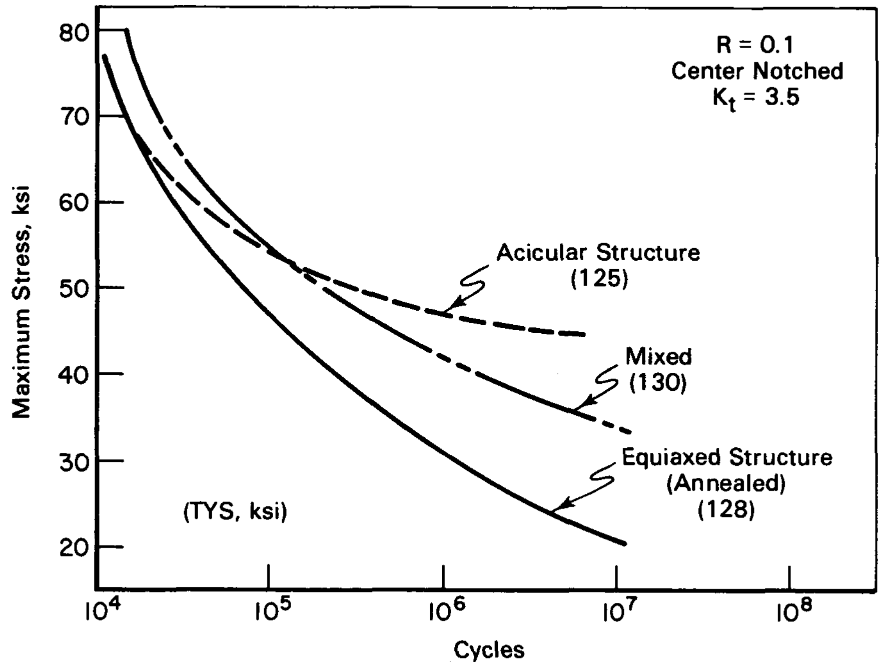


Figure 5-15. Effect of Microstructure on the Room Temperature Notched Fatigue Behavior of Ti-6Al-4V Alloy Plate[5-41]

Various manufacturing processes can have a profound effect on the fatigue properties of titanium alloys or on the structures made from these materials. An example of the latter revealed in the literature shows that the fatigue strength of brazed joints between Stellite erosion shields and Ti-5Al-2.5Sn blades is below that expected for base metal Ti-5Al-2.5Sn (Figure 5-17).[5-24] The reference stated that fatigue fractures originating in the joint propagated into the titanium base metal and sample failure occurred.

The use of titanium alloys for steam turbine blading may be at an advanced stage in the Soviet Union. Russian authors have described evaluations of several titanium alloys for this application although the references do not include the Ti-5Al-2.5Sn or Ti-6Al-4V alloys, both of which are manufactured within Russia. The alloys described include

- VT5, Ti-5Al
- TS5, Ti-(3 to 5)Al-(2 to 3)Sn-(1.4 to 2)Zr-(1.4 to 2)V
- VT3-1, Ti-5.5Al-2Mo-2Cr-1Fe-0.2Si
- VT8, Ti-6.5Al-3.5Mo-0.25Si.

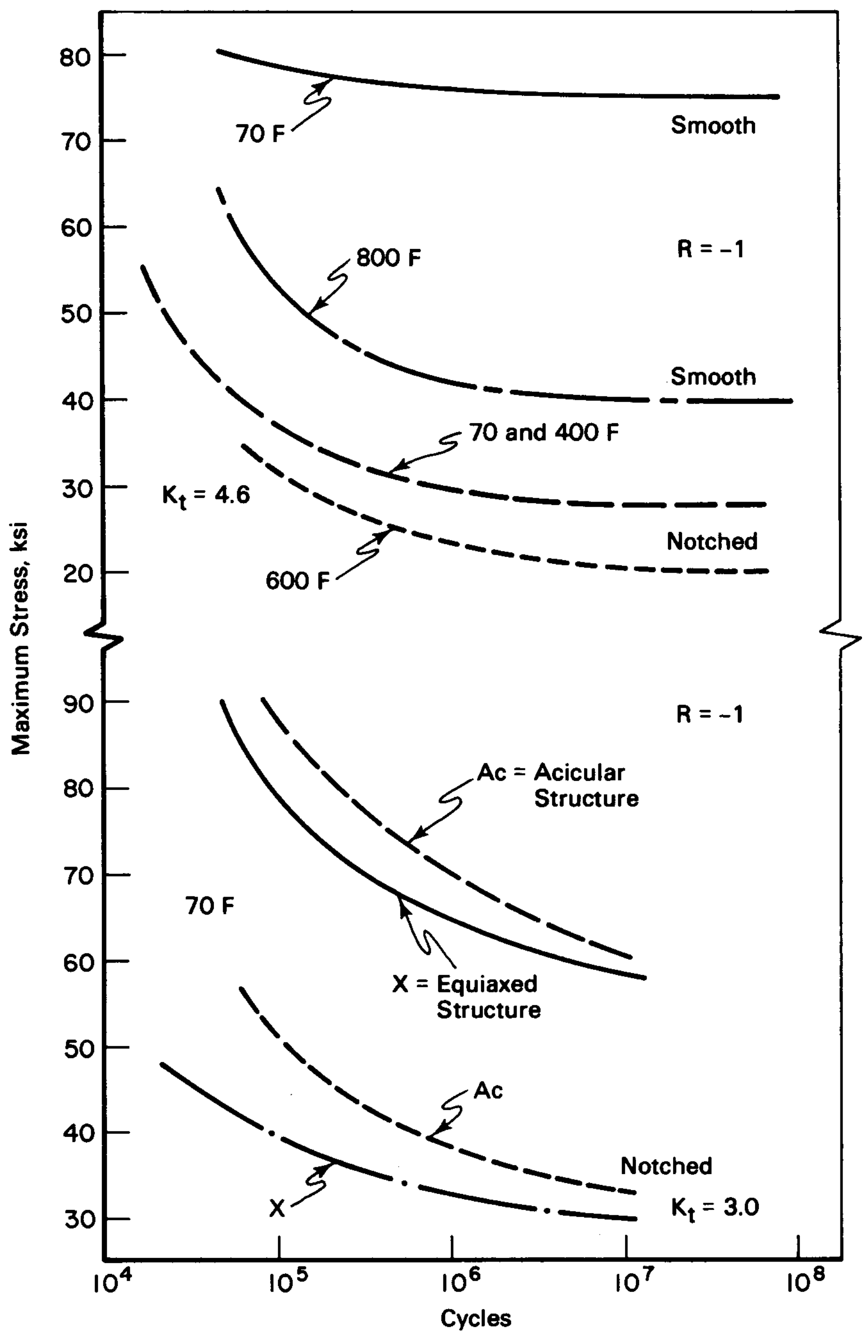


Figure 5-16. Effect of Test Temperature and Microstructure on the Smooth and Notched Fatigue Behavior of Ti-5Al-2.5Sn Alloy Bar Material (Tensile Ultimate, 130 ksi)[5-42]

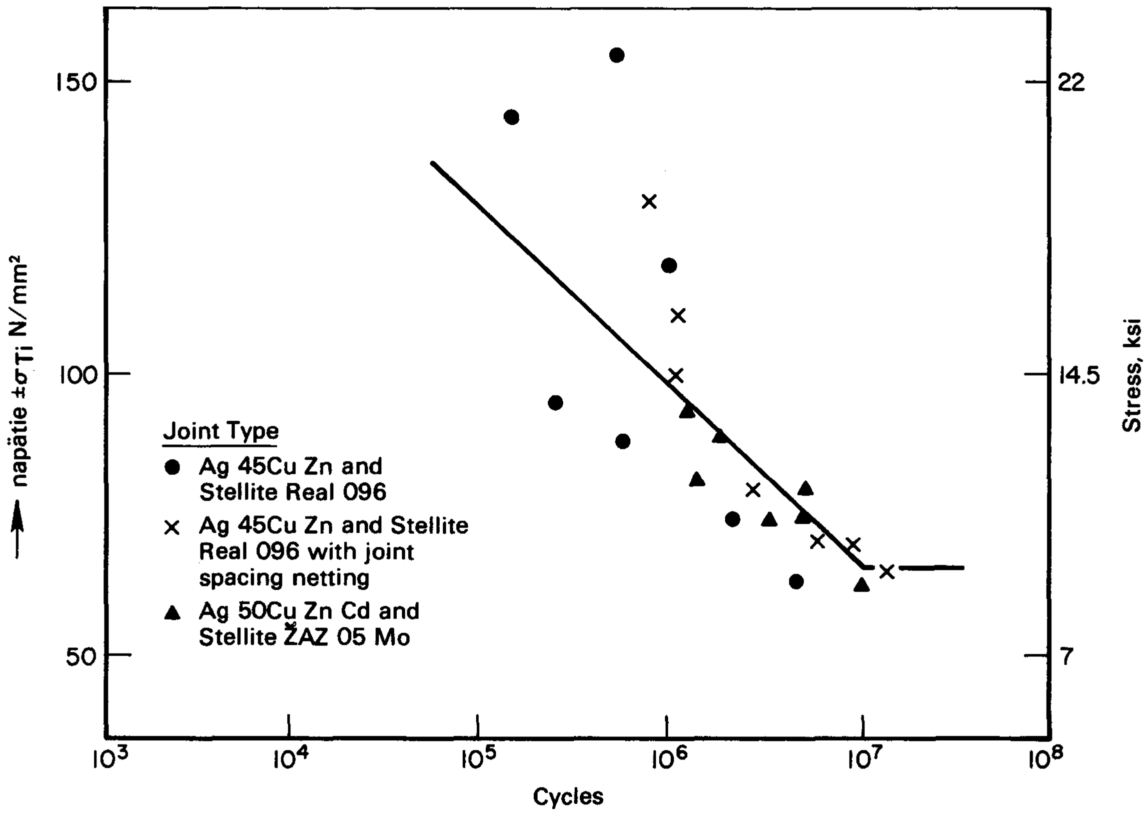


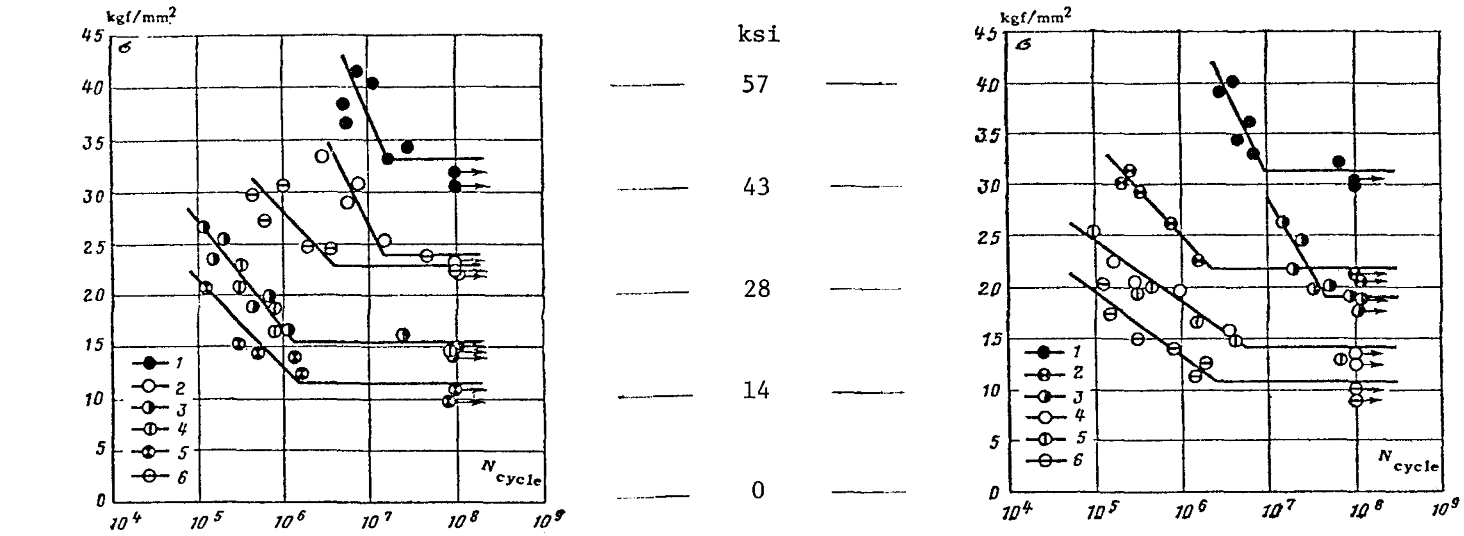
Figure 5-17. Fatigue Life of Stellite/Ti-5Al-2.5Sn Joints Prepared by Brazing[5-24]

The VT5 alloy is perhaps more closely allied to the Ti-5Al-2.5Sn alloy than the TS5 alloy. The TS5 alloy appears to be a Ti-5Al-2.5Sn base with small additions of zirconium and vanadium to make it behave somewhat like the Ti-6Al-4V alloy. Fatigue evaluations have indicated a small advantage for the TS5 alloy over VT5 as shown in Figure 5-18 and as amplified by the text of Reference 5-43.

The room temperature fatigue strength of both alloys (symmetric cycle) is better than the requirement for the blade material of the last stage of the low-pressure section of the K-300-240 turbine. The room temperature values for smooth samples from bars are

- VT5, 40.8 Kg /mm^2 = 58 ksi
- TS5, 43.8 Kg /mm^2 = 62 ksi.

And asymmetrically under static loading of 30Kg /mm^2 (43 ksi):



Fatigue strength of TS5 blade material with symmetric and asymmetric cycles at t_{test} = 20, 100 and 350°C and under conditions of stress concentrations

$1 - \left(\sigma_{-1}^{2A}\right)_{t=20\,°C}$; $2 - \left(\sigma_{a}^{2A}\right)_{t=20\,°C}^{\sigma_{st}=30\,kgf/mm^2}$; $3 - \left(\sigma_{a}^{n}\right)_{t=20\,°C}^{\sigma_{st}=30\,kgf/mm^2}$;
$4 - \left(\sigma_{a}^{n}\right)_{t=100\,°C}^{\sigma_{st}=30\,kgf/mm^2}$; $5 - \left(\sigma_{a}^{n}\right)_{t=350\,°C}^{\sigma_{st}=30\,kgf/mm^2}$; $6 - \left(\sigma_{-1}^{20\,°C}\right)_{n}$

Fatigue strength of VT5 blade material with symmetric and asymmetric cycles at t_{test} = 10, 100 and 350°C and under conditions of stress concentrations

$1 - \left(\sigma_{-1}^{20\,°C}\right)_{s}$; $2 - \left(\sigma_{-1}^{20\,°C}\right)_{n}$; $3 - \left(\sigma_{a}^{20\,°C}\right)_{s}^{\sigma_{st}=30\,kgf/mm^2}$;
$4 - \left(\sigma_{a}^{100\,°C}\right)_{n}^{\sigma_{st}=30\,kgf/mm^2}$; $5 - \left(\sigma_{a}^{20\,°C}\right)_{n}^{\sigma_{st}=30\,kgf/mm^2}$;
$6 - \left(\sigma_{a}^{350\,°C}\right)_{n}^{\sigma_{st}=30\,kgf/mm^2}$.

Figure 5-18. Comparison of the Fatigue Behavior of the VT5 and TS5 Soviet Titanium Alloys[5-43]

- VT5, 26.5 Kg /mm^2 = 38 ksi
- TS5, 25.3 Kg /mm^2 = 36 ksi.

The room temperature values for notched samples ($K_t \simeq 1.8$) are

- VT5, 14.5 Kg /mm^2 = 21 ksi
- TS5, 16.0 Kg /mm^2 = 23 ksi.

At elevated temperatures, as indicated in Figure 5-18, there is no appreciable reduction in fatigue strength up to 212 F (100 C), but 20 to 25 percent reduction at 660 F (350 C). Somewhat disturbingly, it was reported that fatigue samples prepared from forged blades (as opposed to those from bar stock) had fatigue strengths of up to 24 percent lower than the strengths measured for the bar material as shown below.

- VT5, 58 ksi for bar, 44 ksi for blade samples
- TS5, 62 ksi for bar, 47 ksi for blade samples

This result probably reflects the importance of controlling the microstructure of forgings that the Soviets have referred to in other accounts of making turbine blades of titanium.[5-13]

The TS5 alloy also is described in comparison with the VT3-1 alloy [5-44] and the VT5 alloy is further described in References 5-13 and 5-45, the latter in comparison with the VT8 alloy (physical properties only). The VT3-1 alloy has better fatigue strength than the TS5 material, as indicated by the data of Table 5-5 and summarized below.[5-14] Room temperature, 10^8 cycle fatigue strength for smooth samples is shown.

- VT3-1, 50-54 Kg/mm^2 = 71-77 ksi
- TS5, 42-46 Kg/mm^2 = 60-66 ksi

The tensile yield strengths of the billet materials yielding these fatigue results were 138 to 152 ksi and 129 to 130 ksi for the VT3-1 and TS5, respectively. Notched samples ($K_t \simeq 1.8$) of the two materials have approximately equivalent cyclic strength as follows.

- VT3-1, 14 Kg/mm^2 = 20 ksi
- TS5, 13 Kg/mm^2 = 18.5 ksi

However, these data compared with smooth specimen data indicate the greater notch sensitivity of the higher strength VT3-1 alloy as might be expected (N/UN ratio = 0.27 for VT3-1 and 0.30 for TS5).

Table 5-5

ROOM TEMPERATURE (20 C) FATIGUE STRENGTH OF VT3-1 AND TS5 AT 10^8 CYCLES[5-14]

Billet	Specimen	σ_{st} (1) Kg/mm²	VT3-1 σ_{-1} (2) Kg/mm²	VT3-1 σ_a (3) Kg/mm²	VT3-1 ψ (4)	VT3-1 $K_{\varepsilon\phi}$ (5)	TS5 σ_{-1} (2) Kg/mm²	TS5 σ_a (3) Kg/mm²	TS5 ψ (4)	TS5 $K_{\varepsilon\phi}$ (5)
Blades of first batch	Smooth	0	50	--	--	--	42	--	--	--
		45	--	15	0.78	--		10	0.71	--
	Notched(6)	0	31.5	--	--	1.45	--	--	--	--
		45	--	7	0.61	2.15	--	7	--	1.43
Blades of second batch	Smooth	0	54	--	--	--	46	--	--	--
		45	--	24.5	0.66	--	--	21	0.55	--
	Notched(6)	45	--	14	--	1.75	--	13	--	1.61

(1) Static tensile stress (tensile stress in the root section of the fin of the blades) applied asymmetrically (Kg/mm² x 1.42 = ksi).

(2) Strength under symmetrical cycle.

(3) Strength under asymmetrical cycle.

(4) $\psi = \frac{\sigma\text{-}1 - \sigma_a}{\sigma_{st}}$, d = (b-c)/a.

(5) $K_{\varepsilon\phi}$ = σ-1 (smoothly)/σ-1 (notched).

(6) Circular notch 1 mm in depth and 0.5 mm in radius ($K_t \simeq 1.8$).

The degradation in the high cycle fatigue strength of the VT3-1 alloy due to prior low cycle fatigue exposure also was measured and results were compared with those obtained for a 15Cr11MoV steel undergoing the same exposures.[5-46] The prior low cycle fatigue exposure was to simulate turbine startup and shutdown stresses estimated to be operative from 500 to 1000 times over the lifetime of a Soviet turbine. Oversize specimens for the low-cycle exposure were cyclic stressed to 0.7 tensile yield strength levels, that is, to

- VT3-1, 68 Kg/mm^2 = 97 ksi (∿138 ksi TYS)
- 15Cr11MoVSt, 50 Kg/mm^2 = 71 ksi (∿101 ksi TYS).

High cycle fatigue test samples were cut from the low cycle fatigue exposed steel samples after either 500 or 1000 cycles while the VT3-1 samples were taken only from material which had been cycled 1000 times. The low cycle fatigue exposed materials were tested in the smooth and notched (K_t = 1.6 in bending or 2.0 in tension, i.e., ≈ 1.8) conditions. The high cycle fatigue data developed are depicted in Figure 5-19 and are summarized below.

- No prior low cycle fatigue exposure

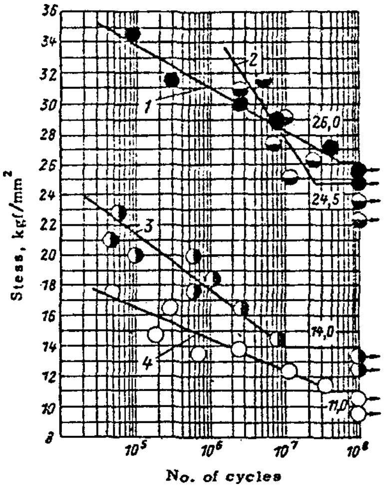
	Smooth Kg/mm^2 (ksi)	Notched Kg/mm^2 (ksi)
VT3-1	24.5 (35)	14.0 (20)
15Cr-11MoV	--	20.5 (29)

- Prior low cycle fatigue exposure

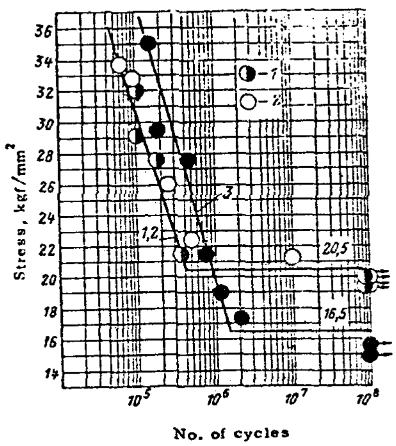
	Smooth	Notched	
	1000 Cycles Kg/mm^2 (ksi)	500 Cycles Kg/mm^2 (ksi)	1000 Cycles Kg/mm^2 (ksi)
VT3-1	26.0 (37)	--	11.0 (16)
15Cr-11MoV	--	20.5 (29)	16.5 (24)

The increase in notch sensitivity of the VT3-1 alloy resulting from low cycle fatigue exposure was noted as unfavorable by the Soviet investigators who suggested that the approximately 20 percent degradation (for VT3-1) should be taken into account at the blade and turbine design stage. They also noted that the VT3-1 was affected to about the same degree as the 15Cr-11MoV steel by the 1000-cycle simulated startup-shutdown exposure.

The alloy developed by the New Metals Division of Imperial Metal Industries, Ltd., Great Britain, IMI-680 (Ti-2.25Al-11Sn-4Mo-0.2Si), like the VT3-1 alloy, also is a high-strength material compared with Ti-6Al-4V or Ti-5Al alloy; about 190 ksi UTS for IMI-680 versus about 147 ksi UTS for Ti-6-4.[5-10] Last-row blade forgings of IMI-680 (for a 300-MW turbine) in the heat treated condition,



Experimental curves of fatigue resistance of smooth (*1, 2*) and notched (*3, 4*) specimens of VTZ-1 alloy under initial conditions (*2, 3*) and after low-cycle ageing on the basis of 1000 cycles (*1, 4*).



Experimental curves of fatigue resistance of 15Cr11MoV steel notched specimens under initial conditions (*1*) and after low-cycle ageing on the basis of 500 (*2*) and 1000 cycles (*3*).

Figure 5-19. Comparison of the High Cycle Fatigue Behavior of Soviet Titanium Alloy VT3-1 and 15Cr-11MoV Steel with and Without Prior Low Cycle Fatigue Exposure[5-46]

were sacrificed for fatigue evaluation, with the results shown in Table 5-6. The high fatigue strength of this high strength material is apparent as is the uniformity of properties from various positions within forgings. Also, there is little degradation in strength due to increasing test temperatures. However, notch sensitivity is indicated, as is usually the case for high strength

Table 5-6

FATIGUE BEHAVIOR OF THE IMI-680 TITANIUM ALLOY IN SOLUTION TREATED PLUS AGED CONDITIONS[5-10]

Test Direction[1]	Test Temperature, F (C)	Rotating Bend Fatigue Strength at 5 x 10^7 Cycles, ksi: Blade Tip Sm[2]	Blade Tip N[2]	Center Sm[2]	Center N[2]	Blade Base Sm[2]	Blade Base N[2]	Root Sm[2]	Root N[2]
SHT[3] 1605 F (875 C), FC to 1290 F (700 C), Age 24h 930 F (500 C), AC [∿195 ksi UTS]									
L	RT (20)	--	--	126	27	110	--	--	--
	212 (100	--	--	--	--	101	--	--	--
	212 (100)[4]	--	--	--	--	110	--	--	--
T	RT (20)	95	--	--	30	--	--	101	--
	212 (100)	101	--	--	25	--	--	--	--
	480 (250)	92	--	--	24	--	--	--	--
	750 (400)	78	--	--	--	--	--	--	--
SHT[3] 1515 F (825 C), AC, Age 24h 930 F (500 C), AC [190 ksi UTS]									
L	RT (20)	106	39	--	--	101	39	--	--
T	RT (20)	--	40	--	--	--	37	--	36
ST	RT (20)	--	--	--	--	--	--	106	44

(1) L = longitudinal, T = transverse, ST = short transverse directions relative to grain flow.

(2) Sm = smooth samples, N = notches samples where $K_t = 2.5$.

(3) SHT = solution heat treatment; FC = furnace cooled; AC = air cooled

(4) Sample tested in steam; all others in air.

materials, for a fairly mild stress concentrating condition (i.e., $K_t = 2.5$). Nevertheless, this material in the fully hardened condition has reportedly performed well as blading in operating steam turbines.

The current survey did not reveal much regarding the fretting fatigue behavior of titanium blading in the root areas. None of the steam turbine manufacturers contacted expressed concern over the potential problem and none cited problems. The Imperial Metal Industries brochure refers to the potential fretting problem as follows.[5-10]

> "Blade root fixings of the fir-tree and pin type have all performed satisfactorily in aeroengine and steam turbine practice without anticipated problems with fretting. On pin fixings, contact stresses up to 45 h bars (∿67 ksi) with significant contact area movement have been employed without recourse to surface hardening and with no fretting effects. Tungsten carbide detonation gun applied spray coatings have, however, been applied in the low stressed areas of compressor blade abutments to prevent fretting in gas turbine practice."

The two aircraft gas turbine engine companies contacted, General Electric at Evendale, Ohio, and Pratt & Whitney Aircraft at East Hartford, Connecticut, stated that they have not experienced fretting fatigue problems in the fan blades of their large engines (the CF6 and JT9D, respectively).[5-9] The fan blades of both engines have two areas for fretting: contact faces of the mid-span shroud and the root attachment hook contact faces. The problem of fretting fatigue is avoided by the use of such treatments as shot peening plus dry film lubricant and tungsten carbide flame sprayed coatings for contact areas. With these precautions, fretting fatigue has not been a factor in the operating experience of these large Ti-6Al-4V fan blades.

5.4 DAMPING PHENOMENA

The property of a material which causes resonant vibrations to diminish with time and which limits the resonant amplitude of absorbed vibrational energy is termed internal friction or damping capacity. A high-damping capacity for structural materials of a steam turbine is desirable since this characteristic is useful in dissipating some of the vibrational energy of the system. A high damping capacity characteristic for turbine blade materials is particularly desirable.

The moving blades of steam turbines are prone to vibrate under the excitations induced by steam loading and rotational forces. In the long blades of the last stages of low-pressure turbine sections, vibration problems can be acute, and, in fact, have led to many fatigue failures (see Table 1-1). While it is usually possible to counter the vibration problem by blade and blade-support design, the complexity of the total possible modes of blade vibration is such as to make important the selection of a high damping capacity material for blades. Unfortunately, the high damping capacity property is not ordinarily found in combination with other properties desired for blades. Designers must select a compromise material and endeavor to produce blades and blade-support systems which are tuned to infrequently encountered excitation frequencies.

The damping design problem is becoming increasingly severe as new machines evolve which have higher steam flows, longer blades, and more intricate blade shapes for the promotion of better efficiencies. Some relief for the problem used by several turbine manufacturers is provided by the practice of tying groups of blades together (e.g., four or more). Blade groups may still vibrate but at lower resonant amplitude, thus minimizing the operating stresses to which individual blades are exposed. Blade groups can vibrate to and fro (axial direction), side to side (rotational direction), and in a twisting mode. Intermediate modes and superposition of modes are possible and are experienced in turbine blades. Individual blades can be designed as either untuned (e.g., massively built) or tuned (i.e., designed to not be in resonance in the first three or four modes) to fit particular situations. Some very high harmonics are sometimes encountered, but fortunately, the higher the harmonic, the lower the excitation.

While blade dimensions are selected (in addition to other requirements) so that at turbine design speed no resonance occurs between the lowest natural blade frequencies and shaft speed multiples, designers don't really know how to precisely calculate for blade damping (e.g., vibration amplitudes), and rely to a large extent on prior experience for some aspects of successful blade design. The experience factor is quite important in selecting the combination of material and mechanical (or system) damping required for a given system. Thus, designers tend to continue the use of a blade material (e.g., 12-chromium steel) and mechanical damping methods (shrouds, ties, and root fixings) which have given acceptable performance in prior machines. Steam flows, which ordinarily provide a positive aerodynamic (viscous) damping, may be as important to the total system damping as material damping and mechanical damping, but effects are not well understood. Nevertheless, aerodynamic damping is additive to material damping and mechanical damping and all three categories are considered in the designing of turbine blades.

One of the concerns with the use of titanium alloy for blading is its relatively low damping capacity. Damping capacity values reported for titanium range from 0.00015 to 0.014 (logarithmic decrement of decay, δ) with a more commonly observed range of 0.001 to 0.005 (δ). Type 403 steel, on the other hand, has a commonly observed damping capacity range of 0.01 to 0.05 (δ). These differences in material characteristics are of some concern to blade designers. The steady stresses imposed on blades (e.g., by centrifugal forces) are easy to accommodate by design. The unsteady stresses (i.e., the vibratory loads) are not easy to design for when both sufficient section strength to provide for centrifugal loading and maximum blade-configuration efficiency are considerations. The problem is related to how much damping can be expected from the material per se: what strength level should be built into titanium blades to accommodate an expected higher vibration loading of the material having relatively low damping capacity?

The titanium turbine blade experience to date has not provided the data to say whether material damping or system (mechanical and aerodynamic) damping is operative. The damping of the large blades of titanium alloys in test or in operational turbines has been augmented by system damping in all cases covered by the survey work. The need to generate specific material damping data for titanium blades under turbine conditions has been cited as an important requisite for titanium blade design.

The survey revealed that several turbine companies, while cognizant of the relatively low-damping capacity of titanium, are testing and using this material for blading without any special precautions in blade design. Other companies are managing the low-damping characteristic of titanium by using carefully designed blade midspan shrouds or ties. Further, it is to be noted that some companies are designing free-standing titanium blades (e.g., BBC) where the only mechanical damping is root damping. In all of the experiences surveyed, there were no difficulties reported for test or operational titanium blades attributable directly to the damping characteristic. At the same time, there have been efforts made to improve the damping capacity of titanium alloys. These have included research programs in alloy development and property modification by heat treatment. In addition, the results of damping measurement studies were reported. The results of some of these programs are described.

Selected results from early (1950's) studies on the damping characteristics of titanium (unalloyed), Ti-4Al-4Mn alloy, and Type 403 stainless steel are given in Table 5-7 as a point of reference.[5-47a] The damping characteristics of these materials are given in terms of specific damping energy (inch-pounds per cubic inch per cycle) which is not possible to relate to logarithmic decrement or internal friction without knowing the constants associated with specimen and machine dimensions. However, the data show that, under the conditions of this test (Ti-4Al-4Mn material annealed 16 hours at 1300 F and furnace cooled; Type 403 steel heat treated for 15 minutes at 1750 F, oil quenched, reheated to 1050 F, held 90 minutes and air-cooled), the titanium alloy had about the same damping capacity as the steel. The apparently anomalous specific damping energy results reported for unalloyed titanium (at S_e, the fatigue strength value at 2 x 10^7 cycles) are not understood.

Another interesting comparison of Type 403 steel and titanium alloy characteristics is afforded by the cyclic stress sensitivity limit (CSSL) data of Table 5-7. The CSSL has been described as the stress level below which damping is independent of the number of strain cycles imposed and as a good indicator of the minimum stress which can cause permanent fatigue damage in materials.[5-47b] The CSSL data of Podnieks and Lazan indicate an advantage for the Ti-4Al-4Mn alloy over Type 403 steel for the material and test conditions examined.[5-47a] (The Ti-4Al-4Mn alloy, although no longer offered commercially in the U.S., is similar in metallurgical behavior and properties to the Ti-6Al-4V alloy.) However, Willertz and Moon point out that the CSSL of Type 403 steel is definitely below the fatigue limit (S_e of Table 5-7) and that prior results to the contrary possibly reflect the insufficient sensitivity of CSSL test procedures to detect metal characteristic changes below the fatigue limit.[5-47b] If this is the case for steel, it also possibly applies to the CSSL result reported for Ti-4Al-4Mn alloy (at room temperature) as well. That is, a more sensitive test

Table 5-7

STATIC AND DYNAMIC PROPERTIES OF TITANIUM, Ti-4Al-4Mn, AND TYPE 403 STEEL MATERIALS[5-47a]

Property	Data for Material and Test Temperature Indicated					
	Unalloyed Ti		Ti-4Al-4Mn		403 Steel	
	RT (20 C)	600 F (316 C)	RT (20 C)	600 F (316 C)	RT (20 C)	700 F (371 C)
Static						
Yield strength (0.2% Offset), ksi	57		139		111	
Ultimate tensile strength, ksi	75.7		152		129	
Elongation in 2 in, percent	24		20		21	
Reduction of area, percent	25		34		65	
Hardness, R_C	15.9		35.8		24-26	
Modulus of elasticity, 10^6 ksi	13.8	10.6	16.9	14.5	30.5	27.0
Fatigue						
Fatigue strength at 2 x 10^7 cycles, S_e, ksi	41	20.5	86	62	65	54
Ratio of S_e to ultimate tensile strength	0.54	0.27	0.57	0.41	0.50	0.42
Damping						
Stress at cyclic stress sensitivity limit, S_L = CSSL, ksi	24	10.5	95	50	66	54
Ratio of stress at S_L to S_e	0.59	0.51	1.10	0.81	1.02	1.00
Specific damping energy at S_L, in-lb/cu in/cycle	0.16	0.07	2.0	1.70	1.40	1.65
Specific damping energy at S_e, in-lb/cu in/cycle	10-150	10-50	1.75	2.4-5	1.4	1.65

procedure for Ti-4Al-4Mn alloy might show a CSSL value lower than the fatigue strength value. The CSSL of Ti-6Al-4V alloy undoubtedly will be determined in the forthcoming EPRI funded program on corrosion-fatigue.

Since the data of Table 5-7 were generated in a single study, they are consistent with regard to test variables and analyses and therefore afford a direct comparison of the damping behavior of the materials evaluated. Additional reference data illustrating Type 403 steel (and other materials) damping behavior are shown in Figure 5-20.[5-48]

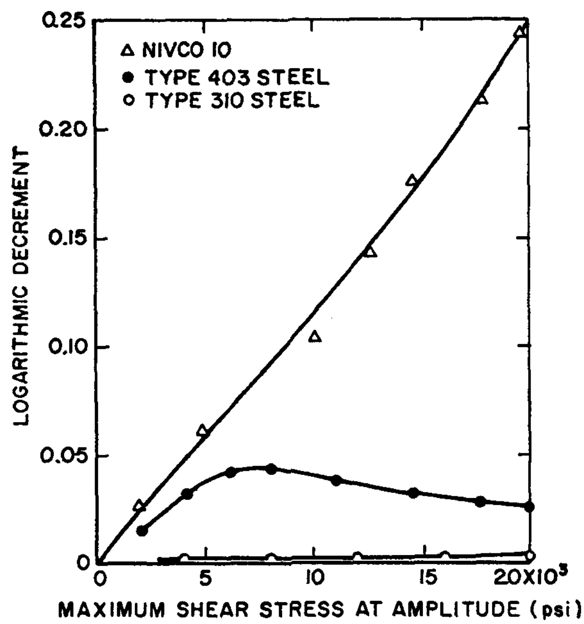


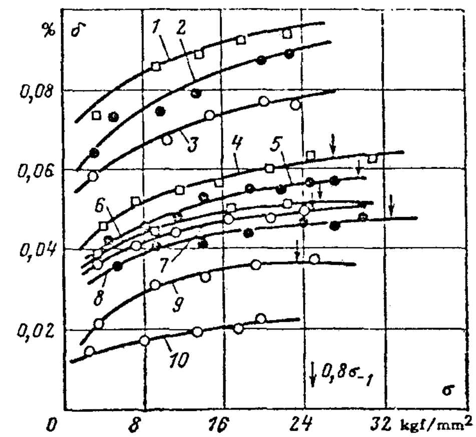
Figure 5-20. Damping Characteristics of Three Engineering Materials as a Function of Shear Stress Amplitude[5-48]

Soviet authors have reported on the damping characteristics of three titanium alloys which are being used or are being examined for use as turbine blading, VT5, TS5, and VT3-1.[5-14, 5-43, 5-44, 5-49] The nominal compositions are

- VT5, Ti-5Al
- TS5, Ti-(3 to 5)Al-(2 to 3)Sn-(1.4 to 2)Zr-(1.4 to 2)V
- VT3-1, Ti-5.5Al-2Mo-2Cr 1Fe-0.2Si (VT3-1 = VTZ-1).

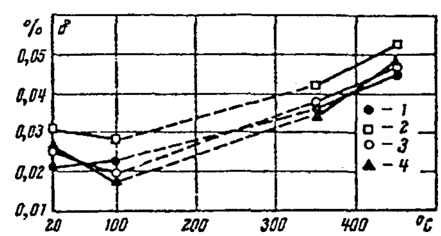
The data reported are shown in Figures 5-21 and 5-22 and indicate the range of damping characteristics for these titanium-base materials for selected test

(a)



Dependence of the vibration decrement of the TS5 and VT5 titanium alloys on the stress amplitude at $t = 20$, 100, 220 and 350°C.
1 – TS5, 350°C (blade); *2* – VT5, 350°C (bar); *3* – VT5, 350°C (blade); *4* – TS5, 20°C (blade); *5* – VT5, 100°C (bar); *6* – TS5, 100°C (blade); *7* – VT5, 20°C (blade); *8* – VT5, 20°C (bar); *9* – VT5, 100°C (blade); *10* – VT5, 220°C (blade).

(b)

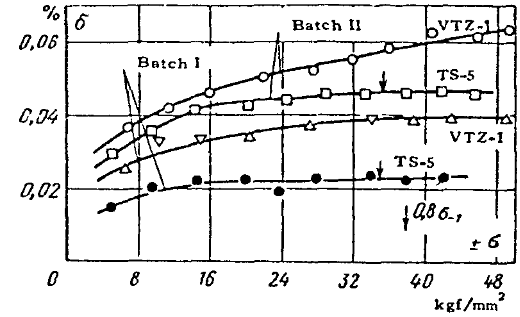


Temperature dependence of decrement of oscillations of VTZ-1 alloy with different type of structure at $\sigma = 0.8\sigma_{-1}$.

1--Fine-grained, equiaxed, Type 2; 2--fine-lamellar, Type 4-6; 3--lamellar, Type 7-8; 4--coarsely lamellar, Type 9

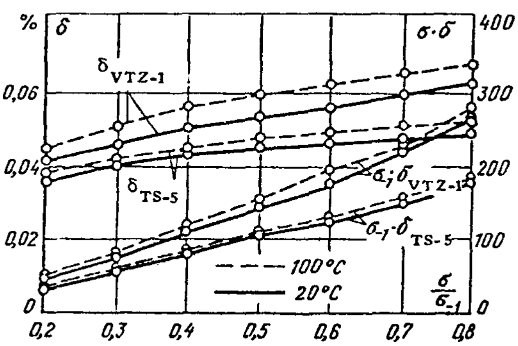
Figure 5-21. Ranges of the Vibration Decrement for (a) VT5 and TS5 Alloys with Stress Amplitude and Temperature Variables[5-43] and (b) VT3-1 Alloy with Microstructure and Temperature Variables[5-49]

(a)



Dependence of the decrement of oscillations of material of the first and second batches of blades made of titanium alloys on the amplitude of sign-changing stress at 20°C.

(b)



Dependence of decrements of oscillations of the second experimental batch of blades made of VTZ-1 and TS5 alloys on the amplitude of relative stress at 20 and 100°C.

Figure 5-22. Ranges of the Vibration Decrement for VT3-1 and TS5 Alloys with (a) Processing and Stress Amplitude Variables and (b) Stress Amplitude and Temperature Variables[5-14 and 5-44]

variables. The somewhat superior damping characteristics of the VT3-1 alloy were cited.[5-44]

Research conducted at the Central Electricity Research Laboratories, Central Electricity Generating Board, Great Britain, was aimed at improving the damping capacity of three titanium-base alloys via microstructural control.[5-50] The three alloys, IMI-318, IMI-551, and IMI-680, were solution heat treated to produce various quantities and compositions of the beta phases in the mixed two-phase structures (Figure 5-23). The three compositions examined were

- IMI-318, Ti-6Al-4V (117KX, a second heat of same)
- IMI-551, Ti-4Al-4Sn-4Mo-0.5Si
- IMI-680, Ti-2.25Al-11Sn-4Mo-0.25Si.

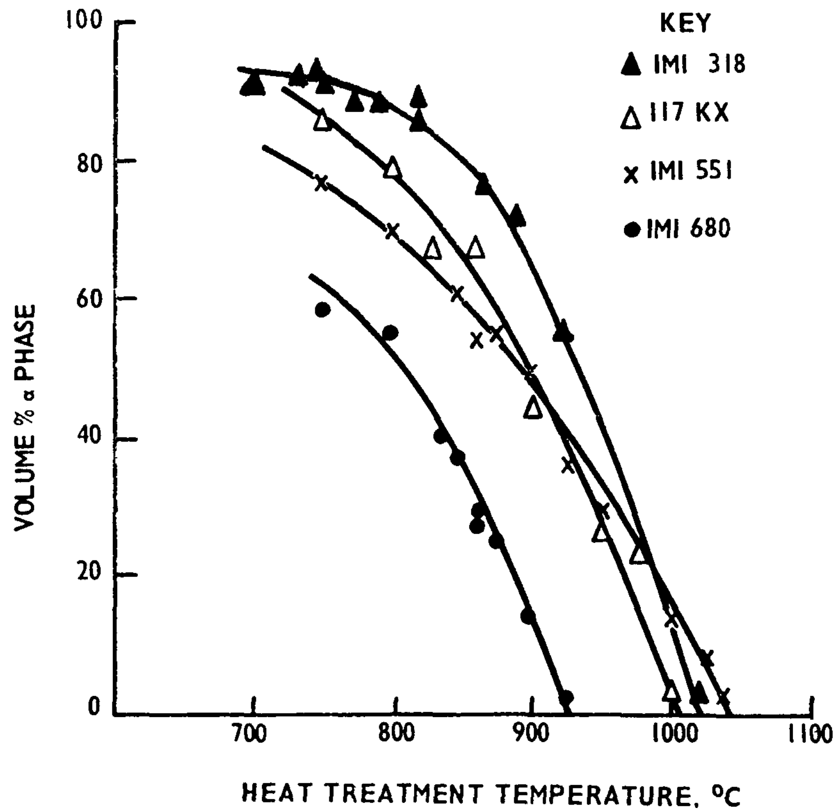


Figure 5-23. Volume Fraction of Alpha Phase (HCP) Observed After Solution Treatment and Quenching from Temperatures Indicated[5-50]

These compositions are sufficiently beta stabilized to permit the retention of untransformed beta phase of Composition X, when the solution treatment temperature is at or below a critical temperature (T_C), as in Figure 5-24. The CEGB work included determinations of the critical temperatures for beta phase retention and the beta transus temperatures for the alloys as depicted in Table 5-8 and tensile properties at selected temperatures as given in Table 5-9.

The untransformed beta phase produced by rapidly cooling metal from solution temperatures at and below the critical temperature is increasingly stabilized with decreasing solution temperature. At solution temperatures near the critical temperature, the beta phase retained to room temperature is unstable and may be very strain transformable (martensitic transformation during deformation) in preferred compositions.[5-51] The condition may be characterized by low tensile yield strength and high plasticity. Similar effects produced in

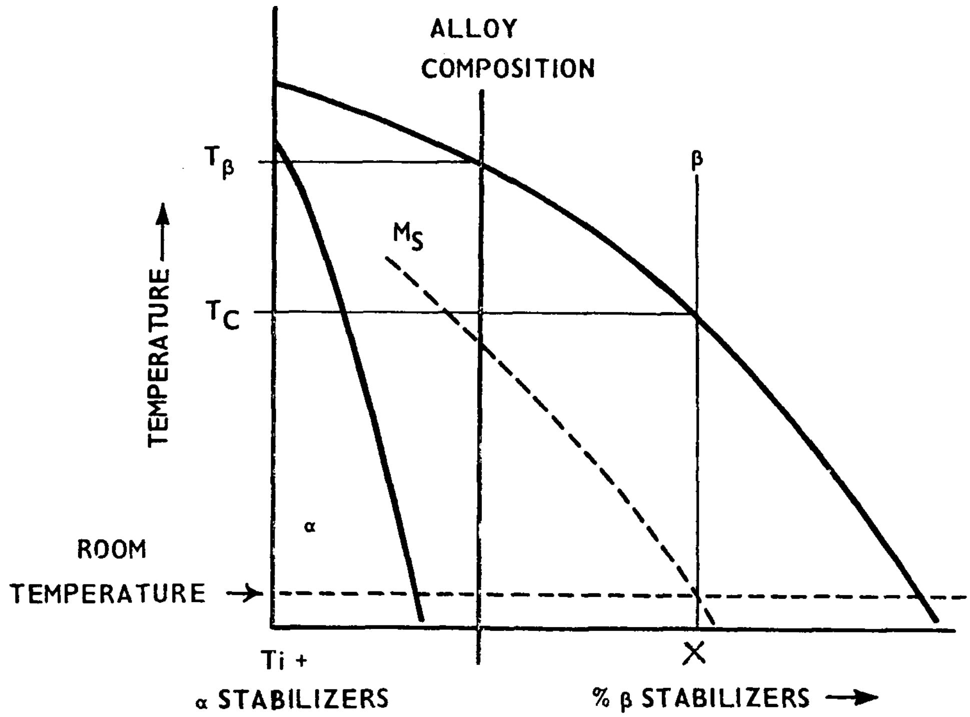


Figure 5-24. Schematic Phase Diagram for Titanium-Aluminum-Base Alloys with Beta Stabilizing Additions[5-10]

Table 5-8

BETA TRANSUS TEMPERATURES AND CRITICAL TEMPERATURES FOR THE RETENTION OF UNTRANSFORMED BETA PHASE AS SOLUTION QUENCHED FOR IMI-318, IMI-551, AND IMI-680 TITANIUM ALLOYS[5-50]

Alloy	Beta Transus Temperature,		Critical Temperature for Beta Phase Retention	
	C	F	C	F
IMI-318	1025	1877	750-770	1380-1420
IMI-551	1050	1922	850-863	1560-1585
IMI-680	930	1706	850-863	1560-1585
(117KX)	(1005)	(1840)	(815-830)	(1500-1525)

Table 5-9

ROOM TEMPERATURE TENSILE PROPERTIES OF THREE TITANIUM ALLOYS AS SOLUTION TREATED AND QUENCHED[5-50]

Alloy	Heat Treatment	0.1% Proof Stress ($MN\ m^{-2}$)	U.T.S. ($MN\ m^{-2}$)	Elongation %
IMI 318	1 h at 817°C WQ 1 h at 870°C WQ	730 730	910 950	15.4 17.2
IMI 551	1 h at 870°C WQ 1 h at 1100°C WQ	780 1200	1180 1310	15.4 0.3
IMI 680	1 h at 870°C WQ 1 h at 950°C WQ	420 360	1110 1180	11.7 11.9

Ti-6Al-4V alloy by heat treatment are well known since the 1950's. The IMI titanium alloys, solution treated over a range of temperatures above and below the critical temperature, were examined for their damping behavior in these conditions in the CEGB study.

Selected results of the low-stress damping measurements per Reference 5-50 are summarized in Figure 5-25. Those for the high-stress damping measurements are summarized in Figure 5-26. The higher damping capacities of these materials quenched from near the critical temperature are immediately apparent. The author concluded that the high damping behavior measured

- Depends on arranging for a metastable β-phase to be retained at the testing temperature, and
- Is thought to be associated with the reversible growth of "Pre-martensitic embryos".

Unfortunately, the metastable beta phase resulting in high damping is quite unstable and aging type thermal exposures degrade the good damping characteristics rather quickly. The effect is shown in Figure 5-27 for the IMI-551 and 275 F (135 C) aging temperature. The IMI-318 and IMI-680 alloys behave similarly, and all three alloys show the instability during aging at temperatures as low as 212 F (100 C). Room-temperature storage (aging) for longer times also is effective in degrading the high-damping levels produced by solution treating. Changes in the microstructures due to aging were not observed and

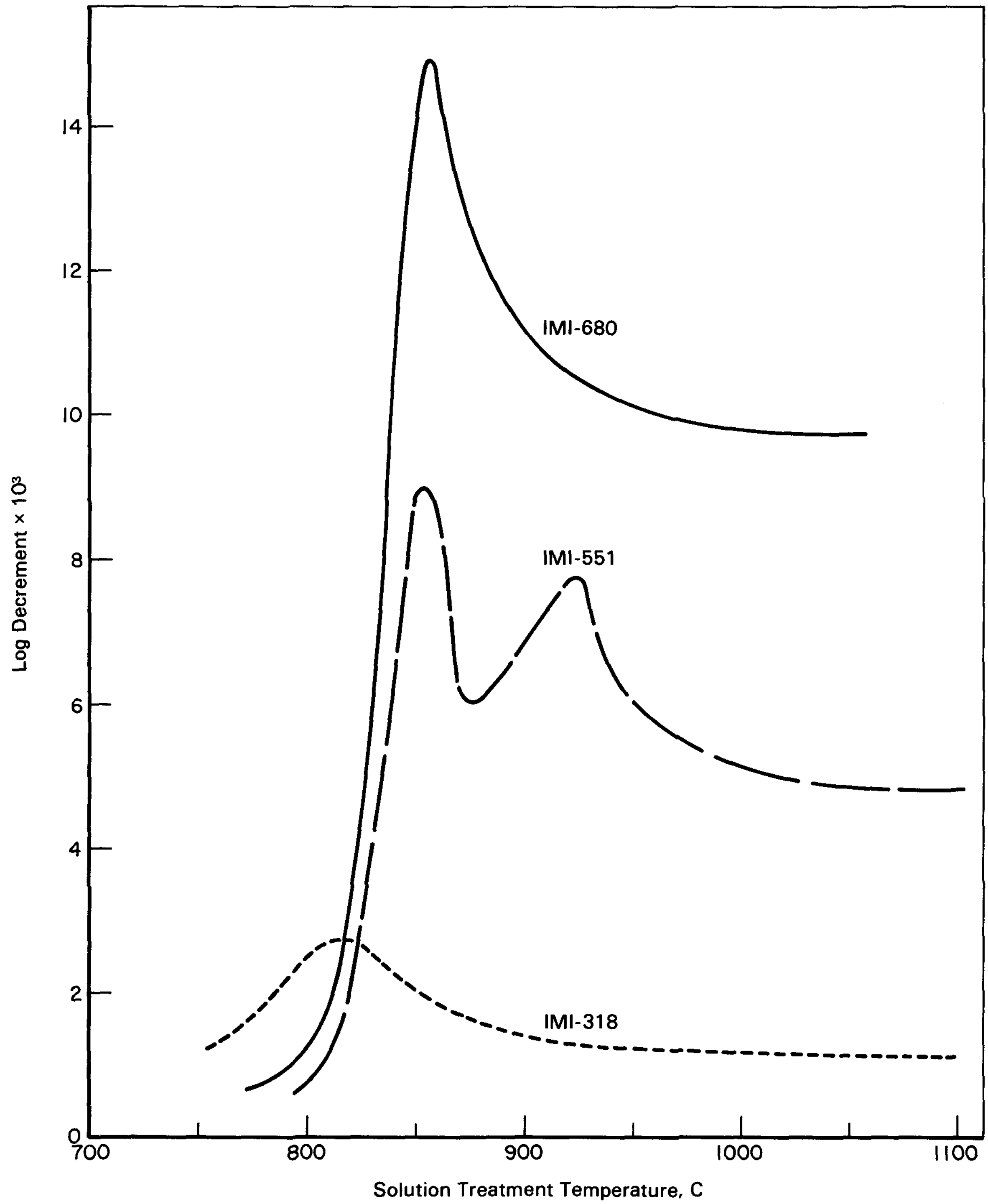


Figure 5-25. Low Stress Damping Behavior of Three Titanium Alloys at Room Temperature Immediately After Quenching[5-50]

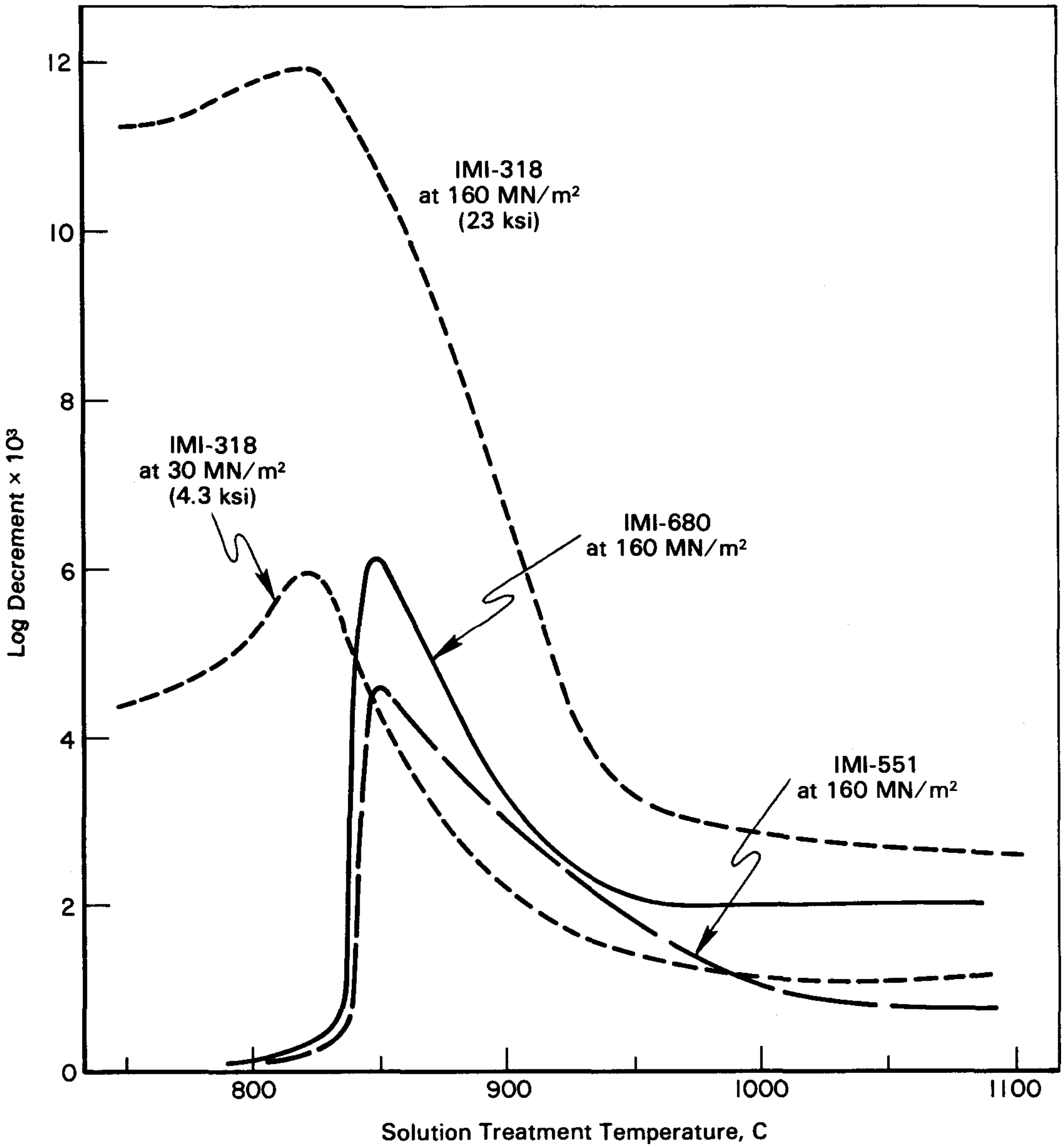


Figure 5-26. High Stress Damping Behavior of Three Titanium Alloys at Room Temperature Immediately After Quenching[5-50]

the author concluded that the loss of damping was perhaps associated with "thermal stabilization" of the beta phase, thus reducing the effect of vibrational stresses on inducing the early stages of martensitic transformation.[5-50]

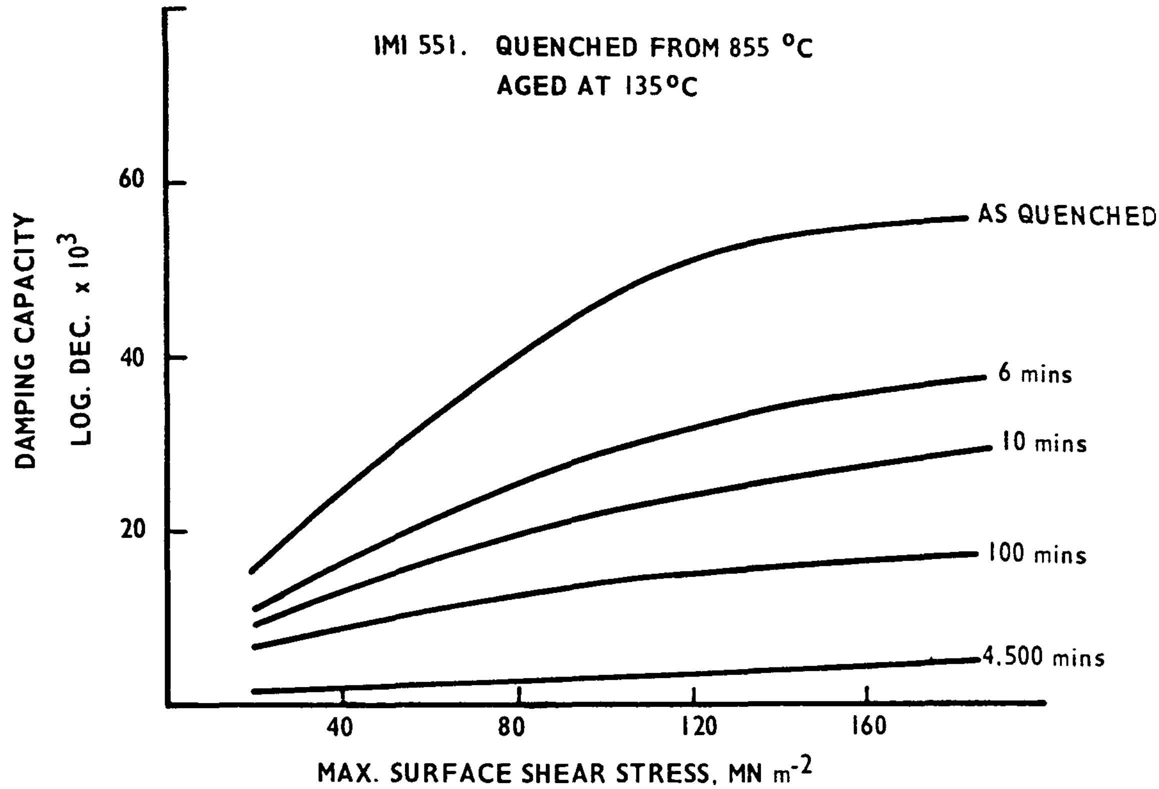


Figure 5-27. Effect of Aging Type Thermal Exposures on the Damping Behavior of IMI-551 as Solution Heat Treated and Quenched from the Critical Temperature[5-50]

5.5 OTHER PERTINENT PHYSICAL PROPERTIES AND CHARACTERISTICS

The record for titanium in applications with regard to its erosion, corrosion, and fatigue resistance is one which appears to make the material attractive for the steam-turbine blading application. However, the above parameters are not the only ones that need be considered. For example, titanium's modulus of elasticity, at essentially one-half that of steel, is possibly a disadvantage. Further, under certain conditions, blades need to be very tough -- very fracture resistant. Under all conditions, a material for blades needs to have the characteristic of good fabricability for ease of manufacturing. A good weldability of the material also might be desirable for some designs. The physical properties of titanium, such as thermal expansion, thermal capacity, and thermal conductivity, are considerations. The information in this section illustrates the traits of titanium regarding the above matters.

The modulus of elasticity for the various titanium alloys considered for steam-turbine blades differs with composition, processing, mill-product form, measurement technique, etc. For example, tensile modulus for the alpha titanium alloy, Ti-5Al-2.5Sn, has been reported as ranging between 15.5 and 16.0 x 10^3 ksi. The data offered in this section, using Ti-6Al-4V alloy as an exemplary material, is intended to illustrate general alloy characteristics rather than to present definitive engineering data. Nevertheless, the data cited are from engineering data handbooks and authoritative reports and can be used as initial guidelines in considering Ti-6Al-4V for turbine blades if that becomes desirable.

The room temperature elasticity values for Ti-6Al-4V alloy reported in Military Handbook 5 [5-52] are

- E, tension, 16.0 x 10^3 ksi
- E, compression, 16.4 x 10^3 ksi
- G, torsion, 6.2 x 10^3 ksi
- μ, Poisson's ratio, 0.31.

The above values reported are the same for sheet, strip, plate, bars, and forgings in either the annealed or the solution-treated plus aged conditions. However, the results reported for annealed, standard-processed Ti-6Al-4V sheet obtained via precision measurement techniques are slightly different, as shown below.[5-53]

Property	No. of Tests	Range	Average
E, tension, 10^3 ksi(1)	16	15.4-17.6	16.5
E, compression, 10^3 ksi(1)	16	15.7-18.0	16.6
μ, Poisson's ratio(2)	10	0.287-0.391	0.342

(1) Via Tuckerman optical strain gage.

(2) Via two-element rosette resistance strain gages.

The elastic modulus at various temperatures for Ti-6Al-4V alloy may be estimated by multiplying the room-temperature values in the above tabulations by the temperature factors shown as a curve in Figure 5-28.[5-52] The effect of temperature on the elastic modulus of selected Soviet titanium alloys is shown in Figure 5-29.[5-45]

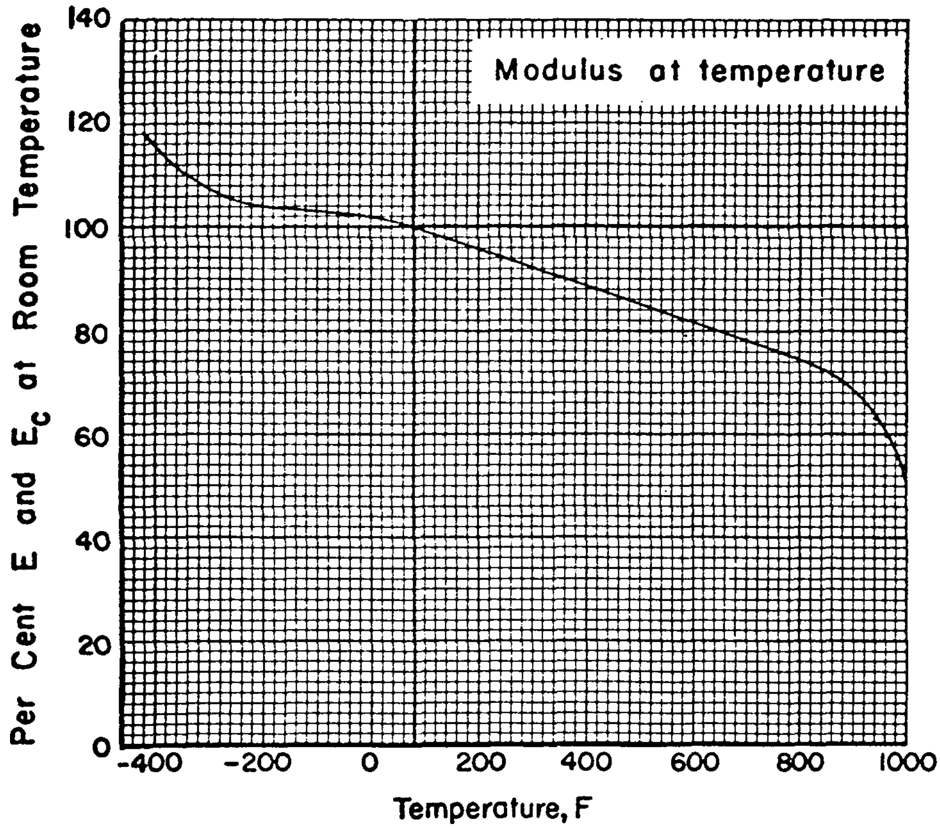


Figure 5-28. Effect of Temperature on the Tensile and Compressive Modulus of Ti-6Al-4V Alloy Sheet and Bar[5-52]

There are several turbine-blade design considerations that relate to modulus of elasticity values. For example, in retrofitting titanium alloy blades to steel discs that have been designed for steel blades, the question arises as to whether the loads on the root hooks would be properly distributed.[5-9] Some companies surveyed are concerned that, with a direct geometrical substitution of titanium for steel buckets, the top titanium hooks would tend to support the entire load. Other companies have cited their experiences in using titanium blades wherein the titanium root design has accommodated the distribution of stresses to the three holding points very well because of the low modulus, stress-strain characteristics of titanium. Thus, there are apparently differences in experiences possibly owing to differences in designs. The area is undoubtedly one which should receive design attention due to the potential problem.

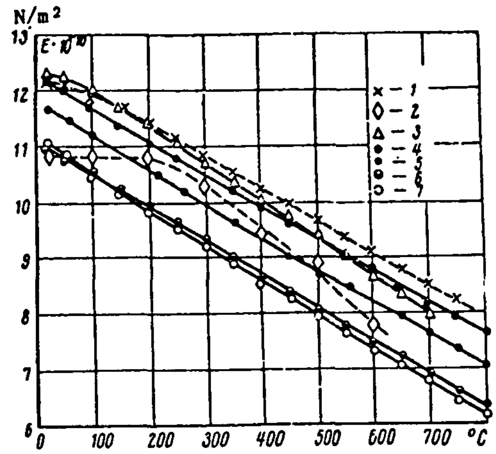


Figure 5-29. Effect of Temperature on the Tensile Modulus of Selected Soviet Titanium Alloys[5-45]

1, VT8, Ti-6.5Al-3.5Mo-0.25Si; 2, Same, different heat; 3, VT5, Ti-5Al; 4, Same, different heat; 5, Ti-6Al; 6, Ti-4Mo; 7, TGO, Unalloyed titanium.

Titanium blade detwisting under centrifugal forces and blade bending (axially) under steam loading are also areas needing design attention with regard to the relatively low modulus of titanium.[5-9] The blade detwist-modulus relationship is rather straightforward and a major problem in this design area is not anticipated. It is believed that the blade flutter problem may not be as easily dismissed when designing with titanium. Blade flutter is usually experienced under low-flow, high-back-pressure conditions (e.g., start-up, shutdown, and steam dump situations) and is associated with blade bending in the axial direction. When a blade bends, it presents a changed profile to the axial flow force which may cause still greater bending. A freely bending titanium blade may present a radically different profile to the axial mass flow. The concern is related to how much more the relatively low modulus titanium blades would bend than steel blades, and, therefore, how much greater motion factor would need to be design accommodated. No experience has been accumulated (or at least reported) concerning this potential problem with titanium, but its properties suggest that improperly designed titanium blades might be susceptible to blade flutter phenomena.

The impact toughness and the fracture resistance of titanium in combination with other characteristics such as low density and corrosion resistance made it an attractive candidate for armor from its earliest recognition as a new structural metal. The use of Ti-6Al-4V alloy as a crack stopper in airframe sheet-stringer structures also was widely employed early in the history of its applications. Currently, titanium alloys, including Ti-6Al-4V, are used in numerous airframe and aircraft engine applications where high-fracture toughness and crack propagation resistance are premium requirements.

Properly processed and heat-treated titanium alloys have a high toughness and an excellent service record regarding toughness can be cited. For example, the large fan blades, annealed Ti-6Al-4V alloy, of the General Electric Company's CF6 aircraft gas turbine engine have encountered and stood up well to foreign object damage (FOD) in service connected experiences.[5-9] Figure 5-30 shows the bent and torn fan blades of a CF6 engine which was believed to have ingested portions of an aircraft tire and wheel rim. This case illustrates the excellent ballistic impact toughness of the Ti-6Al-4V blades under extreme high-stress conditions.

The need for high-fracture toughness and crack-propagation resistance in steam-turbine blading stems from the need for an FOD resistant and a fatigue notch insensitive material in blades. Steam-turbine blades may be subjected to FOD in cases where up-stream blade and/or nozzle malfunctions and failures occur (e.g., due to water induction at steam extraction points and resultant temperature anomalies) resulting in blade debris traveling downstream into other blades and nozzles. The reliability of a turbine section in part depends on the capability of its materials to continue holding loads under adverse high-stress conditions.

An example of Ti-6Al-4V steam turbine blades maintaining their integrity under accidental FOD conditions was reported.[5-54] A small (7000 hp) industrial turbine manufactured by the Terry Corporation experienced an accidental loss of oil, causing thrust-bearing failure, which allowed rubbing between rotating and stationary components. The steel blading in the high-pressure stages was broken, cracked, and pulled out of the turbine hubs while the Ti-6Al-4V last-stage blades did not crack or pull out of hubs. The nicked, bent, and twisted titanium blades were salvaged by reworking to the proper shape and used in the repaired machine.

Additional selected data for the Ti-6Al-4V alloy are presented which afford some insight into the ability of this material to perform well in such situations.

Figure 5-30. Bent and Fractured Fan Blades from CF6-50A[5-9]

(Photographs courtesy of General Electric Company)

The behavior of the Ti-6Al-4V alloy in the Charpy V-notch impact-energy absorption test for both the annealed and aged conditions is shown in Figure 5-31.[5-55] It is to be noted that there is no sharp ductile-brittle transition temperature for this alloy. The impact-energy absorption value for the temperature range typical of the last stages of low-pressure steam-turbine sections is in the 20 to 25 ft-lb range.

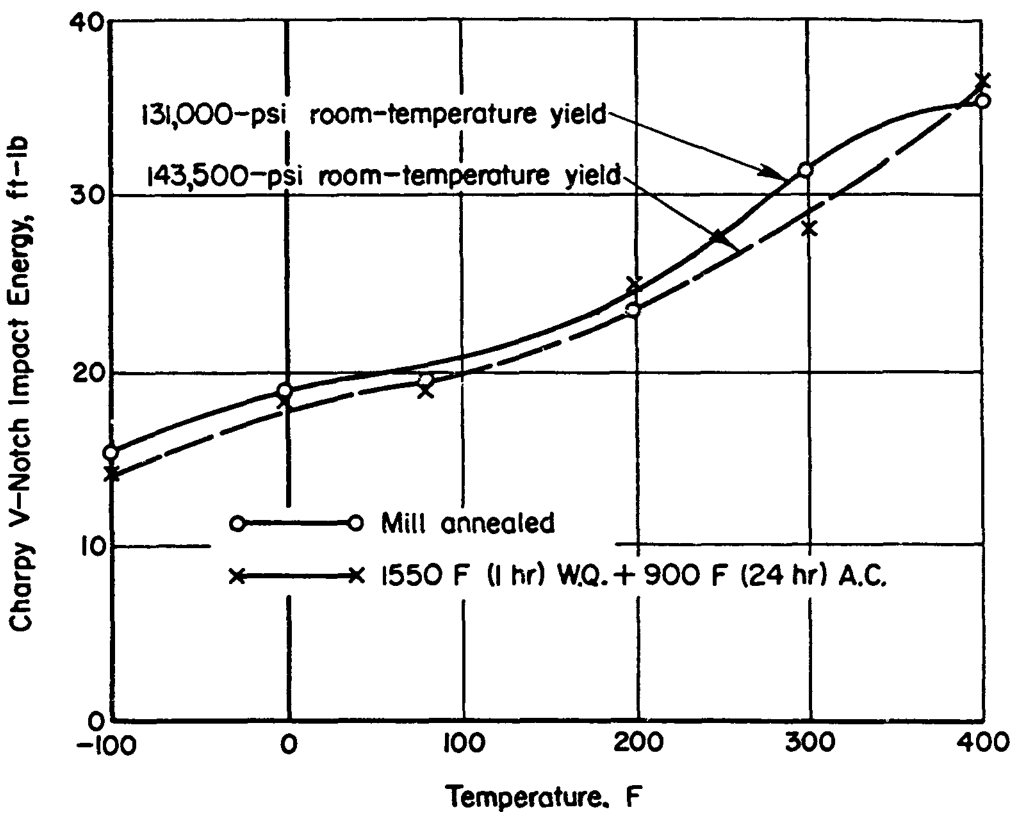


Figure 5-31. Charpy V-Notch Impact Energy Absorption for Ti-6Al-4V Alloy in Two Conditions of Heat Treatment[5-55]

Representative fracture-toughness values for Ti-6Al-4V alloy forgings and plate are given in Table 5-10.[5-56] These data show some differences in toughness due to annealing treatment, mill product, section size, and specimen orientation. The range of fracture toughness values experienced with a variety of standard annealed mill products having tensile strengths between 120 and 145 ksi (i.e., all materials within specification limitations) is shown in Figure 5-32.[5-57] The recrystallization annealing treatment recently developed (e.g., 4 hours at 1700 F, furnace cool to 1400 F no faster than 100 F/hour, cooling from 1400 F to below 900 F within 45 minutes) is expected to improve the consistency of properties, including the fracture characteristics at moderately high values, of Ti-6Al-4V alloy from lot to lot and for the various mill-product forms being used. Figure 5-33 shows the effect of increasing test temperature on fracture toughness -- toughness increases with increasing temperature as tensile strengths decrease.[5-58] Constant amplitude fatigue-crack-growth-rate tests on the same annealed material (2 hours at 1300 F) were conducted on samples with longitudinal orientation. A double cantilever beam specimen was used and the load was cycled at 600 cycles per minute. Data for annealed material and for annealed material additionally exposed for 1000 hours at 800 F are shown in Figure 5-34.[5-58] The 800 F exposure slightly reduced the crack-growth resistance of annealed Ti-6Al-4V. However, this exposure temperature is quite higher than would be expected in areas for titanium use in steam turbines.

Table 5-10

ROOM TEMPERATURE PLANE-STRAIN FRACTURE TOUGHNESS DATA FOR Ti-6Al-4V ALLOY ANNEALED FORGINGS AND PLATE[5-56] (Compact Tension Specimens)

Condition	Form and Thick., in.	Avg Yield Str., ksi	Specimen Orientation	Thick., (B) in.	Width (W) in.	Crack Length, in.	K_{IC}, ksi-$\sqrt{in.}$
Mill anneal, 1000 F, 2 hr, AC	2.3 Billet	145 145	L-T L-T	1.249 1.250	2.500 2.498	1.250 1.264 Avg	51.3 50.5 50.9
Mill anneal, 1300 F, 2 hr, AC	2.3 Billet	127 127	L-T L-T	1.253 1.251	2.500 2.498	1.271 1.225 Avg	86.8 85.0 85.9
Mill anneal, 1300 F, 2 hr, AC	2.3 Billet	120	L-T	1.250	2.500	1.277	80.3
Mill annealed	1.25 Plate	119 119 119	T-L T-L T-L	1.247 1.245 1.245	3.500 3.495 3.499	1.817 1.741 1.824 Avg	94.8 95.3 97.0 95.7
Recrystallize annealed	1.5 Plate	121 121	L-T L-T	1.500 1.496	6.003 6.002	3.103 3.080 Avg	86.6 91.0 88.8
Recrystallize annealed	2.0 Plate	119 119	L-T L-T	1.780 1.873	6.003 6.003	3.075 3.138 Avg	97.3 96.6 97.0

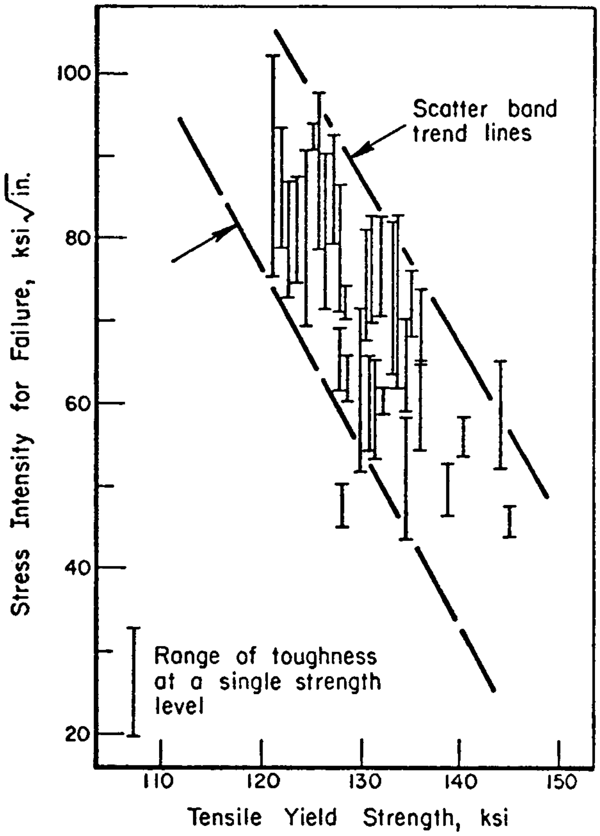


Figure 5-32. Fracture Toughness-Tensile Yield Strength Relationship Observed for Annealed Ti-6Al-4V Bars, Plates, and Forgings[5-57]

The thermal properties of Ti-6Al-4V alloy are shown in Figure 5-35.[5-59] Data from several sources are shown: There is no evidence to indicate which of the values are more nearly correct. Steam turbines are heat engines, and component materials must perform at elevated temperatures. Titanium alloys have been routinely used at temperatures to 600 F and, in several applications, to much higher temperatures. The Soviets have investigated the long-term use of properties of titanium over a broad temperature range and have measured the physical properties of the VT5, Ti-5Al, and VT8 (Ti-6.5Al-3.5Mo-0.25Si) alloys over the 20 to 800 C (68 to 1470 F) range as shown in Table 5-11.[5-45] The Soviet authors point out that the linear thermal expansion coefficient of the titanium alloys is lower by 20 percent than for 2Cr13 steel and that the specific heat and thermal conductivity changes with temperature are quite different than for steel as well. These characteristics for titanium alloys should be carefully considered in designing titanium components for their compatible use with steel structures.

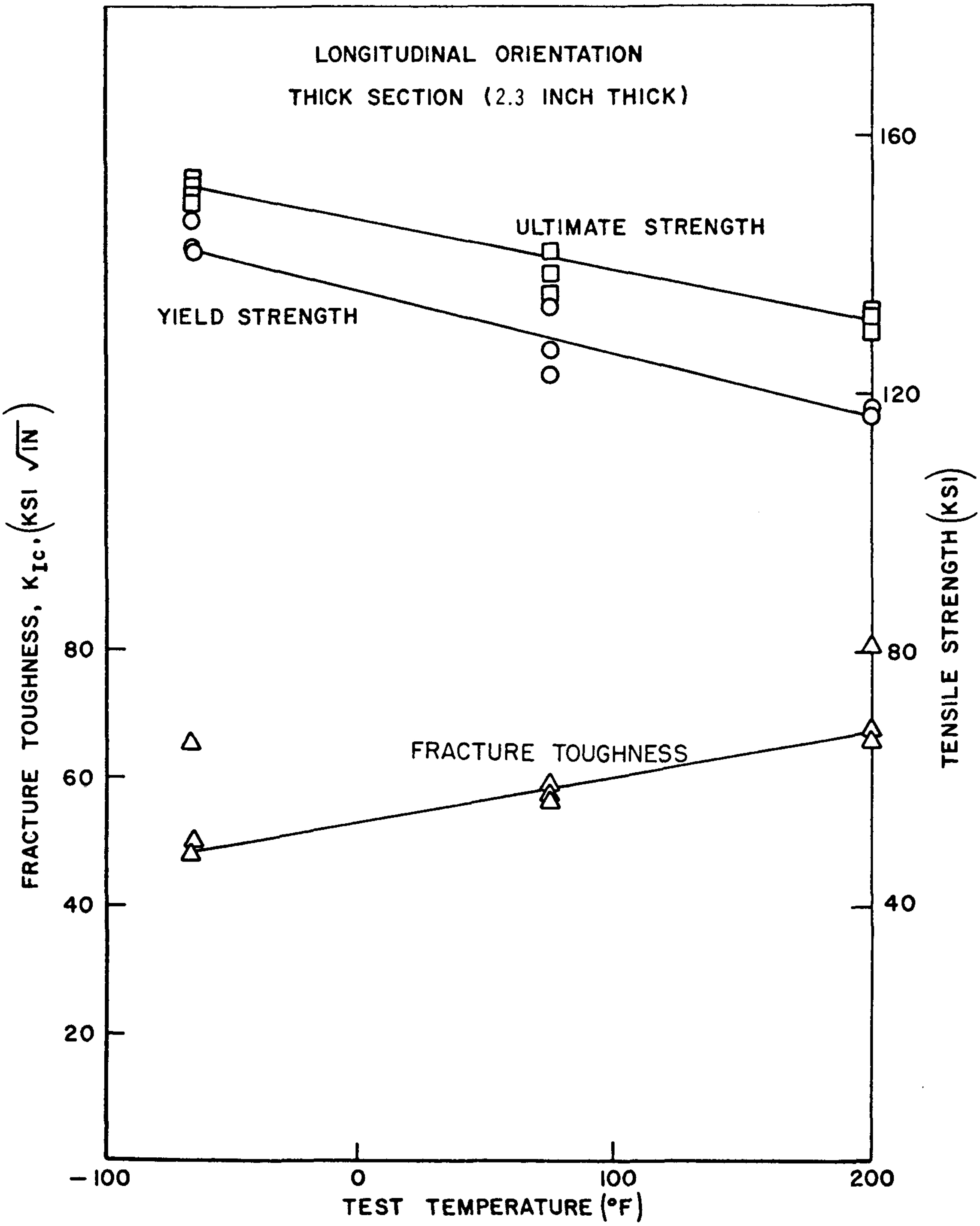


Figure 5-33. Effect of Test Temperature on the Fracture Toughness and Tensile Strength of an Annealed Ti-6Al-4V Alloy Forging[5-58]

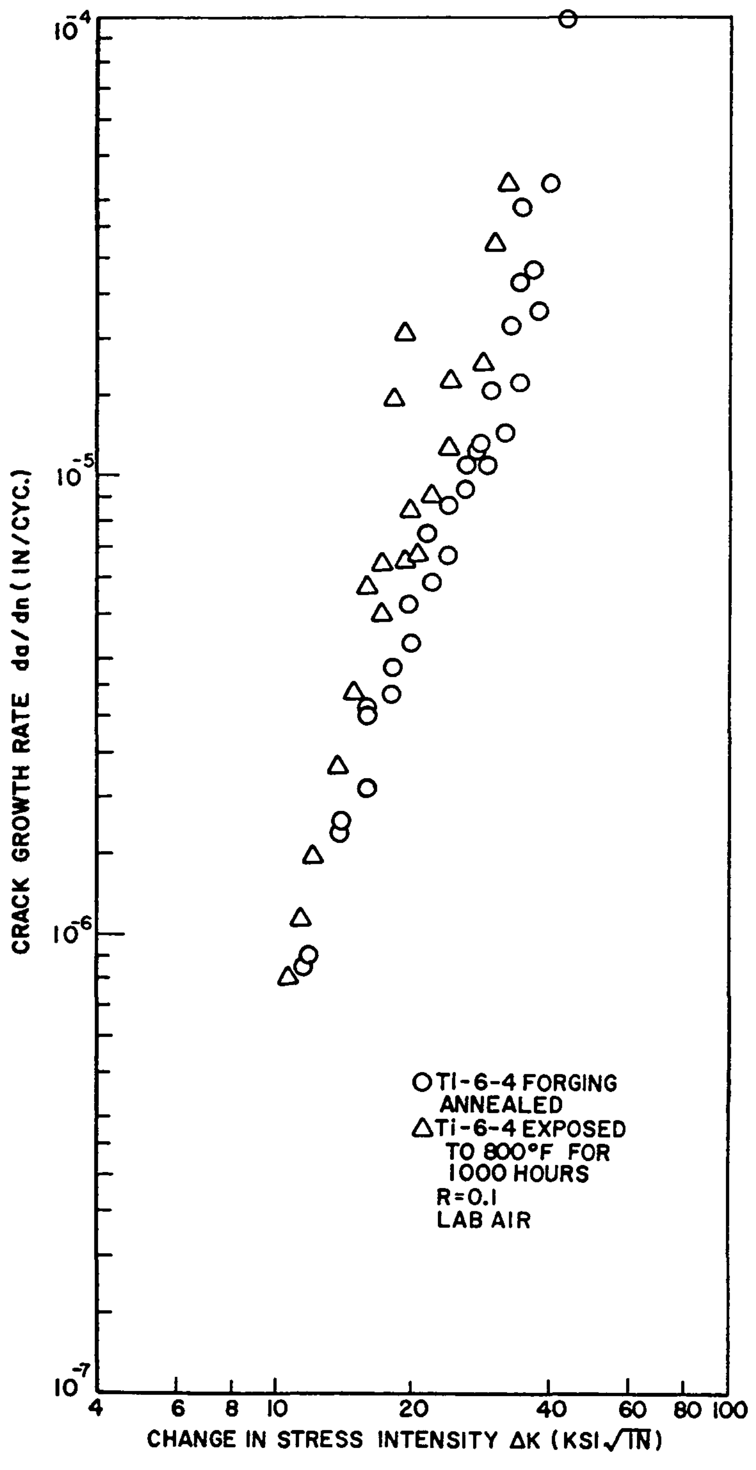


Figure 5-34. Crack-Growth Resistance of a Ti-6Al-4V Alloy Forging Annealed 2 Hours at 1300 F and as Thermally Exposed 1000 Hours at 800 F[5-58]

(a)

(b)

(c)

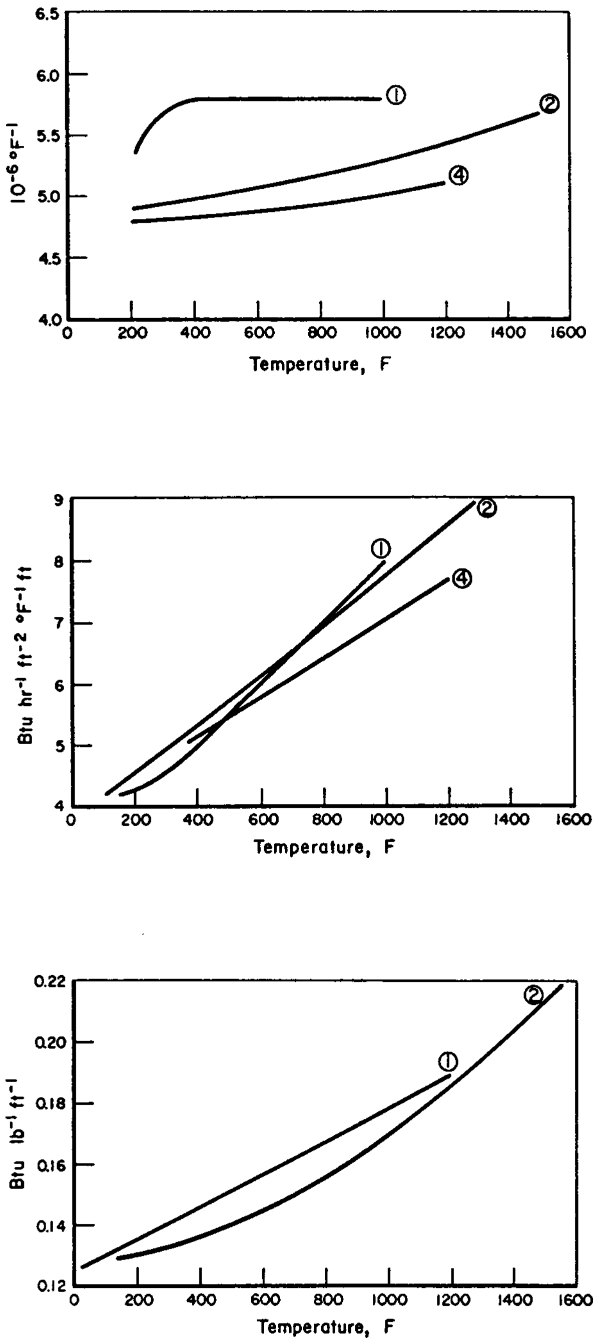


Figure 5-35. Thermal Properties of Ti-6Al-4V Alloy (a) Mean Coefficient of Thermal Expansion Between Temperature Indicated and 68 F, (b) Thermal Conductivity, and (c) Specific Heat[5-59]

Table 5-11

PHYSICAL PROPERTIES OF TITANIUM ALLOYS VT5 AND VT8[5-45]

Properties	Alloy	Temperature, C								
		20	100	200	300	400	500	600	700	800
$\alpha_{20t}.10^6$, 1/deg(1)	VT5	--	8.99	9.44	9.80	10.04	10.22	10.39	10.53	--
	VT8	--	8.26	9.25	9.80	10.03	10.18	10.24	10.24	10.57
$\alpha.10^6$, 1/deg(1)	VT5	--	9.4	10.0	10.55	10.65	11.3	11.45	--	--
	VT8	--	9.3	10.3	10.6	10.6	10.9	10.25	11.3	--
$d.10^{-3}$, kg/m^3(2)	VT5	4.412	4.402	4.390	4.376	4.362	4.348	4.334	4.319	--
	VT8	4.461	4.452	4.439	4.425	4.411	4.396	4.383	4.370	4.353
c_p, kJ/kg. deg(3)	VT5	--	0.615	0.655	0.675	0.695	0.725	0.745	0.745	--
	VT8	--	0.55	0.58	0.62	0.64	0.68	0.735	0.75	--
c_p20-t, kJ/kg. deg(3)	VT5	--	0.6	0.62	0.64	0.65	0.665	0.675	0.685	--
	VT8	--	0.535	0.56	0.575	0.59	0.605	0.62	0.64	--
λ, W/m. deg(4)	VT5	--	10.5	11.8	12.8	13.6	14.6	15.8	17.2	--
	VT8	--	9.4	10.8	12.2	13.6	15.0	16.4	17.8	19.1
$a.10^5$, m^2/s(5)	VT5	--	0.39	0.41	0.435	0.45	0.465	0.49	0.535	--
	VT8	--	0.385	0.42	0.445	0.48	0.50	0.51	0.545	--
$\rho.10^8$, ohm.m(6)	VT5	143.2	152.4	162.3	170.1	176.3	180.0	183.1	184.8	--
	VT8	165.4	170.9	175.9	179.6	182.0	183.5	183.5	183.5	182.1
$L.10^8$, V^2/deg^2(7)	VT5	--	4.30	4.04	3.79	3.57	3.38	3.30	3.28	--
	VT8	--	4.28	4.01	3.84	3.69	3.56	3.46	3.35	3.25
$E.10^{-10}$, N/m^2(8)	VT5	12.31	11.98	11.38	10.67	10.01	9.35	8.65	7.94	--
	VT8	12.16	11.89	11.40	10.82	10.21	9.63	9.06	8.49	--

(1) Mean coefficient of thermal expansion.

(2) Density.

(3) Specific heat.

(4) Thermal conductivity.

(5) Thermal diffusivity.

(6) Electrical conductivity.

(7) Lorenz number.

(8) Elastic modulus.

While the experience in fabricating titanium alloy components has accumulated to large proportions in the brief history of the metal, the fabrication "know-how" is not as widely distributed among metalworking firms as might be desired. It is important that manufacturers of titanium components have a background in successful titanium fabrication or expend the time and effort to develop such a capability in order to produce parts meeting the full potential of titanium materials. The survey revealed that there were cases where titanium components were not being fabricated using optimum procedures.[5-9] There is an extensive literature available on preferred techniques for fabricating titanium, including the technologies for welding and brazing, which should be utilized when titanium is selected for steam turbine components.[5-39,5-60,5-61,5-62]

5.6 LOW-PRESSURE TURBINE SECTION EFFICIENCY AND POWER

The thermal efficiency of large modern steam turbines is on the order of 35 percent, swinging higher or lower with a complexity of operating limitations and with various turbine designs. A large fraction of the total power in the steam of turbine generator sets is extracted in the low-pressure section(s) and the last stage(s) accounts for a very large proportion of the power extracted. The importance of overall machine efficiency is much greater as a result of factors such as the high price of fuel. Thus, a more efficient last stage of the low-pressure turbine section becomes very desirable. The potential for increasing the efficiency of the low-pressure sections of turbines by utilizing longer last-stage blades, implying the use of titanium blades in designs which are size limited by the properties of steel blades and rotors, was therefore a topic of discussion during the survey. In short, was there a benefit derivable from the use of longer last-stage titanium blades due to an increased and otherwise unobtainable efficiency in turbine ends which might be in addition to any benefit obtained through increased reliability of titanium blades?

Increasing the efficiency of low-pressure steam-turbine sections by increasing the length of the last-stage blades is particularly effective when the condenser back pressure is low, a condition achievable at low cost by once-through cooling in geographic areas with unrestricted water supply. Low back pressures have been used by utilities in the past in the Great Lakes area and by TVA and AEP in some areas. Environmental restrictions on the permissible temperature rise of water returned to lakes, rivers, or estuaries (restricted to a rise of 1.5 F for Great Lakes water, for example) have effectively removed this option and forced most new power plants to resort to high cost cooling towers or cooling ponds. The magnitude of the cooling problem is clear when it is realized that about one-half of the heat input to fossil-fueled plants is rejected to the condenser (about two-thirds of the heat input to nuclear-fueled plants).[5-63]

The use of longer last-stage blades results in a larger annulus area and lower blade loading for a given steam throughput. The mechanical duty on such longer blades, and consequently their reliability, may be greater or less, depending on their design, buffeting stresses during off-peak operation, and many other factors.[5-9] In any case, leaving losses tend to be lower with a larger annulus area, with other conditions relatively constant, and therefore longer blades present the potential for increased last-stage efficiency.

As an example of the potential for increased efficiency, the General Electric Company offered the following for discussion purposes.[5-9] Consider a condition of a 2-inch Hg back pressure and a 15,000-pound steam per hour per square foot ($lb/hr/ft^2$) loading rate. If the steam loading on last-stage blades is reduced to 10,000 $lb/hr/ft^2$ by increasing the blade length (e.g., from 30 to 33.5 inches), the exit velocity would be reduced two-thirds and the heat rate reduced by 2 percent. Thus, if the original overall thermal efficiency was 38 percent, an increase of 2 percent corresponds to 38.8 percent overall (new) efficiency. If adequate cooling is not available to achieve a 2-inch Hg back pressure, for example, in a situation where a cooling sufficient only to achieve a 4-inch Hg back pressure was available, there would be substantially no difference in efficiency with the longer blades. Thus, greater thermal efficiency could be achieved with the increased annulus area, provided a sufficiently low back pressure could be obtained with optimized exit cooling.

The difficulties of meeting steam turbine, condenser cooling requirements in the years ahead are discussed in a paper by Westinghouse Electric Corporation authors.[5-63] The main thrust of their report concerns how the forthcoming less-than-optimum and expensive cooling systems (e.g., dry towers) and consequent higher condenser back pressures will affect steam-turbine design. It was pointed out that last-stage efficiency peaks at some optimum exit velocity (Figure 5-36) which may not be obtainable at high condenser pressures when low steam loading is utilized (Figure 5-37).[5-64] Thus, the direction for efficiency would be to maximize last-stage steam loading by increasing steam flow for a given annulus or by decreasing annulus area for a given steam flow.

Therefore, in situations where nonoptimum cooling prevails, longer last-stage titanium blades would not be appropriate. Conversely, in areas where lower exhaust cooling temperatures can be achieved, it would appear appropriate to explore the potential benefits of longer last-stage titanium blades.

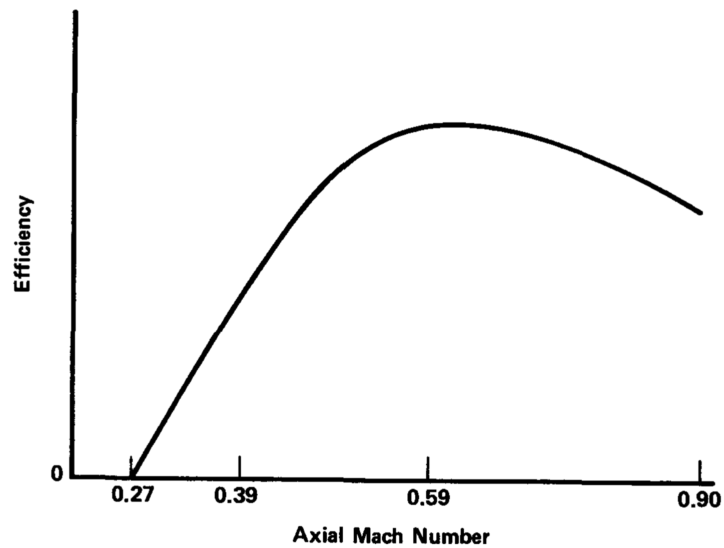


Figure 5-36. Exhaust Stage Efficiency Versus Axial Mach Number[5-64]

The potential for titanium blading for use in attaining an increased efficiency and power in turbines via the ability to increase last-stage-annulus area was discussed during the survey with reference to the Imperial Metal Industries (IMI) experience.[5-11] The IMI-operated turbine (manufactured by Stal Laval of Sweden) was originally a 12-MW radial- (two) axial-flow design with axial section last-stage blades of 8.5 inches (aerofoil length) and last-stage outer blade diameter of about 66 inches. At overhaul, due to severe blade erosion, etc., the last-stage discs were reworked to permit installation of 9.5-inch blades (aerofoil length) of titanium alloy, IMI-680 (Ti-2.25Al-11Sn-4Mo-0.25Si), within the same outer blade diameter (66 inches). Thus, the last-stage annulus area was increased, and the reworked turbine was then capable of peak outputting 13.5 MW, representing a 15 percent increase over the output of the original turbine set. Steam wetness increased from 2 percent in the original machine to 9 percent in the redesigned turbine. Assuming that total steam

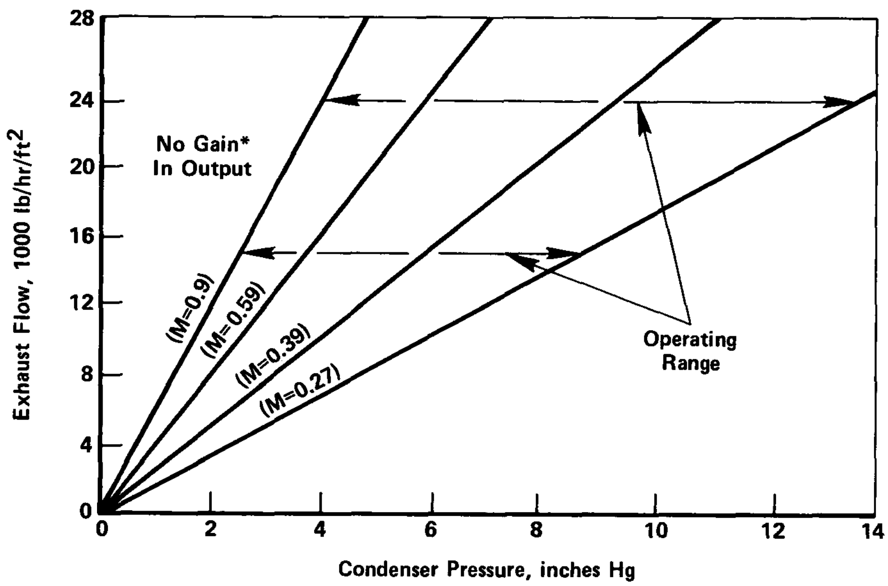


Figure 5-37. Exhaust Stage Operating Range for Various Steam Flows and Condenser Pressures[5-64]

(*Due to "choking" at velocities >0.9 Mach. Last-stage work is zero at $\leq$0.27 Mach.)

flow was not increased, the case is an example of extracting additional power by increasing the exhaust annulus areas. Energy losses were possibly minimized by optimizing last-stage steam loading.

The relationship between energy losses (approximately proportional to steam exit velocity squared) and steam load on last-stage blades was discussed. Steam loading is dependent on such factors as mass flow, condenser pressure, and blade height or total annulus area. Energy losses are high at low-steam loads, then decrease to a minimum with increasing steam load (an optimum load), then again increase with increasing steam load (relate to Figures 5-36 and 5-37). Last stages are usually designed so that steam loading is at a value somewhat higher than at the minimum energy loss point to be amenable to limit-bending stresses on blades and back-pressure limitations. The design is usually optimized on the basis of other factors as well as on the exit-loss factor, so that while the design is close to the exit-loss minimum, it is not quite there. It was suggested that the reason there was improvement in the IMI turbine was that the design was not optimized originally. (Apparently the original design was far above optimum steam loading and exit velocity values.)[5-9] Redesign, by increasing annulus area and optimizing the hub/tip ratio, resulted in reduced last-stage steam loading and therefore decreased steam exit velocity to approach the minimum energy loss.

Smaller turbines than the above described IMI machine also have utilized last-stage titanium blading for improved performance. A Terry Corporation steam turbine of axial flow design and rated at 5400 hp* at 7486 rpm was reworked to substitute a single last row of Ti-6Al-4V alloy blades for the original last two rows of martensitic stainless steel blades.[5-54] The reworked turbine could be safely operated at 7700 rpm (924 ft/s tip speed for the 27.5-inch OD stage), with greater mass flow, to develop 7200 hp. The blade and stage information are given in Table 5-12. It is to be noted that there was no alteration of the shell diameter. Stationary elements (diaphragms and nozzle blocks) were replaced to provide more high-pressure nozzle area. An outside diameter shroud band on the titanium alloy stage was made from unalloyed titanium strip.

Table 5-12

COMPARISON OF DIMENSIONS AND OPERATING DATA FOR A SMALL INDUSTRIAL STEAM TURBINE BEFORE AND AFTER REWORKING[5-54]

Comparative Feature	Original Staging		After Rebuild
Stage number	7	8 (last)	7 (last)
Blade material	Steel	Steel	Ti-6Al-4V
Active blade length, inch	2.250	3.313	3.688
Pitch line diameter, inch(1)	25.438	24.438	23.813
Outside diameter, inch(2)	27.688	27.751	27.501
Shell diameter, inch	29.375	29.375	29.375
Maximum operating load	(5400 hp at 7486 rpm)		(7200 hp at 7700 rpm)

(1) Diameter at midpoint of active blade length.

(2) Diameter at tip of blade, not including 0.063-inch-thick shroud.

The purchasers of large steam turbines for power generation generally consider in detail the trade-off between turbine size, efficiency, reliability, and cost of electricity generated with current fuels for the various options that are

*One horsepower (hp) is approximately 0.77 kilowatt (kw).

possible by last-stage turbine design. In most cases, efficiency improvement could be offered today at higher cost using the numerous available options, by increasing the number of low-pressure exhaust paths and the length of last-row blades. For example, GE offers a large number of options in the last stage: double or four-flow exhaust, or a combination of 2, 4, and 6-flow, and blade lengths of 23, 26, 30, and 33.5 inches. The utilities generally select designs approaching maximum last-stage mass flow loading to keep the machine as simplified as possible and the initial cost to a minimum.

5.7 COST INFORMATION AND COST-BENEFITS[5-9]

One of the reservations toward the extensive use of titanium alloy for steam turbine blading, as put forward by several manufacturers contacted, was the high cost of titanium. The turbine companies suggested several factors which contribute to the higher cost for titanium blading. Major factors are outlined below.

- The higher initial cost of a titanium alloy blade versus a steel blade (this includes higher material cost on a weight basis, which is not so great on a volume basis, and higher fabrication costs, including high forming and machining costs).
- Turbine stage installation costs varying from essentially no cost differential (for cases where shrouds, lacings, or covers were quite simple) to considerably higher cost for titanium blade installation (for example, where titanium weldments were used in shrouding or covers).
- Design engineering costs, where the case for substituting titanium blades having the same configuration as steel blades in existing machines or slightly modified machines is expensive but not as expensive as an engineering program dedicated to a new titanium blade and machine design. (Kobe Steel authors point out that the natural frequency of as-aged Ti-6Al-4V alloy differs from that of 12-chromium steel by only about 2 percent i.e., $F \approx \sqrt{\frac{E}{d}}$, indicating that the straight substitution of titanium blades for steel blades is not far fetched in some respects.)

When these cost factors and others that might pertain to various companies are considered, the difficulty of knowing what the titanium/steel blading cost differential actually might be for any given case is apparent. Not surprisingly, in view of this complex of factors, a range of cost differentials was reported from the companies contacted. The details of which factors were being considered in the estimates were, in general, not given in the responses. Selected cases are cited as follows:

- In one case, where, obviously, only the blade cost differential per se was being described, it was estimated that titanium alloy blades cost about 1.2 to 1.3 times the cost for the same geometry steel blades.
- In another case, small (4 to 5-inch length) Ti-6Al-4V compressor blades for a series production Pratt & Whitney Aircraft Company engine cost 1.4 times the cost of the same blade in Greek Astroloy (AMS 5616). The quantity ordered of each was not given but probably was large.
- Small Ti-6Al-4V steam turbine blades were estimated to cost about 2.2 times the cost of same configuration type 403 steel blades. Production quantities of both blade types were indicated.
- Several of the large steam turbine companies, and one of the manufacturers of smaller turbines, estimated that the titanium/steel blading cost ratio is about 3/1. Which factors were considered in these estimates was not defined. However, a production case was considered.

In order to resolve at least a part of the titanium blade cost question, the survey work included solicitation of blade cost information from TRW, Inc., an experienced manufacturer of blades of many types and in many materials. A hypothetical steam turbine blade design having 31-inch total length and 27-inch active blade length, 3.3-inch blade tip width and 4.8-inch blade base width, a single integrally forged shroud projection in the tapered and twisted blade, and a 4 x 5 x 2.5-inch three-hook, fir-tree root base (straight), was suggested for consideration. It was requested that the cost differential for Ti-6Al-4V/Type 403 steel blades of this configuration be determined based on a production run of 2000 blades for each material.

The TRW people utilized their regular cost estimating procedures and current material, tooling, and labor costs to determine the following. In the case where an erosion shield was joined by brazing to blades of both Ti-6Al-4V and Type 403 steel, the Ti-6Al-4V blade would cost approximately 1.2 to 1.25 times the 403 steel blade. In comparing a Ti-6Al-4V unshielded blade with a Stellite-shielded 403 steel blade, the Ti-6Al-4V blade would cost only about 1.1 to 1.15 more than the steel blade. In all cases considered by TRW, the blades would be supplied to the manufacturer in the finished machined condition.

A specific case for the higher cost of titanium end-blading relative to 12-chromium steel end-blading was discussed informally with BBC of Switzerland.

A total of 480 blades, of 48-inch length, for a 1200-MW machine (three double-flow low-pressure turbine sections) was considered. The cost of a steel blade for this application was given as $750. If Ti-6Al-4V steel blades cost three times as much, total end blading would cost $360,000 in steel and $1,080,000 in titanium. The cost differential at $1,500 per blade would be $720,000. If the cost of the turbine is figured at $50/kw, the overall turbine cost would be $60 million, and end-blading costs would represent the following percentages of total costs:

- Steel blading, 0.6 percent
- Ti-6Al-4V blading, 1.8 percent
- Cost differential, 1.2 percent.

A 1 percent cost differential for the titanium alloy end-blading of a large (unspecified) steam turbine also was estimated by Westinghouse, who utilized the 3 to 1 titanium-to-steel blade cost estimate. Thus, two manufacturers of large turbines agree that, even when using a conservative three-times-steel cost ratio for titanium blades, the increased cost increment for the overall turbine is nominal. Nevertheless, the competition in steam turbines is so great that a 1 percent differential in first cost for a titanium bladed turbine may affect the decision for titanium blading adversely. Thus, considerations of lifetime turbine cost and efficiency become paramount.

The justification for the higher cost of titanium end blading might be associated with either (a) achievement of an end-blade length not possible with steel blading, (b) end-stage power and/or efficiency improvements not possible with steel blading (e.g., some optimized hub/blade-tip ratio design), (c) blade reliability improvements not achieved with steel blades in the experience to date, or (d) the secondary contributions to reliability, such as lowering the tendency for disk cracking. (For example, disk cracking that might result from high-blade loading and the necessity to heat treat disks to high-strength levels when using steel blades. The possibility exists that lower and more reliable disk-strength levels could be employed when utilizing lower weight titanium blades.) While at this point in time it cannot be stated with certainty that titanium alloy blading would afford any improvement in (b), (c), and (d) above, and the need for (a) is questionable, it is possible to discuss the size of an improvement needed in order to justify the higher cost of titanium blading. Consider the following.

The forced outage (FO) data given in Table 1-1 of Section 1 show that in a 10-year period there were 61,152 hours of FO in fossil-fueled turbines of 200 MW and greater due to blade failure directly or due to vibration problems attributable to blade malfunction. If the base is expanded to include fossil-fueled turbines in the 60 to 600-MW range, the total FO in a 10-year period was 90,588 hours. Thus, from 6100 to 9000 FO hours per year were attributable to blade problems in the 1964-1973 period.

Discussions concerning the cost of FO revealed that the outage of single turbines of the 200 MW and larger sizes can cost from $100,000 to $500,000 per day. Typically, the cost of replacement power might average about $2000 per hour for a unit of 200 MW size, $9000 per hour for a 600 MW unit, and $16,000 per hour for a 800 MW unit. There are also the costs of the repair work per se to be considered. For convenience, an average value of $10,000 per hour might be used to represent the cost of electricity purchased during FO. Assuming this cost to be realistic for an average turbine, the total cost per year due to blade related FO (from the 6100 to 9000 hours FO described previously) is $61 to $90 million.

The use of the $10,000 cost per hour value can be used to measure the length of FO time that a more expensive titanium bladed turbine would need to avoid in order to justify the greater expense. If one assumes that titanium blading would serve to eliminate 100 percent of blade FO, the avoidance of only 72 hours of FO over the lifetime of the turbine would equal the initial higher cost of titanium blades in the case of the 1200-MW turbine cited. At a less optimistic end of the scale, where titanium blading might eliminate only 20 percent of blade FO, the avoidance of 360 hours of FO (15 days) over the turbine's life would equal the cost of the titanium investment. However, a single FO for blade repairs may have a duration of 4 to 10 weeks. Thus, avoidance of a single blade related FO would more than pay the differential for higher cost titanium blades in a specific unit.

The difficulty of treating the cost of blade failure on an overall average basis is apparent. Nevertheless, it is equally apparent that a relatively small reduction in FO represents a savings of many dollars. While it was not possible to collect any data that revealed a specific reliability improvement for titanium blading, the cost information cited reveals that only a marginal improvement in reliability, achievable with titanium blading, could cancel higher investment costs over a turbine's lifetime, in all probability. The utility owner may be willing to increase initial investment when it can be shown that such investment decreases the probability that his particular unit will fail.

The cost-benefits accruing to the electric power generating industry, due to the elimination of some portion of the blade FO problem per the use of titanium blading, can be calculated using the FO historical data and previously described assumptions. For example, if by using titanium blading, blade FO could be reduced by 20 percent, $12 to $18 million savings per year might be realized ($61 to $90 million X 0.2). The savings that might accrue as a result of utilizing titanium blading for improved turbine power and efficiency cannot be calculated at this time, but a potential for savings appears possible in this area based on selected experiences surveyed. The general corrosion resistance of titanium, in combination with its additional attractive characteristics determined in tests and in actual turbine performances, suggest that a 20 percent blade reliability improvement -- perhaps even a 50 percent improvement -- is an achievable goal meriting considerable attention and funding. The potential for improved power and efficiency in moderately sized turbines via titanium end blading should be explored. The benefits that might be attainable with longer titanium blades for larger machines are not now apparent.

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Section 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The many objectives of the survey program on the status of titanium blading for steam turbines were met to various degrees and thanks are due to cooperating manufacturers. The information provided by turbine manufacturers and other interested companies resulted in the following conclusions.

(1) Many of the steam turbine companies included in the survey are taking an active role in promoting titanium blading by (a) exploring metal characteristics in developmental and/or operational blade test programs and (b) exploiting titanium in production turbines. Activity exists on a worldwide basis.

(2) Titanium is commonly used in blade-related applications such as tie wires and covers and in other nonblade-related uses, e.g., heat exchangers.

(3) Titanium materials are used or are being examined for use in small-, medium-, and large-sized turbines.

(4) Titanium blades are an established production item in small turbines and in selected blading applications for medium-sized turbines.

(5) Very long titanium blades for very large turbines are in the developmental test stage only, and only in the Soviet Union and Switzerland.

(6) Small current demand for very large turbines obviates the immediate interest in very long titanium blades by many companies.

(7) Intermediate-sized titanium blading is being examined in medium-sized turbines in operational tests by several companies. Test conditions are relatively undemanding, (e.g., with regard to erosion).

(8) The titanium characteristics, such as low damping capacity, thought to be marginal for providing a trouble-free performance in demanding-blade applications by some manufacturers, have not proven to be a source of problems in operational test or in commercial operation.

(9) In side-by-side operations and operational test comparisons, titanium blading is not inferior in performance to 12-chromium steel blading generally, and is superior to 12-chromium steel in erosion, erosion-corrosion, and corrosion resistance in specific cases.

(10) As a result of blade and machine design, operating conditions, metal characteristics, or a combination of these factors, commercial and operational-test titanium blades are highly rated in erosion resistance, corrosion resistance, and specific strength, and are not deficient, based on the performance record, in toughness, fatigue strength, stiffness, damping, and other physical characteristics.

(11) Titanium alloy characteristics applicable to and required by blading can be optimized through microstructural control.

(12) The good performance of titanium blading in small-to-medium-sized turbines is not necessarily applicable to performance in large turbines. Threshold conditions for inadequate titanium blade performance are largely unknown.

(13) The high specific strength of titanium alloys permits machine designs of increased power in small machines.

(14) Increasing the power and efficiency of select-sized turbines through optimization of end-stages, wherein longer titanium blading could be used to optimize annulus area and hub/tip ratio, is a potential benefit worthy of investigation for areas where cooling water adequacy is not a limitation.

(15) The cost for titanium blades per se is only 10 to 15 percent greater than the cost of steel blades, while total costs for substituting titanium blading for steel blading in existing machines or for introducing titanium blading in a new design have been estimated to be three times the cost for using steel blading.

(16) The cost of incorporating titanium end blading in a large turbine, on the order of 1 percent of turbine costs, equates monetarily with avoidance of a rather short period of forced outage time assuming only a 20 percent effectiveness in reducing forced outage via the use of titanium blading.

(17) Widely applied titanium turbine blading at a relatively small but undetermined cost has the potential of affording the electric power generating industry large savings, estimated at several million dollars per year, through reduction in forced outages.

(18) Information and data available through survey efforts to indicate cost-benefits to the industry and to individual producers through the use of titanium blading are inadequate to determine precisely either costs or benefits at this point in time.

(19) The titanium blading in steam turbine experience appears sufficiently successful to merit additional study.

6.2 RECOMMENDATIONS

The widespread testing and the somewhat restricted commercial use of titanium for blading and other uses in steam turbines leads to a number of conclusions as outlined previously. The conclusions reveal the knowledge gaps relating to titanium turbine applications, which in turn suggest areas for recommended activities. The general recommendation, in view of the overall encouraging record for titanium in turbines, is to initiate investigations to develop information that apparently does not exist, but which is needed if it is to be decided whether or not titanium is a viable turbine material and under which conditions. The specific areas for recommended action are listed.

(1) Determine the threshold and limiting conditions for the erosion of titanium alloys over a range of operating turbine variables. The erosion resistance of titanium under the variables of blade material (composition, structure, and properties), time and temperature, and reactant characteristics (steam wetness quantitatively and the water droplet characteristics of size, shape, velocity, and attack angle), should be determined.

(2) Determine the most acceptable solution to the problem of shielding titanium blades for conditions where the intrinsic erosion resistance is not sufficient. The program should include joining studies between titanium and erosion-resistant materials such as Stellite, the weld overlay of hard materials approach such as with titanium alloy on titanium alloy, thick coatings, and metallurgical, mechanical, and operational characterization studies.

(3) Determine the corrosion resistance of titanium in a variety of reactants and conditions prevailing in steam turbines. The EPRI-funded research program on corrosion-fatigue will define probable reactant species through investigation of steam chemistry. A program effort in this area should include the corrosion characterization of joints between titanium and shielding (e.g., Stellite by brazing) and of titanium-steel couples.

(4) Determine the operational limitations of titanium blading relative to the low modulus and low damping capacities as well as to the fatigue strength characteristics of selected materials. A standard material in a common condition, e.g., annealed Ti-6Al-4V alloy, should be compared with another material or another condition, e.g., IMI-680 alloy or Ti-6Al-4V alloy with optimized microstructure. Blade design iterations should be incorporated in a test program which utilizes equipment capable of exploring the full spectrum of blade loading as might exist in an operating turbine. A test turbine program is visualized.

(5) Determine the possibilities of optimizing turbine end-stage dimensions for improvement in power and efficiency via a design study program. The effects of enlarging the annulus area and optimizing the hub/tip ratio by utilizing titanium blades having dimensions beyond those possible with steel blades, e.g., due to rotor strength or dimension limits, should be determined in conjunction with the variables of steam loading and back pressure. An analytical

study is visualized initially with the possibility of a follow-on program wherein an operating turbine modification phase might be implemented.

(6) Encourage the expanded operational testing of titanium blades having the same design as steel blades in operating turbines with blade problems to determine the possibilities of blade reliability improvements and to increase operational experience generally. Design data would not be obtained from such experiences but conditions unsuitable for titanium blading might be identified. Further, considerable cost-benefit information could be obtained from participating power producers.

While there is no firm priority suggested for the recommendations, it would appear appropriate to concentrate initially on programs which might delineate the potential for near-term benefits in small-to-medium-sized machines. Development of the data base necessary for the utilization of titanium in very large machines would appear to be of lesser importance during this time of low demand for very large machines. However, all of the research needs doing and has the potential of a substantial payoff.

APPENDIX A

MICROSTRUCTURE CONTROL AND THE EFFECT OF MICROSTRUCTURE ON THE PROPERTIES OF Ti-6Al-4V

by

J. C. Williams

Appendix A

MICROSTRUCTURE CONTROL AND THE EFFECT OF MICROSTRUCTURE ON THE PROPERTIES OF Ti-6Al-4V

A.1 INTRODUCTION

Titanium alloys are frequently classified according to their equilibrium constitution. Ti-6Al-4V is an $\alpha+\beta$ alloy because, under equilibrium conditions, it consists of $\sim$ 85 v/o α-phase and $\sim$ 15 v/o β-phase. The microstructure of $\alpha+\beta$ Ti alloys is generally described in terms of the morphology of the coarse α-phase (called the primary α) and, additionally, in terms of other microstructural constituents which might be present in the matrix which contains the primary α-phase. For example, one microstructural condition might be described as equiaxed primary α in an α' martensite matrix.

The properties of Ti-6Al-4V are strongly dependent on microstructure; in many cases the strength depends largely on the nature and distribution of the matrix phases, whereas the fracture-related properties depend to a significant extent on the morphology and distribution of the primary α. Thus, the fracture behavior can be varied independently of strength.[A-1] The morphology and distribution of primary α largely depend on the processing history, while the character of the matrix is usually controlled by postprocessing heat treatment. Thus, both processing and heat treatment have an important effect on the performance of Ti-6Al-4V and other $\alpha+\beta$ Ti alloys. There is an additional factor which has an important effect in $\alpha+\beta$ Ti alloys because the α-phase is hexagonal and therefore is anisotropic. This factor is preferred orientation or texture as it is more commonly called. Texture is developed as a result of hot working and thus is also dependent on processing history.

In the subsequent sections, the effect of processing and heat treatment on microstructure will be summarized, then the effect of microstructure and texture on properties, especially fatigue strength will be described.

A.2 MICROSTRUCTURE CONTROL IN Ti-6Al-4V

The primary α-phase morphology is usually classified as acicular or equiaxed. These morphologies are controlled during elevated temperature forging or rolling by the processing temperature (relative to the β-transus), by the extent of reduction given the material during working, and by the cooling rate after the working operation. These factors have been described elsewhere.[A-1,A-2] and will be only briefly summarized here.

Acicular α-phase morphologies result from working Ti-6Al-4V in the β-phase field or from reheating into the β-phase field after working. The details of the acicular morphology depend on cooling rate. Air cooling after working results in the nucleation and growth decomposition of the β-phase to form a Widmanstatten α+β structure. This structure is also often called a β-annealed microstructure. Water quenching after working results in a martensitic transformation of the β-phase to the hexagonal α' martensite. This structure is also often called a β-quenched microstructure. The α' has an acicular morphology with the average plate size being smaller than the Widmanstatten α by a factor of two or three.

Working Ti-6Al-4V in the two-phase α+β-phase field results in a reduction in the length:width ratio of the primary α and, if sufficient working is accomplished, leads to an equiaxed α-phase morphology with β-phase at grain boundary triple points. The relation between amount of work and α-phase morphology is imprecise and also depends on strain rate and working temperature. However, a practical upper limit to strain rate is imposed by the adiabatic heating which accompanies rapid straining. In general, for working operations performed at ∿ 100 F below the β-transus, about 50 percent reduction is required to achieve completely equiaxed structures. Thus, in the forging of thin sections, attainment of equiaxed microstructures may be difficult because the "dead zone" adjacent to the dies may represent a significant fraction of the total section thickness and this zone may never receive the equivalent of a 50 percent reduction.

In plate rolling, it is common mill practice to continue the warm working of Ti-6Al-4V plate down to temperatures in the 1600 F range followed by annealing at 1300-1500 F for a short time in order to achieve an equiaxed grain structure. It has only been recently recognized that the equiaxed structure results from subsequent recovery and/or recrystallization of the α-phase during annealing. Recent studies of recrystallization behavior of Ti-6Al-4V have shown that material worked down to 1600 F and annealed at 1350 F is incompletely recrystallized. These studies have also shown that a postworking annealing treatment of 1700 F for at least 4 hours is required to fully recrystallize the α-phase. Thus, earlier material purchased in the mill annealed condition described in specification MIL-T-9046 was generally in an unrecrystallized or incompletely recrystallized condition, since that specification only required annealing at 1300 F for the order of minutes.

There are other important microstructural features which affect the properties of Ti alloys, but which cannot be seen in the light microscope. Of these, the most important one in Ti-6Al-4V is the formation of the ordered α_2-phase.[4-3] This phase forms as a uniform distribution of small, coherent precipitates and its presence results in concentrated slip in localized bands.[A-4] Such slip behavior has associated with it lower ductility and toughness and severe degradation of stress corrosion resistance.[A-5] The lower composition limit for α_2 formation is not presently well defined, but is in the 5.5-6.5 w/o Al range. Recent studies[A-6,A-7] have shown that oxygen content has a significant effect on the formation of α_2 and that higher oxygen content promotes α_2 formation. Thus, both the Al and oxygen content of the particular heat of material have an effect on the propensity for α_2 formation and combined Al contents approaching 6.5 w/o and oxygen contents approaching 0.2 w/o as permitted in MIL-T-9046 can lead to α_2 formation.

A.3 EFFECT OF MICROSTRUCTURE ON FRACTURE-RELATED PROPERTIES

In Ti-6Al-4V, the effect of microstructure on the fracture-related properties of fatigue strength, fracture toughness (K_{IC}), fatigue crack propagation (FCP) rate and stress corrosion cracking (SCC) resistance is very pronounced. Unfortunately, the data are not as complete as might be desired in many instances, and one is forced, at the moment, to identify trends rather than well-established correlations. These trends do indicate that not all of the aforementioned properties are optimum in the same microstructure. Thus, the pacing properties for a particular application should be identified and the optimum microstructure selected accordingly. In last-stage steam turbine blades, there is general agreement that fatigue strength and stress corrosion fatigue are the pacing properties. Thus, the remainder of the discussion will focus on the effect of microstructure on fatigue.

The effect of microstructure on the smooth bar fatigue strength of Ti-6Al-4V has been the object of study by Lucas.[A-8] by Stubbington and Bower,[A-9] and by Sparks and Long.[A-10] The former two investigations have concluded that Widmanstatten $\alpha+\beta$ microstructures have inferior high cycle fatigue* (HCF) strengths compared with equiaxed $\alpha+\beta$ microstructures. Even when the lower tensile strength associated with the Widmanstatten $\alpha+\beta$ microstructures are considered, the fatigue ratio (defined as fatigue strength/tensile strength) is lower for the Widmanstatten $\alpha+\beta$ microstructures. The origin of this effect has been investigated by Stubbington and Bower[A-9] who have shown that the Stage I fatigue cracks are initiated at α/β interfaces. Thus, Widmanstatten $\alpha+\beta$ microstructures might be expected to exhibit poor fatigue resistance due to the large α/β interfacial area. These authors also suggested that slip length in the α-phase was important. The Widmanstatten microstructure would be undesirable on this count, also because the Widmanstatten packets are the effective slip length. To examine the effect of slip length, they produced some material with equiaxed 10 μm diameter α grains.[A-9] This material was found to have a HCF strength which was 50 percent greater than that of the Widmanstatten $\alpha+\beta$ material. Moreover, this fine-grained material had a HCF strength which was $\sim$ 15 percent better than the best commercially produced equiaxed microstructure material tested in an earlier investigation.[A-11] On the other hand, Sparks' and Long's[A-10] data obtained from well-worked forgings with relatively small Widmanstatten packets show that both equiaxed and acicular microstructures have similar fatigue strengths. Thus, the variability in HCF strength with microstructure appears to be significantly influenced by the uniformity of working and the resultant microstructural refinement.

In a separate investigation, Lucas[A-8] showed that β-quenched material had decidely superior HCF strength compared with material with β-annealed or equiaxed microstructures. Although Lucas offered no explanation for this effect, some speculation will be included here. The β-quenched material has a small α' plate size which also has a small slip length. In view of Stubbington and Bowen's[A-9] results cited above, it is suggested that the martensitic $\beta \rightarrow \alpha'$ transformation may provide an in-situ means of refining the grain size (slip length). A similar effect of slip length refinement has been noted in connection with the data of Sparks and Long.[A-10]

*The term "high cycle fatigue strength" as used here means the stress amplitude indicated on S/N curve at 10^7 cycles.

Direct comparison of fatigue strengths determined by different workers is difficult because of the strong influence of surface finish, specimen alignment, and differences in detailed test methods on the measured fatigue strength. Thus, direct comparison of the HCF strength of Lucas' β-quenched material and Stubbington and Bowen's fine-grained, equiaxed material and the other results cited above must be approached cautiously.

Still another investigation by Eylon and Pierce showed that the notched (K_t=3.5) fatigue behavior of Ti-6Al-4V is better in acicular microstructures than in equiaxed ones.[A-12] Similar results also have been reported by Sparks and Long.[A-10] These data appear to conflict with the smooth bar results cited earlier. In this regard, it should be recalled that early Stage I crack initiation was the primary factor responsible for limiting the smooth bar HCF strength of β-annealed Ti-6Al-4V. In notched bars, the extent of stage I crack growth is generally much more limited. Further, crack initiation occurs at a much earlier stage in the specimen life. These factors tend to suggest that notched fatigue behavior is more sensitive to crack growth than to crack initiation. As will be discussed below, the superior notched fatigue behavior of β-annealed microstructures can be accounted for on this basis.

The low cycle fatigue (LCF) strength* of Ti-6Al-4V is an important consideration in the anticipated life of gas turbine components, especially fan and compressor disks. Accordingly, the effect of microstructure on LCF behavior has been empirically characterized but not systematically investigated. As in other structural materials, the LCF life of Ti-6Al-4V correlates with tensile ductility (percent reduction in area). Thus, the low tensile ductility of β-quenched or β-annealed materials makes them unattractive for LCF-limited applications. Lucas' data confirms this point.[A-8] Bowen and Stubbington have also examined the effect of α+β working on LCF behavior and have reported improvements in LCF strength in material consisting of 40-60 v/o, fine-grained, equiaxed primary α and a fine Widmanstatten α+β transformed β structure. (Bowen and Stubbington describe the transformed β as α' martensite, but examination of their micrographs show that the structure was formed by nucleation and growth.)

Other workers have also concluded that equiaxed primary α is beneficial to LCF life[A-13] as might be expected on the basis of the tensile ductility/LCF life

*Fatigue strength corresponding to a 10^3 cycle life correlation mentioned earlier. Typical current practice in the gas turbine industry is to use a lower volume fraction equiaxed primary α ($\sim$ 30 v/o) in a tempered α' matrix in order to achieve the higher tensile strengths required to avoid burst limitations at maximum speed. No attempt has been made to analyze the variations in LCF strength as a function of strength/ductility and primary α grain size. A study in which these parameters were independently varied would be useful in defining the trade-off between strength and LCF strength. Since slip length appears to be important in fatigue crack initiation, processing methods which lead to smaller primary α grain sizes should be beneficial to both LCF and HCF strengths.

The previous discussion has addressed the role of microstructure in fatigue crack initiation without any mention of its subsequent effect on fatigue crack propagation (FCP) rate.* Several recent papers have shown that microstructure can also affect FCP rate in Ti-6Al-4V. Since smooth bar fatigue life is a composite parameter which reflects both the initiation of a fatigue crack and its propagation to failure, the role of microstructure on FCP rate must also be considered. It has been shown that, at FCP rates in the 10^{-6} mm/cycle range, FCP rates can vary by at least an order of magnitude.[A-1,A-14,A-15] Lower FCP rates are observed in acicular microstructures with the slowest rate corresponding to the β-quenched microstructure. The fastest FCP rate was observed in mill-annealed material typical of that described earlier. The reasons for reduced FCP rate in acicular microstructures are not completely clear, but electron fractography has shown that a much higher density of secondary cracks is associated with these microstructures than with equiaxed structures.[A-1] In view of this, it has been suggested that α/β interfaces and α' boundaries lead to this secondary cracking and cause temporary local crack arrest with a lower resultant average crack growth rate.

In long-life components, such as steam turbines, the threshold stress intensity, ΔK_{th}, below which no crack growth occurs is of primary interest. Determination of this parameter requires FCP tests to be run at FCP rates less than 10^{-8} mm/cycle. These tests are very expensive and, consequently, no systematic program has been conducted at these FCP rates. As a result, no reliable information presently is available regarding the effect of microstructure on FCP rate in the range of ΔK_{th}.

*FCP rate as used here refers to the rate of Stage II crack growth.

The entire question of FCP at such low rates as described above also is clouded by the possibility that, at such low stress intensities, FCP may occur by Stage I crack growth rather than by Stage II crack growth. Such a distinction is usually not made, but recent work has shown that the fractographic appearance of the fracture surface in regions corresponding to very low crack growth rates is more characteristic of Stage I than of Stage II.[A-16] Thus, if the definition of FCP rate is broadened to include both Stage I and Stage II crack growth, then the fraction of total fatigue life which is encompassed by both stages becomes significant. This is verified by the work of Thompson and Backofen[A-17] which shows that Stage I crack growth occurs after an early fraction of fatigue life. In this regard, a study of microstructure effects on Stage I crack growth would contribute significantly to a better understanding of this point and may be important to the life of steam turbine components which operate in the HCF regime. It is believed that a significant fraction of HCF life corresponds to crack growth as opposed to crack initiation when the crack growth occurring during both Stages I and II is considered. In this connection, it is suggested here that the improvement in HCF strength reported in β-quenched structures[A-8] is due at least in part to a reduction in FCP rate.

A.4 THE EFFECT OF TEXTURE ON FATIGUE BEHAVIOR OF Ti-6Al-4V

Texture has several important effects on the fatigue behavior of Ti-6Al-4V. Firstly, the extent of texture is usually more severe in equiaxed than in acicular microstructures. Thus, valid comparisons of the effect of microstructure on fatigue must be conducted under circumstances of constant texture. Secondly, the presence of texture causes significant directionality in yield stress, Young's modulus and Poisson's ratio.[A-18,A-19] Such variations also complicate comparison of properties in various microstructures because of simultaneous variations in extent of texture. Lastly, texture appears to have intrinsic effects on fatigue strength and fatigue crack growth rate; samples with a high density of basal poles oriented parallel to the loading axis have a lower fatigue strength compared with samples oriented with the basal poles normal to the loading axis.[A-18] Similarly, fatigue crack growth samples oriented with a high density of basal poles parallel to the crack growth direction show an increased FCP rate compared with samples of other orientations. [A-19,A-20] Bowen has analyzed the directionality of FCP rate in texture sheet in terms of the number and type of deformation modes available to accommodate the localized deformation which accompanies crack extension.[A-20] He has also been able to account for the observed variations in fracture topography. The reader is referred to his original article for details.

The current state-of-the-art practice in forging or hot rolling does not incorporate texture control. Therefore, the foregoing remarks are intended to emphasize that the texture is a potential unrecognized variable in studies of the effect of microstructure on properties. Accordingly, conclusions regarding microstructural effects should be examined with respect to texture effects as well. Finally, the products with controlled microstructure and texture intensity and orientation have the potential for improved fatigue life. Implementation of such products may represent the next incremental improvement in Ti-6Al-4V performance.

A.5 CONCLUSIONS

(1) Refinement of slip length appears to be beneficial to fatigue life. This can be accomplished by extensive $\alpha+\beta$ working and recrystallization, by quenching from above the β-transus to form α' martensite, or by β working and rapid cooling to form small Widmanstatten $\alpha+\beta$ packets.

(2) The variation in notched and smooth HCF strength of Widmanstatten microstructure material may be related to slower FCP rates in notched bars and earlier Stage I initiation in smooth bars.

(3) Texture affects both HCF strength and FCP rate.

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