**ELECTRON BEAM WELD REPAIR AND QUALIFICATION
OF TITANIUM GAS TURBINE ENGINE FAN BLADES**

by

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B.A.Sc.Eng.

A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfilment
of the requirements for the degree of

Master of Engineering

**The Ottawa-Carleton Institute for Mechanical and Aerospace Engineering
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**ELECTRON BEAM WELD REPAIR AND QUALIFICATION OF TITANIUM
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submitted by Pierre Azar, B.A.Sc.Eng.
in partial fulfilment of the requirements for
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Thesis Supervisor

Chair, Department of Mechanical and Aerospace Engineering

Carleton University

January 15, 1996

ABSTRACT

The concept of repair and rejuvenation of service exposed gas turbine engine components is now widely accepted by most commercial aero engine users. The predominant mode of damage to gas turbine engine fan blades is foreign object damage (FOD). FOD is primarily caused by the ingestion of birds, rocks and ice during service, particularly during takeoff and landing. Impact of these objects can cause a twist in the blade airfoil which can deflect the leading edge into the inlet guide vanes.

The objective of this project is to refurbish severely foreign object damaged Ti-6Al-4V fan blades to a near new condition by an electron beam welding process. The repair process involves the removal of the damaged portion of the airfoil using an abrasive water jet cut method followed by electron beam welding of a pre-formed titanium patch. Non-destructive (visual, fluorescent penetrant and X-Ray) and metallurgical (destructive) inspections were carried out to verify the weld quality with respect to porosity, cracks, lack of fusion and microstructural texture. A coordinate measuring machine was used to establish an average data file for the original fan blade geometry taken from six new (baseline) fan blades. A numerical-control computer aided manufacturing process was used to restore the original geometry of the fan blade during machining. A number of bench tests were carried out prior to the part acceptance for spin pit and/or engine test, including: surface residual stress, surface hardness, natural frequency (FEM model and actual), vibration and ballistic impact.

The electron beam process yields acceptable welds within the aerospace industry standard limits. The repair cost is 65% of the new part replacement cost and provides 100% reduction in the current FOD rejection rate for the engine and fleet examined. Based on the results attained in this study, the electron beam weld repair scheme presented was deemed viable for the repair of foreign object damaged titanium gas turbine engine fan blades.

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NOMENCLATURE

α	Non-Dimensional coefficient for multi-mass systems.
α_1	Air incidence angle at compressor rotor entry.
β_1	Air deflection angle at compressor rotor exit.
ΔT	Change in Kinetic Energy.
θ	X-ray beam diffraction angle.
λ	Wavelength.
ν	Poisson's ratio.
ρ	Density.
σ	Stress.
σ_L	Fatigue endurance limit stress.
σ -N	Curve representing the number of cycles to failure as a function of the level of alternating stress.
σ_a	Stress amplitude.
σ_{am}	Fatigue strength for zero mean stress.
σ_{ct}	Centrifugal tensile stress.
$(\sigma_{ct})_{max}$	Maximum centrifugal tensile stress.
σ_{gb}	Gas bending stress.
$(\sigma_{gb})_{max}$	Maximum gas bending stress.
σ_m	Mean stress.
σ_r	Blade root stress.
σ_u	Ultimate strength.
σ_{ys}	Yield strength.
ψ	X-ray beam tilt angle.
ω	Angular velocity.
ω_n	Natural frequency.
a	Acceleration.
a	Amplitude.
a_r	Cross-section area at blade root.
a_x	Cross-section area.
A	Annulus area.
A_{ipp}	Trailing edge tip peak to peak displacements.
AECL	Atomic Energy of Canada Limited.
af	Amplitude-Frequency.
AMS#	Aerospace Material Specification.
AMS	American Materials Society.

NOMENCLATURE (Continued)

ASTM	American Society for Testing and Materials.
AWJC	Abrasive Water Jet Cutting.
AWM	Airworthiness Manual (Transport Canada Publication).
b	Hub-tip ratio.
bcc	Body-centre cubic.
BF	Back face of blade airfoil.
c	Blade airfoil chord.
C.G.	Blade centre of gravity.
C_1	Air velocity.
C_1	Aircraft velocity.
CAD	Computer Aided Design.
CAM	Computer Aided Manufacturing.
CANMET	Canada Centre for Mineral and Energy Technology.
CBA	Cost Benefit Analysis.
CCV	Concave.
CCVX	Centre convex.
CF	Canadian Forces.
CMM	Coordinate Measuring Machine.
CNC	Computer Numerical Control.
CVX	Convex.
C_{wl}	Air whirl velocity at compressor rotor.
d	Atomic spacing in samples (x-ray).
d_x	Cross-section ratio of hub-tip ratio.
d_ψ	Lattice spacing at a tilt angle ψ (x-ray)
DAG	Molybdenum-Disulphide solid film lubricant (GE specification).
DND	Department of National Defence (Canada).
dv	Volume element.
DVT	Dovetail.
E	Young's Modulus of elasticity.
EB	Electron beam.
EDM	Electron Discharge Machine.
f	Natural frequency.
F	Inertia force on blade element.
FAA	Federal Aviation Administration (US).

NOMENCLATURE (Continued)

FAR	Federal Aviation Regulations (US).
FEA	Finite Element Analysis.
F_{ele}	Element force (FEM).
FEM	Finite Element Method.
FEM	Finite Element Model.
FOD	Foreign Object Damage.
g	Gravitational force.
G	Linear impulse momentum.
G_c	Critical Crack extension force
GE	The General Electric company.
h	Strip of blade height.
HAZ	Heat Affected Zone.
HCF	High Cycle Fatigue.
hcp	Hexagonal close-packed.
Hz	Hertz (cycle/second)
I	Moment of inertia of cross-sectional area.
IAR	Institute of Aerospace Research (NRCC).
IGES	International Graphic Exchange System.
K	A constant expressing the relationship of stress at point of failure to trailing edge deflection.
K.E.	Kinetic energy.
K_c	G_c value corrected for modulus.
l	Length (beam).
LCF	Low Cycle Fatigue.
LE	Leading edge.
m	Mass.
MIG	Hot wire metal inert gas.
MSI	Military Support Instructions.
MTC	Manufacturing Technology Centre (NRCC).
n_{xr}	X-ray beam order of reflection.
n_i	Actual stress cycles applied at stress level.
n	Number of blades in one compressor stage.
N	Rotational speed.
N_f	Number of cycles to failure (HCF test).

NOMENCLATURE (Continued)

N_f	Cycles to failure at one applied stress only (HCF).
NDI	Non-Destructive Inspection.
NISA	Numerically Integrated elements for System Analysis.
NRCC	National Research Council of Canada.
OEM	Original Equipments Manufacturer.
P.E.	Potential energy.
r	Radius.
RA	Reduction of area.
R_c	Rockwell hardness.
r_r	Blade root radius.
r_t	Blade tip radius.
r_t/r_r	Blade hub-tip ratio.
S_a	Single amplitude stress at maximum computed stress location (psi).
S_b	Bullet finite movement distance.
SML	Structures and Materials Laboratory.
ST	Solution Treat.
STA	Solution Treat and Age.
T	Kinetic Energy.
TCA	Transport Canada Aviation.
TE	Trailing edge.
TIG	Tungsten Inert Gas.
U	Blade speed.
U_t	Blade tip speed.
U_w	Work.
US	United States of America.
UTS	Ultimate Tensile Strength.
V_i	Air velocity relative to blade rotor speed U.
V_b	Bullet velocity relative to blade rotor speed U.
W	Weight (beam).
Y	Yield stress.
z	Smallest value of blade root section modulus.

Chapter 1

Introduction

New materials and high-technology production methods are the key to higher performance and longer life of the lighter, modern gas turbine engines. Titanium is used in the compressor section of aircraft engines because of its low density, high specific strength, and corrosion resistance, however, after thousands of operating hours it can accumulate damage. Various types of damage have been observed on service exposed titanium rotor fan blades, including: high strain low cycle fatigue (LCF), foreign object damage (FOD), wear and fretting. FOD is the predominant mode of damage for rotor fan blades which leads to their removal from service with considerable low cycle fatigue life remaining [1].

FOD is primarily caused in service by the ingestion of birds, rocks and ice, particularly during take-off and landing. The impact of these objects can cause a twist in the blade airfoil which can deflect the leading edge into the inlet guide vanes. Performance losses (e.g., 2% Thrust Specific Fuel Consumption loss) created by leading edge cutback due to FOD can also represent a significant economic factor [2].

Repairs of foreign object damaged (FOD'ed) rotor fan blades have been carried out at many commercial airline overhaul facilities and at the blade manufacturers. For instance, the repair work at Union Carbide's Coatings service plants at N. Kansas City, Missouri and Hayward, California covers first and second stage compressor fan blades on both the Pratt and Whitney JT3D-7 engine (used on the Boeing 707) and JT8D-1 to -17 engines (used on the Douglas DC-9, the Boeing 727 and Boeing 737). It also covers fan rotor blades on the JT9D engine (used on the Boeing 747) [2]. Similarly, since 1973

the Lufthansa repair shop in Hamburg, Germany, estimates it saves ten million Deutsche marks (DM) each year just on the repair of 700 FOD'ed fan blades from the General Electric CF6-50 engine (used on the Airbus) [3]. Electron beam welding is being used by Chern-tronics which has reduced its reject rate by nearly 62% and production cost by 50% in rebuilding thousands of titanium jet engine blades each month at its El Cajon, California plant [4]. Electron beam welding is also being prescribed by the engine manufacturers as the mandatory "**welding tool**" for these repairs [19,22].

1.1 Background

Titanium rotor fan blades being retired from military aircraft gas turbine engines also suffer similar types of damage to those observed on commercial engine fan blades (Fig. 1.1). However, for the higher performance military engines requiring higher thrust and aggressive flight missions, the rotor blades normally have complex geometries (e.g., airfoil thickness and twist angle) which make the repair of such components very challenging. **Orenda**, an aerospace division of **Hawker Siddeley Canada Inc.**, has initiated a program under contract from the Department of National Defense (DND) to establish cost effective repair techniques of service exposed gas turbine components in terms of overall life cycle management. The overall program objectives were:

- Select and develop repair processes;
- Verify the repair procedures by component and engine test qualification;
- Transform the repair processes into manufacturing technology; and
- Assess repair costs throughout the program to ensure cost effectiveness when related to new part replacement cost.

This thesis forms a part of an on going repair development and qualification program for different components of gas turbine engines used in the Canadian Forces (CF) fleet. The repair development covers a wide range of engine components extending from the cold section through the hot section and into the exhaust section. There are no established Original Engine Manufacturer (OEM)-qualified repairs for the components being considered, in particular, for repair of FOD'ed fan blades made of high strength Ti-6Al-4V (AMS 4920A). Therefore, the development and qualification of electron beam weld (EB-Weld) repair techniques for FOD'ed fan blades is important to DND with respect to new part replacement cost. A comprehensive and cost effective EB-Weld repair scheme was established for FOD'ed first stage titanium rotor fan blade under the objectives of this thesis. The repair process is shown in Figure 1.2 and the procedures are summarized in Table 1.1 and are described in greater detail in Chapter 3.

1.2 Objectives

The two main objectives of this thesis are:

- 1) To develop a cost effective electron beam weld repair process for severely FOD'ed first stage titanium rotor fan blades used in gas turbine engines.
- 2) To verify the repair procedures by component test qualification. The qualification tests include: surface residual stress measurement, surface hardness measurement, natural frequency, vibration and ballistic impact.

Chapter 2

Literature Review

2.1 Ti-6Al-4V

Titanium and its alloys are classified into three categories depending on the microstructural phases present: 1) alpha, α , a hexagonal close-packed structure (hcp); 2) beta, β , a body-centre cubic structure (bcc); and 3) alpha-beta [38]. Ti-6Al-4V is an alpha-beta alloy with total alloy content controlled to produce an attractive annealed strength. It can be heat treated to yield a material having mechanical properties in the range of many high-strength steels. It has good stress rupture properties at temperatures up to 800°F (427°C) and can be formed or welded by conventional procedures [38]. The fatigue properties are good and the crack propagation characteristics are acceptable [38]. Its inherent toughness can be enhanced by altering interstitial content. It suffers no degradation of fatigue properties or corrosion in salt water. Ti-6Al-4V is stable at temperatures ranging from -423° to +1000°F (-252° to 538°C) [39]. The Ti-6Al-4V alloy gained initial acceptance, and then larger scale use in the compressor sections of jet engines. Material in the annealed condition, used primarily as wheels and blades produced as closed-die forging, has seen service temperatures up to 750°F (399°C)[38]. The complete OEM material specification of 6Al-4V Titanium base alloy for forged compressor blades and vanes are found in Reference 45 and 46.

2.1.1 Physical Metallurgy of Ti-6Al-4V

A great wealth of data exists on the metallurgy of Ti-6Al-4V and therefore only a general review relevant to the scope of the thesis will be presented here. The 6 percent

aluminum addition stabilises the alpha phase, resulting in an increase in the $\alpha + \beta \rightarrow \beta$ transformation temperature ($1820^{\circ} \pm 50^{\circ}\text{F}$) ($993^{\circ} \pm 10^{\circ}\text{C}$) [38]. It also increases the elevated temperature strength level [38]. The 4 percent **vanadium** content increases the strength level by two mechanisms: first by substitutional solid solution hardening, and second, more importantly, by stabilizing the beta or elevated temperature phase, thereby making the β to α hardening reaction possible through heat treatment [38]. The addition of vanadium improves hot workability by causing more of the ductile beta phase to be present at hot working temperatures [38]. The percent by weight of the alloy's metallic additions has given rise to its designation, Ti-6Al-4V [39]. The complete composition of the alloy required by OEM for the first stage titanium rotor fan blades is presented in Table 2.1 [39,45,46].

Some additional flexibility in properties is obtained by variations in the interstitial elements (stabilizers) within the limitations of the chemistry specification. The alpha phase stabilizers or interstitial elements include aluminum, oxygen, carbon, and nitrogen. Beta stabilizers are typical metals such as copper, chromium, molybdenum, iron, tin, and vanadium. Small changes in the oxygen level will cause changes in the beta transus temperature [39]. This is important in considering forging and heat treating temperatures, both of which are dependent on the beta transus. The Ti-6Al-4V alloy, like all titanium grades, is double melted by consumable electrode techniques to guarantee control of its metallic and interstitial additions. Both primary and secondary melting are completed under vacuum to minimize potential contamination by oxygen, nitrogen and hydrogen. A clean ingot with a high degree of homogeneity are the absolute requirements in the strict aircraft standards for producing mill shapes [39,47,48].

2.1.2 Thermal Treatments of Ti-6Al-4V

Titanium and titanium alloys may be heat treated for the following purposes:

- a) To reduce residual stresses developed during fabrication (stress relieving);
- b) To produce an optimum combination of ductility, machinability, and dimensional and structural stability (annealing);
- c) To increase strength (solution treatment and aging); and
- d) To optimize special properties such as fracture toughness, fatigue strength and high-temperature creep strength [67].

Various types of annealing, solution treating and aging treatments, are imposed to achieve selected mechanical properties. Stress relieving and annealing may be employed to prevent preferential chemical attack in some corrosive environments, to prevent distortion (a stabilization treatment) and to condition the metal for subsequent forging and fabrication operations [41]. The Ti-6Al-4V alloy is noted for its attractive mechanical properties in both the annealed and in the fully heat-treated condition. Recommended thermal treatments for this alloy are listed in Table 2.2 and a phase diagram that predicts the effects of forging and heat treatment temperatures on the phase morphology of Ti-6Al-4V is shown in Figure 2.1 [38].

2.1.2.1 Stress Relief

Stress relief cycles can be performed without adversely affecting strength and ductility [40,41]. Stress relieving treatments decrease the undesirable residual stresses that result from: (a) nonuniform hot forging deformation, cold forming and straightening, (b) asymmetric machining of plate (hogouts) or forgings, and (c) welding and cooling of castings [41]. Removal of such stresses helps maintain shape stability and eliminates unfavourable conditions, such as the loss of compressive yield strength commonly known as the Bauschinger effect [41]. Stress relief of Ti-6Al-4V alloy may be accomplished in the general range of 1000° to 1200°F (538° to 649°C) with time being dependent on the temperature used and the percent stress relief desired as shown in Figure 2.2

[39,40,47,48]. The OEM requires that finished first stage titanium rotor fan blades be stress relieved at 1020°F (549°C) for 2 hours, then air cooled [45,46].

2.1.2.2 Anneal

Annealing of titanium and titanium alloys serves to increase fracture toughness, ductility at room temperature, dimensional and thermal stability, and creep resistance [41]. Because improvement in one or more properties generally is obtained at the expense of some other property, the annealing cycle should be selected by an objective criterion. Annealing of all forms of Ti-6Al-4V may be accomplished at 1350° to 1500°F (732° to 816°C) for 1/2 to 4 hours. Air cooling from the annealing temperature can be employed without impairing stability [39,47,48]. After forging, the OEM requires that all parts be annealed at 1300°F (704°C) for 2 hours, then cooled at a rate equal to air cool [45,46]. The OEM microstructure acceptance standards of annealed Ti-6Al-4V is in Figure 2.3.

2.1.2.3 Strengthening Heat Treatment

The origin of heat treating responses of titanium alloys lies in the instability of the high-temperature beta phase at lower temperatures. Heating Ti-6Al-4V to the solution-treating temperature produces a higher ratio of beta phase. This partitioning of phases is maintained (retained) by quenching; on subsequent aging, decomposition of the unstable beta phase occurs, providing high strength [41]. To obtain high strength with adequate ductility, it is necessary to **solution treat** at a temperature high in the alpha-beta field, normally 50 (10°C) to 150°F (65°C) below the beta transus of the alloy. If high fracture toughness or improved resistance to stress corrosion is required, beta annealing or beta solution treating may be desirable. A change in the solution-treating temperature

of alpha-beta alloys alters the amount of beta phase and consequently changes the response to aging. Selection of solution-treating (ST) temperature is usually based upon practical considerations such as the desired level of tensile properties and amount of ductility to be obtained after aging [41]. Because ST involves heating to temperatures only slightly below the beta transus, proper control of temperature is essential. If the beta transus is exceeded, tensile properties (especially ductility) are reduced and cannot be fully restored by subsequent thermal treatment [39,40]. The main conventional heat treatment for Ti-6Al-4V and the resulting microstructures are given in Table 2.3 [38].

The choice of ST temperature also depends on the product. Solution treatment of Ti-6Al-4V sheets and light plate can be accomplished from a lower temperature (1660 to 1700°F) (904 to 927°C) than heavier sections (1750°F) (954°C) due to faster quench rates possible on lighter sections. Heat treating times on sheet products should be kept to a minimum due to oxidation and contamination problems that are time dependent and occur rapidly at these high temperatures. Longer times are desirable for heavier sections to insure uniformity of heat treatment throughout the section [39,40]. The rate of cooling from the ST temperature has an impact on strength. If the rate is too low, appreciable diffusion may occur during cooling, and decomposition of the altered beta phase during aging may not provide effective strengthening. The microstructure of Ti-6Al-4V quenched from temperatures approaching the beta transus frequently contains fine acicular alpha product. This phase is alpha prime which can occur without exceeding the beta transus temperature. An example of this structure is shown in Figure 2.4 [39,40]. The final step in heat treating Ti-6Al-4V to high strength consists of reheating to an **aging** temperature of 1000°F (538°C) for 4 hours, followed by air cool. Aging causes decomposition of the supersaturated beta phase retained on quenching. **Overaging** can be accomplished by aging at temperatures over 1000°F (538°C) and up to 1150°F

(621°C) for 1 to 8 hours. The overaging treatment may be used to lower the strength level of material that has been heat treated to too high a strength level and it may serve to increase the tensile ductility [41].

2.1.2.4 Mechanical Properties of Ti-6Al-4V

The American Society for Testing and Materials (ASTM) has developed accepted standards for performing room temperature tensile tests (E-8) including standards for calculation of the material properties [44]. Tensile tests provide material strength and ductility data in terms of load versus displacement from which basic material properties including: yield strength (σ_{ys}), modulus of elasticity (**E**), ultimate tensile strength (**UTS**), elongation and reduction of area (**RA**) can be determined. The yield stress can be determined using the intercept given by the 0.2 percent offset strain on the stress-strain curve, while the slope of the offset can be used as an estimate of the modulus of elasticity. The ultimate tensile strength is defined as the maximum stress achieved for each specimen and can be found by dividing the maximum load by the initial cross-sectional area. The specimen elongation and reduction of area can both be calculated as a percentage of their original values, using the gauge length and cross-sectional area measured from the specimen before and after testing. Stress-strain curves of Ti-6Al-4V annealed sheet and bar are shown in Figures 2.5 and 2.6. The guaranteed and the typical properties of Ti-6Al-4V sheet and plate in both the annealed and the heat treated condition are given in Table 2.4 [39]. The forged annealed properties of Ti-6Al-4V required by the OEM (Reference 45 & 46) for tensile test specimens shall meet the following minimum requirements at room temperature:

Tensile Strength, psi	135,000 (930 MPa)
Yield Strength (0.2% offset), psi	125,000 (862 MPa)
Elongation (% in 4D)	10
Reduction in Area, %	25
Grain Orientation:	Longitudinal direction

The effects of solution temperature variations on mechanical properties of Ti-6Al-4V are shown in Figure 2.7 and Figure 2.8. The deleterious effects of quench delays in ST of Ti-6Al-4V are illustrated in Figure 2.9. It should also be noted that the section size of the solution treated (quenched) product has a significant effect on the resulting properties as shown in Figure 2.10 for solution treated and aged (STA) Ti-6Al-4V bar. The modulus of elasticity of annealed and STA Ti-6Al-4V is presented in Figure 2.11. The impact resistance of Ti-6Al-4V is a reverse function of the strength level and the interstitial content of the alloy. Good impact values are obtained for this alloy as demonstrated in Figure 2.12 which shows that a better impact resistance is obtained for the aged material than the annealed [39]. The crack propagation characteristics of a material include its resistance to cracks growth and its load carrying ability in the presence of stress concentrations. Fracture mechanics assumes the pre-existence of flaws, inhomogeneities and discontinuities in a material. It is from these flaws that cracks often nucleate and grow under cyclic load [27,49]. The prediction of crack nucleation and propagation is beyond the scope of this thesis, however, it must be recognized that any local geometries, physical or metallurgical (welds, cutouts, notches, impact cracks, etc.) which intensify the stress are a prospective site for fatigue crack initiation.

To illustrate the ability of Ti-6Al-4V to carry a load in the presence of a notch, or a material crack, Figure 2.13 shows a plot of the residual strength versus the fraction of the remaining load carrying area. For comparison, the plot of a perfect material, which sustains no loss in load carrying ability in the presence of this crack, is included

and shows that the annealed material has a better load carrying ability than the STA [39]. The critical crack extension force, G_c , is also of interest to the designers. In simple terms G_c is a measurement of the crack extension force at the onset of rapid crack propagation. In order to compare the G_c with that for other materials, K_{Ic} is normally used which is nothing more than the G_c value corrected for modulus. The crack extension force, K_{Ic} , versus the strength level is plotted in Figure 2.14 and may be observed for both G_c or K_{Ic} value. The plot in Figure 2.14 shows that for higher strength Ti-6Al-4V alloy, a lower fracture toughness level is obtained. However, at the high strength level of 130 ksi (569 MPa) as required by the OEM material specification (Reference 45 & 46), it can be seen from the plot that a good fracture toughness level was maintained (K_{Ic} =140 ksi (613 MPa), G_c =1200 lb/in (21439 kg/m)) [39].

2.2 Electron Beam Welding of Ti-6Al-4V

Fusion welding of Ti-6Al-4V alloy by tungsten inert gas (TIG), hot wire metal inert gas (MIG), laser and electron beam can be performed when the material is in the annealed, the solution treated, or the fully aged condition, and may be welded with or without filler wire [39]. Electron beam and laser welding processes are capable of providing extremely similar high-quality weld application properties including: high welding speeds with high depth-to-width ratio weld profiles (Fig. 2.15), low distortion workpiece, minimal undercut and porosity and good repeatability of established weld parameters as opposed to a TIG or MIG method [1,50,51]. In electron beam and laser welding processes the heat affected zone (HAZ) is very localized, is accurately perpendicular to the plate being welded and the geometry no longer inhibits a plane-strain structure [51,57,76]. The analogy to the definition of plane-strain is that, if the z-

direction of a stressed cracked-body (thickness) is large, then all **z**-direction strains and displacements are zero [27]. This definition could well describe the behaviour of a thick section fracture, except for the region close to where the crack meets the free surface faces [27]. In that region the **z**-direction strain and displacements are not zero, and lead to the development of shear deformation or "shear lips" near the free surface [27]. Therefore, in a thick section, plane-strain conditions are governed by the material thickness. In a thin, cracked body subjected to in-plane loads, there is essentially no constraint in the **z**-direction (i.e., 3-dimensional strain state), and plane-stress conditions prevail. This lack of constraint is contrasted with the plane-strain condition and leads to relatively large plane-stress yield zones which are on the order of the material thickness [27]. The pictorial representation of plane-strain and plain-stress behaviour is shown in Figure 2.16.

However, the fundamental nature of the high-energy beams of each process uses is radically different, therefore the EB-welding process has been favoured over the laser technique for the weld-repair of titanium rotor fan blades [19,22,51,52]. The most significant advantage of EB over laser welding is the shielding of the weld and the HAZ to preclude pick-up of any contaminants from the air by the molten or hot titanium. Titanium alloys readily pick up interstitial elements like oxygen, nitrogen, and hydrogen, which can lead to mechanical property degradation such as cracking in the HAZ [39,40,75,76]. Shielding can be accomplished by flooding the area immediate to the weld with an inert gas or can be accomplished by welding in a chamber filled with an inert gas and purged of the common contaminants. However, the high vacuum environment of about 1×10^{-4} Torr (0.013 Pa) associated with the EB-welding process inherently provides better atmospheric protection [67]. Joint cleaning and fit-up are also important factors in welding Ti-6Al-4V structures and the EB-welding process is sensitive

to these factors despite its advantages over other techniques [39].

During a fusion welding process, changes in microstructures occur that include variations in the constitution and morphology of the microstructural constituents in the weld affected material. The five cooling curves in Figure 2.17 show the temperature distribution across a typical weld bead and past four selected points in the adjacent base metal [68]. The resulting microstructures depend both on the thermal cycles incurred during welding and on the phase transformation characteristics of the alloy [53]. The temperatures in Figure 2.17 can be instructively re-plotted as a function of elapsed time at the four different thermocouple distances from the weld bead. This technique was used in Figure 2.18 which has been derived from the data shown in Figure 2.17. Cooling curve 1 picks up the temperature when the heat source brought point 1 to the molten state and passed on. Point 1 then cools rapidly while the temperature is high, but slower and slower as the gradient decreases. The temperature at point 2 rises very rapidly as it receives heat from the weld metal, reaching a maximum temperature only a little less than the temperature of the weld at that moment, after which cooling sets in. Note that the cooling rate at any temperature is slower at point 2 than at point 1. Cooling is slower still the farther we move from the weld (curves 3&4) [68].

Since the mechanical properties of Ti-alloys are heavily dependent on microstructure [54,55], the microstructural alterations which occur during welding of titanium alloys may lead to large variations in properties between the weld and base metal [53]. The base metal regions at the weld fusion boundary are rapidly heated to the effective liquidus temperature. In the adjacent heat-affected zone the alpha-phase (hcp) plus beta-phase (bcc) microstructure can revert to a fully beta structure if the beta-transus temperature is exceeded [67]. The beta grains at the edge of the weld pool act as ideal substrates upon which growth of the phase into the molten pool and the weld fusion zone

can occur. As the columnar grains grow into the fusion zone, their actual shape and size depend on the geometry of the molten weld pool which is determined by the heat input of the welding process [67]. Thus, the welding process and base metal geometry can significantly influence the resulting size and shape of beta grains in the fusion zone. However, when all precautions are observed, good quality welds can be made in Ti-6Al-4V. Some typical weld mechanical property values are listed in Table 2.5 [39].

2.2.1 Post-Weld Heat Treatment

Titanium alloy weldments are post weld heat treated for:

- a) relief of residual stresses imparted during the welding operation;
- b) modification of the metastable weld zone microstructure;
- c) completion of the second step in a two-step base metal heat treatment; and
- d) stabilization of the microstructure for weld structure applications at elevated temperature [67].

Knowledge of the residual stress distribution in weld-repair is necessary to assess the risk of crack growth in service. Defects in the weld-repair or its HAZ are most commonly oriented parallel to the welding direction [79,80]. Hence, residual stress transverse to the weld is of particular interest and its distributions can display almost yield magnitude at the weld surface, but decrease to zero with depth [79].

Of the various techniques for measuring residual stresses, x-ray diffraction method is the most widely used [92]. It is the only technique that is applicable to all crystalline materials, that can measure the absolute stress in the component without the need for a measurement of the sample in the unstressed state, and that is capable of making measurements in a localized region as small as 0.039 in (1 mm) in diameter. The penetration of long wavelength x-rays is only a few tens of microns, therefore it is used to measure surface stresses. Stresses are determined by measuring the strain in the atomic lattice and by relating the strains to stresses through elasticity theory [92]. An

incident beam of essentially monochromatic radiation of wavelength λ is diffracted at an angle 2θ (Figure 2.19) which obeys **Bragg's Law**:

$$n_{xr}\lambda = 2d \sin\theta \quad 2.1$$

where n_{xr} is the order of the reflection and d is the atomic spacing of the selected crystalline lattice planes [92]. The sample surface is at an angle θ to the incident beam, and only grains with atomic planes parallel to the surface diffract. From the 2θ position of the peak, the atomic spacing of the diffracting planes may be determined.

When the sample is tilted an angle ψ (Figure 2.19), the atomic planes that make an angle ψ with respect to the surface now diffract. If there is no stress in the sample, the two diffraction curves superimpose. However, in the presence of surface stresses, the atomic planes in different orientation are compressed or dilated and a peak shift results. The stress, σ , can be determined from the shift through the relationship:

$$\sigma = \frac{E}{1+\nu} \times \frac{1}{\sin^2\psi} \times \frac{(d_\psi - d_o)}{d_o} \quad 2.2$$

where d_o is the lattice spacing corresponding to the unstressed condition, d_ψ is the lattice spacing at a tilt angle ψ and E and ν are Young's modulus and Poisson's ratio appropriate to the selected crystallographic planes. The values of d_ψ are obtained from Bragg's Law (Equation 2.1) by careful analysis of the diffraction peak. Note that it is not necessary to know the d -spacing of the unstressed material. Thus, an accurate and rapid measurement of the location of the diffraction peaks can be used to determine the presence of loading or residual stresses [92].

The stress values shown in Figure 2.20 represent the residual stresses distribution of TIG-welded 6Al-4V titanium sheets measured experimentally using strain gauges [80].

The magnitude of the transverse stress is relatively low (below 10 ksi, 69MPa). The transition of residual stresses longitudinal to the weld occurs sharply from a peak tensile stress of approximately 60,000 to 70,000 psi (413 to 482 MPa) in the weld to a compressive stress maximized at less than 10,000 psi (69MPa) at a distance about 1 inch (2.54 cm) from the weld [80].

Complete removal of residual stresses can be accomplished by a stress relieving heat treatment cycle [80]. The recommended stress relieving times and temperatures of welded Ti-6Al-4V in the heat-treated conditions are given in Table 2.6 [39]. Heat treatment of rapidly cooled welds (electron beam and laser) in near-beta and alpha-beta alloys at relatively low temperatures between 750-1022°F (400-550°C) results in micro-precipitation of beta phase at sub-boundaries and dislocations of the supersaturated hcp martensite structure [69]. This precipitation reduces the concentration of beta-stabilizing elements in the alpha-prime phase so that it ultimately approaches that of equilibrium alpha phase. At these relatively low aging temperatures, the alpha plate size and morphology is comparable to that of the as-welded alpha-prime. However, as the heat-treatment temperatures are increased above 650°C (1200°F), appreciable alpha plate coarsening occurs. As this intergranular coarsening proceeds, thickening of semi-continuous or continuous alpha at beta grain boundaries also takes place [67,78]. The effect of thermal treatment on the microstructure of Ti-6Al-4V is shown in Figure 2.21 and the properties of welds after various thermal treatments are given in Table 2.7 [39].

For welded aerospace components, the properties of greatest significance are strength, ductility, fracture toughness, and fatigue [67]. The strength of the weld zone is a function of the strength of the individual phases and the distribution and morphologies of these phases. The fine, predominantly alpha-prime structures in rapidly cooled near-alpha and alpha-beta alloy weldments exhibit high strength levels that can

become even higher after low-temperature post-weld heat treatment [53,67]. As the microstructure coarsens due to a reduced weld cooling rate or increased post-weld heat treatment temperature, intergranular slip becomes easier and yield and ultimate tensile strengths decrease [70]. Unlike the alpha-prime martensite structures, the alpha-double-prime orthorhombic martensite that forms in rapidly cooled laser and electron-beam weldments in the more stabilized alpha-beta alloys is relatively soft and low in strength. The low to moderate temperature aging of these rapidly cooled structures produces extremely fine alpha-beta structures of high hardness and strength that decrease with increased post-weld heat treatment temperature [67]. Surface hardness measurements were carried out on EB-weld repaired first stage titanium rotor fan blades to compare the weld surface hardness versus the forged baseline blade surface hardness. The surface hardness tests conducted in this study followed the standard test methods for Rockwell hardness described in ASTM E18-89a (Reference 81 &82). The test parameters are presented in more detail in Chapter 3.

Low ductility is produced in the weld fusion and near heat-affected zone of titanium weldment structures. This poor ductility results in part from a coarse prior-beta grain size and preferential crack propagation along prior-beta grain boundaries that can completely transverse the weld thickness [67]. When grain-boundary alpha is present in conjunction with a fine transformed-beta intergranular microstructure obtained during continuous cooling or by low-temperature post-weld heat treatment, greater slip incompatibilities can exist at their boundaries. When stressed, the softer grain boundary alpha will begin to deform before the high-strength intergranular microstructure, and since slip is incompatible with the adjacent transformed data, slip concentration in location will promote low ductility fracture along prior-beta grain boundaries. This grain boundary fracture can often be preceded by void formation or grain boundary sliding

[71,72]. When grain-boundary alpha is present in conjunction with a coarser alpha plus retained beta microstructure, strength differences between the grain-boundary alpha and transformed-beta structures are less and slip initiating in the grain boundary alpha can be more easily accommodated intergranularly, thereby preventing slip concentration and improving macroscopic weld ductility and promoting a more transgranular fracture [70]. Thus, the best combination of weld tensile properties requires a trade-off between weld strength and ductility. However, even when weld strengths are lowered to that of the base metal, weld zone ductility will remain below that of the alpha-beta processed base material [67].

In general, the fracture toughness of the weld fusion zone in titanium weldments is equivalent to that of the base material at comparable strength levels [53]. Certain alpha-beta alloys exhibit fracture toughness significantly below that of the base material when welded using high-energy density processes [73]. The rapid cooling rates promote the formation of fine, martensitic structures with relatively low fracture toughness, even after post heat treatment at intermediate temperatures. The S-N fatigue properties of weld structures in Ti-6Al-4V are similar to that of the base material if the weld zones are free of defects such as porosities and undercut [53]. Failure in transverse-oriented specimens occur in the base metal remote from the weld zone [53,67,77]. This greater resistance to crack initiation of these composite weld structures relates to the higher strength levels of the weld regions since the large prior-beta grain/transformed beta microstructures, which characterize these regions generally exhibit reduced resistance to cyclic crack initiation compared to equiaxed-alpha type base metal structures [67]. Failure in the HAZ can be found when the tensile direction is parallel to the grain rolling direction [77]. A tensile test of the weld in the transverse and longitudinal direction to the load is not included in the scope of this study. However, room temperature test

procedure has been prepared in accordance with ASTM E-8 (Reference 98).

The OEM specifications for EB welding, joint cleaning and preparation and radiographic inspection of fusion weld can be found in Reference 58 to 63, respectively. These specifications were reviewed and compared with the applicable Pratt and Whitney standard (Reference 64) and the Aerospace Material Specification AMS 2680A and AMS 2681A (Reference 65 and 66) to establish the electron beam welding process parameters, the surface preparation procedures and the internal discontinuity limits as presented in detail in the following Chapters.

2.3 Foreign Object Ingestion

Experience acquired with aircraft gas turbine engines has revealed that foreign object ingestion has, at times, resulted in safety hazards. Such hazards may be extreme and possibly catastrophic involving: explosions, uncontrollable fires, engine disintegration, and lack of containment of a broken blade [5,20,26,33]. In addition, lesser but potentially severe hazards may involve: airflow disruption with flame outs, lengthy or severe power losses, momentary disruptions and possibly minor blade damage. While the magnitude of the overall hazards from foreign object ingestion are often dependent upon more than one factor, **engine design** appears to be the most important [5,7,8,21,35,43].

The foreign objects considered typical by the United States (US) Federal Aviation Administration (FAA) and its equivalent agency in Canada, Transport Canada Aviation (TCA), are detailed in reference 6 and may include the following:

- 1) A cleaning cloth of typical size;
- 2) A mechanic's hand tool of pocket size;
- 3) A small size of aircraft steel bolt and nut typical of aircraft inlet hardware;

- 4) A piece of aircraft tire tread of length equal to the tread with a representative size tire;
- 5) Water in the form of rain and snow;
- 6) Gravel of mixed sizes up to 1/4 inch (0.6 cm);
- 7) Sand of mixed sizes (typical of airport surface material);
- 8) Ice of typical size and forms;
- 9) Hail stones of approximately 0.8 to 0.9 specific gravity and of 1 to 2 inch diameter (2.54 cm to 5.08 cm); and
- 10) Birds in weight categories as follows:
 - a) Small birds of 2 to 4 oz (0.06 to 0.11 kg) (Starlings).
 - b) Medium birds of 1 to 2 lbs (0.45 to 0.90 kg). (Pigeons)
 - c) Birds of 4 lbs (1.8 kg) and over (Geese, buzzards, largest gulls and ducks).

Engine substantiation may be based on consideration of **only** those foreign objects (e.g., water, ice, hail stones & birds) which are known to cause the more severe effects than on **all** typical foreign objects listed above. In addition, component tests with complete compressors or turbine sections are acceptable as backup tests [6].

2.4 Foreign Object Impact Damage

Damage done by a metallic object can range from minor to complete destruction of the compressor, depending upon the size of the object, the rotor and the aircraft speed. The ingestion of hard but brittle objects such as rocks and hard ice will not cause extensive damage, because they tend to shatter, however, stress risers can result. A metallic object may leave an imprint on the blades and stator vanes, whereas a hard but brittle object does not leave an identifying mark on the blades or stators. Soft objects such as rags, soft ice, and birds can cause the compressor or fan blades to bend forward as shown in Figure 2.22, such that the leading edge of the blade tip rub against the trailing edge base of the stator vane in front of it. All but soft ice could be expected to leave residue within the engine's bleed valves, bleed lines, stator vanes and other engine components. The foreign object, after striking a blade, can bounce back against the

stator vanes in front of the blade and strike another blade. This can continue several times, peening both the stator vanes and blades until the blades jam and rip out several stator vanes. A chain reaction can then take place from blade to stator, breaking off most of the stator vanes and bending and breaking all of the blades. The broken blades and stators pile up and log jam near the rear of the compressor which can cause the compressor to fail [33].

Impact fracture of a rotating blade involves a combination of bending and transverse shear. In the bending mode, the fibres on the impact are in tension, and the tension field quickly moves across the blades as the fracture progresses to completion. It can be assumed that the material used in the rotating components is ductile and that the features of a fractured surface are characteristic of ductile materials [11,27]. Ductile material fractures as a result of shearing flow of the material at an angle approximately 45 degrees to the applied tensile stress. This gives rise to a characteristic appearance of the fracture surface shown in Figure 2.23, typified often by a lip at the edge, formed by shearing forces as the two parts of the component separate [12]. The examination of fracture surfaces (fractography) can supply information as to the prior state of stress and may be done macrographically or microscopically. Macrographic examination is usually considered to be that done with the naked eye, or with no more than a magnification of ten. There are two ranges of microscopic examination of significance in fractography: the first is by means of optical microscopy, and usually extends up to 60 power, while the second must be performed with scanning electron microscopy. Using this technique magnification of 5,000 (or greater, if necessary) can be obtained. The macrographic face of the impact fracture surface tends to be rough and angular because of the shearing flow as illustrated in Figure 2.24, however, there may be a distinct pattern of ridges roughly parallel to the direction of fracture progression as shown in Figure 2.25. Ductile

fractures are usually transgranular, while brittle fractures are usually intergranular [12]. Microscopic examination of a short-term fracture surface in a ductile material reveals as the phenomenon known as **dimples** as shown in Figure 2.26. These are formed by plastic stretching of pores in the crystals as the specimen deforms. Dimples normal to the direction of loading are roughly equiaxed or slightly elongated under transverse loading. A magnification of 300 is required for the identification of dimples [10,11,12,13,27].

2.5 Foreign Object Impact Testing

Engine ice-ingestion and bird strike certification tests are performed on engines to predict the dynamic impact response for both the engine and its component materials. The FAA acceptable means of compliance for substantiating engines for foreign object ingestion are outlined in Part 33 of the Federal Aviation Regulations (FAR), and its equivalent, Chapter 533 of the Airworthiness Manual (AWM) published by Transport Canada Aviation (TCA), Reference 14. The requirements of FAR 33 and TCA/AWM 533 are compared in Table 2.8. The test engine shall be subjected to a FOD test to demonstrate compliance without causing catastrophic engine failure or excessive power losses. The US military engine specifications prepared by the Naval Air Propulsion Centre for use by the US-Navy are detailed in Reference 15 and reflect OEM FOD qualification tests for the engine found in Reference 16. However, **"subject to approval of the using service, the FOD test may be considered by bench testing on individual blades or rig testing on full scale fan or compressor components in lieu of complete engine testing"** [15]. If the test is to be conducted on a component level basis, details of the test shall be presented in the pre-test data, however, test conditions, duration and

severity shall be equivalent to the complete engine test described in the Reference regulations [15]. An important evaluation tool used in component-level testing for determining blade bird-strike capability is the **whirligig** test facility where the stresses and deflection caused by bird strikes and air loading are approximated under engine-operating conditions. The vibratory stresses are induced by arranging a series of high pressure air jets to impinge on the blading and a jelly bird projectile is shot from a pneumatic cannon at the fixtured rotating engine-ready blades. A crack occasionally develops in the airfoil ahead of the mid-span damper of the fan blade as a result of the impact and projectile velocities are increased until the blade fracture [34,35]. Schematic of a bird-strike test facility is shown in Figures 2.27 and 2.28.

The original engine or equipment manufacturers design turbine and compressor rotors to have a sufficient strength margin to allow operation with likely variations in materials and operating environment. It is standard practice for the manufacturer to specify a material that is suitable for the service, and that the material meets the manufacturer's specifications for mechanical and physical properties [9,10]. Further, non-standardized and economical test methods have been developed and validated to predict the dynamic impact response (bird-strike resistance) of fan blades [31]. For example, during the development of fan blade materials, Howmet in the USA, utilised an instrumented pendulum to transfer energy to a machined fan blade cross section as shown in Figure 2.29. The apparatus used by Howmet in the simulated bird-strike test is similar to a **Charpy** impact test, but had different energy ranges and uses a rigidly clamped sample. The simulated-test method was validated and accepted by comparing the relative performance of materials subjected to the simulated bird-strike to that of the same materials tested by conventional bird-strike testing [31].

Conventional FOD testing conducted on a component-level basis is expensive and

the test equipment is not readily available to nor accessible for the engine users [34]. A non-standard and inexpensive ballistic-impact test method was designed and developed to effectively simulate service induced damage due to birds, rocks, ice or hail striking the first stage titanium rotor fan blade during takeoff, cruise and descent. The ballistic-impact test method used a Magnum calibre revolver with different bullet sizes shot at fixed engine-ready fan blades to simulate the impact energies required for the different engine settings. The calculation for the required kinetic energies relative to the aircraft and fan rotor speeds is presented in detail in Chapter 3. The relative damage of the EB-Weld repaired fan blades subjected to the simulated FOD testing corresponded to the service induced FOD, thereby, validating the simulated method as a screening tool for the fan blades EB-Weld repair development. Although the ballistic-impact test method used engine-ready fan blades, it does not require expensive set-up and the simulated test is more rapid, less expensive, and more readily accessible for the user compared to conventional FOD test required by the OEM.

2.6 Stresses in Rotor Blades

There are three main sources of stress in fan or compressor blades: 1) centrifugal tensile stress (the largest, but not necessarily the most important because it is steady stress), 2) gas bending stress (fluctuating as the rotor blades pass by the trailing edges of the nozzles), and 3) centrifugal bending stress when the centroid of the blade cross-sections at different radii do not lie on a radial line (any torsional stress arising from this source is small enough to be neglected) [88].

2.6.1 Centrifugal Stress

Steady stresses in blading are important in determining the margin available for vibration stress (high cycle fatigue), and creep distortion in turbines. These stresses are within reasonable limits in compressor blades, but are particularly high in low hub-tip ratio fan blades and in turbines [26]. For this reason we often see the presence of a part shroud in fan blades to limit vibration stress levels and provide rigidity for bird strike. The most important component of steady blade stress is the centrifugal stress. The forces on a blade element shown in Figure 2.30(a) lead to the equation:

$$(\sigma + d\sigma)(A + dA) + F - \sigma A = 0 \quad 2.3$$

where F is equal to inertia force on element radius r , angular rotational speed ω , therefore:

$$F = \frac{\rho A dr}{g} \times \omega^2 r \quad 2.4$$

Substituting, we obtain:

$$A d\sigma + \sigma dA = -\left(\frac{\rho A \omega^2}{g}\right) r dr \quad 2.5$$

The centrifugal stress in the rotor blades depends on the rotational speed, the blade material and the length of the blade [88]. When the rotational speed is specified, the allowable centrifugal tensile stress places a limit on the annulus area but does not affect the choice of blade chord. The maximum value of this stress occurs at the root and is readily seen to be given by:

$$(\sigma_{cl})_{\max} = \frac{\rho_b \omega^2}{a_r} \int_r^t a_r r dr \quad 2.6$$

Where ρ_b is the density of blade material, ω is the angular velocity, a_r is the cross-sectional area of the blade and r and t refer to root and tip of the blade.

For simplicity, if the blade cross section is assumed to be constant from root to tip, then:

$$(\sigma_{cl})_{\max} = \frac{\rho_b}{2} (2\pi N)^2 (r_t^2 - r_r^2) = 2\pi N^2 \rho_b A \quad 2.7$$

where N is the rotational speed (rev/s) and A is the annulus area = $\pi(r_t^2 - r_r^2)$

The tip speed is given by:

$$U_t = 2\pi N r_t \quad 2.8$$

thus, the centrifugal tensile stress can be written also as:

$$(\sigma_{cl})_{\max} = \frac{\rho_b}{2} U_t^2 \left[1 - \left(\frac{r_r}{r_t} \right)^2 \right] \quad 2.9$$

$$\left(\frac{r_r}{r_t} \right) = \frac{r_m + (\frac{h}{2})}{r_m - (\frac{h}{2})}; \text{Where } A = \frac{U_m h}{N}; U_m = 2\pi N r_m; r_m = (r_t^2 - r_r^2) \quad 2.10$$

It is immediately apparent that the centrifugal stress is proportional to the square of the tip speed, and that a reduction of hub-tip ratio (r_r/r_t) increases the blade stress. The hub-tip ratio is also important with regard to aerodynamic considerations. It should be noted that, for a rotational speed N , the root stress σ_r is the same for a long blade of low hub-tip ratio as for a short high hub-tip ratio blade, if the annulus area are the same.

Also, the stress is independent of blade chord [26].

In practice, the blade sectional area will be decreased with radius (e.g., tapered blade in chord and thickness) to relieve the blade root stress and the loading on the disc carrying the blades, so that the integral would be evaluated numerically or graphically [91]. For preliminary design calculation it is sufficiently accurate (and on the safe side) to assume that the taper reduces the stress to 2/3 of the value of an untapered blade. Thus:

$$(\sigma_{ct})_{\max} = \frac{4}{3} \pi N^2 \rho_b A \quad 2.11$$

A simple analytical expression can be deduced, however, for a linear variation of cross-sectional area from root to tip. If the hub-tip ratio is **b** and the ratio of the cross-sectional area at the tip to that at the root is **d**, the stress in a tapered blade is given by:

$$(\sigma_{ct})_{\max} = \frac{\rho_b}{2} U_t^2 (1 - b^2) K \quad 2.12$$

$$K = 1 - \left[\frac{(1-d)(2-b-b^2)}{3(1-b^2)} \right]; \text{typical value: } 0.55 < K < 0.65$$

Direct centrifugal tensile stresses are not of major concern in compressor blades [88]. The first-stage blades, being the longest, are the most highly stressed and typical allowable stress is limited to 0.7 x 0.2% yield or stress to rupture, which allows some margin for vibration stresses [26].

2.6.2 Gas Bending Stresses

The force arising from the change in angular momentum of the gas in the tangential direction, which produces the useful torque, also produces a gas bending moment about the axial direction, namely M_w in Figure 2.30(b). There may be a

change of momentum in the axial direction, and with reaction blade (i.e., the fluid accelerates and experiences a pressure drop during its passage) there will certainly be a pressure force in the axial direction. There will also be a gas moment M_a about the tangential direction:

$$\left[\frac{(P_2 - P_1)2\pi r}{n} / \text{unit-height} \right] \quad 2.13$$

Resolving these bending moments into components acting about the principal axes of the blade cross-section, the maximum stresses can be calculated from **Bernoulli** bending $\sigma = Mc/I$ given by:

$$\sigma_{gb} = \frac{x}{I_{yy}} (M_a \cos \Phi - M_w \sin \Phi) + \frac{y}{I_{xx}} (M_w \cos \Phi + M_a \sin \Phi) \quad 2.14$$

A twisted and tapered blade must be divided into strips of height δh as shown in Figure 2.30(c) and the bending moments calculated from the average face acting on each strip. The gas bending stress σ_{gb} will be tensile in the leading and trailing edges and compressive in the Back Face (BF) of the blade and even with tapered twisted blades the maximum value usually occurs at either the leading or trailing edge of the root section [26,88]. Because M_w is by far the greater bending moment, and the principal xx axis does not deviate widely from the axial direction (angle ϕ is small), a useful approximation for preliminary design purposes is provided by:

$$(\sigma_{gb})_{\max} = \frac{m(C_{w1m} + C_{w2m})}{n} \times \frac{h}{2} \times \frac{1}{zc^3} \quad 2.15$$

where n is the number of blades, the whirl velocities C_w are evaluated at the mean diameter, and z is the smallest value of the root section modulus (I_{xx}/y) of a blade of unit chord. Clearly σ_{gb} is directly proportional to the number of blades and section modulus. It is convenient to treat the section modulus as the product zc^3 because z is largely a function of blade camber angle ($\approx$ gas deflection) and thickness chord ratio [26,88].

2.6.3 Stresses Due to offset Centroid

Unlike the centrifugal stress the bending stresses can be shown to vary as $(\text{Chord})^2$ and are of increasing importance with low aspect ratio blading [26]. In the derivation of centrifugal stress it was assumed all sections had their Centre of Gravity (C.G.) on a radial line. If they are offset, the blade tends to straighten under centrifugal force, and this effect will produce a bending moment. It is customary to "stack" or "tilt" the blade sections as shown in Figure 2.30(d) such that this bending moment essentially cancels the gas bending moment, and leaves only the centrifugal stress component [26]. It must be remembered, however, that a) these two stresses would only cancel each other at the design operating condition, b) σ_{gb} is only a quasi-steady stress and c) the centrifugal bending stress is very sensitive to manufacturing errors in the blade and blade root fixing. The σ_{gb} is often not regarded as being offset by any centrifugal bending stress and usually the latter is merely calculated using the extreme values of manufacturing tolerances to check that it is small and that at least it does not reinforce σ_{gb} [88].

2.7 High Cycle Fatigue in Rotor Blades

Cracks and fractures in gas turbine parts, both rotating and stationary, occur as

a result of four mechanisms: short-term loading, fatigue, creep, and embrittlement. In practically all cases of short-term loading, cracks progress almost instantly to complete fracture. Fatigue, creep, and embrittlement are time-dependent phenomena, so cracks may sometimes be detectable before complete fracture occurs. There are several significant variations of fatigue; these are: high-cycle fatigue (HCF), high-frequency fatigue, low-cycle fatigue (LCF), and thermal fatigue where combinations may exist. Differentiation between these terms is related by number of cycles, stress level relative to yield, and fracture appearance [11,18,27]. The most likely initiating failure mechanisms for major components of gas turbines are given in Table 2.9 [10].

Prevention of fatigue failure is one of the most important aspects of the design, operation, and maintenance of turbomachinery. Fatigue failures in turbomachinery may be described as either not-life related or life related. The first category consists of high-frequency fatigue due to blade, stationary vane, and disc vibration, which is usually resonant vibration. The second category consists of low-cycle fatigue, thermal fatigue, and corrosion fatigue. The second should be considered life-related, since fatigue cracking will eventually occur if the machine continues to run, subject only to the variables of material fatigue strength and the severity of the local stress raising mechanism [11,17,18,27].

The σ -N curve (i.e., number of cycles to failure as a function of the level of alternating stress) in Figure 2.31(a) (often called S-N diagram in literature) shows the general cycle regimes of the various types of fatigue. The LCF is generally considered to be damage associated with cycles-to-failure of 10^4 or less. This regime (left side of curve in Figure 2.31(a)) involves high stresses, and relatively few applications including: start-ups, followed by periods of operation and shutdown. In this region the material is operating in the inelastic part of the stress-strain curve, and it has been found that LCF

is better correlated with strain cycling than with stress cycling [26]. Thermal fatigue is closely related to LCF but in this case the large plastic strains result from transient thermal fatigue where ductility in the material is important, since a single cycle can easily fail in brittle material. For LCF a fixed loading cycle is generally adopted, with times adjusted to match anticipated engine usage, e.g., start-up-idle-maximum power, cruise-idle-shut down [26].

The HCF regime involves low stresses and rapid cycling typically due to vibratory loads. The stresses in this region (right side of curve in Figure 2.31(a)) are usually just above the fatigue strength including stress concentrations, unless the component suffers damage that would increase the stress concentration at the point of maximum stress, or the material becomes corroded [18]. The latter circumstance is the basis of corrosion fatigue, whereas **high-frequency** fatigue falls into the category of **high-cycle** fatigue. However, the process of blade failure in high-frequency fatigue is brief: once the excessive alternating vibration stresses are established, the initial crack appears in a few hours and at a low vibratory frequency (typical value of 200 Hz) [11,18].

In HCF we can find a fatigue limit stress, or endurance limit:

$$\sigma_L = 0.5 \text{ UTS}^1 \quad 2.16$$

below which the material can operate indefinitely and show no evidence of fracture, e.g., in titanium and most ferrous alloys. However, for non-ferrous materials such as aluminum alloys and composite materials, it was found that such materials did not possess an endurance limit, but rather continued to exhibit fracture, provided that the repetition of load was continued for a sufficiently large number of times, as shown in Figure 2.31(b). For these materials, it is customary to define the stress to cause failure in a given number of cycles (say $N_f=10^6$) as the endurance limit stress [91].

The endurance limit, σ_L , is an important material property for members subjected

to fatigue loading as long as the number of cycles of loading approaches the number associated with σ_L . It should be noted that other fatigue properties for each material can be obtained from the σ - N curve. Many members are subject to fewer cycles than are associated with the endurance limit. For each value of N_f in Figure 2.31(b) there is a stress σ_{am} , the fatigue strength; a specimen subjected to completely reversed cycles of stress at σ_{am} will fracture after N_f cycles. Note that $\sigma_{am} = \sigma_L$ at the endurance limit.

The σ - N curves in Figure 2.31(b) remain valid for constant amplitude ($\pm\sigma_{am}$) tests. However, deviations from constant amplitude alternating stress may alter the σ - N curve. For example, if a steel is subjected to cyclic stress of constant amplitude for a sufficiently long time below the endurance limit (point *A* in Figure 2.31(b), its endurance limit may be increased (point *B*). This process, known as coxing, is sometimes employed to improve resistance to fatigue fracture [91]. Application of heat treatment cycles may slightly improve the UTS limit but could affect other properties such as toughness. A more frequently used method is to introduce compressive residual stress by shot or glass peening [26].

As noted above, the σ - N curve gives the fatigue strength σ_{am} for specified N_f for members subjected to completely reversed loading (loading under the condition of zero mean stress). Non-zero mean stresses have a marked effect on the fatigue strength. There have been several relations proposed to describe the effects of mean stress. Three such relations are (for one dimensional testing):

(a) **Soderberg relation**

$$\frac{\sigma_a}{\sigma_{am}} + \frac{\sigma_m}{Y} = 1 \quad 2.17$$

(b) **Gerber** relation

$$\frac{\sigma_a}{\sigma_{am}} + \left(\frac{\sigma_m}{\sigma_u}\right)^2 = 1 \quad 2.18$$

(c) **Goodman** relation

$$\frac{\sigma_a}{\sigma_{am}} + \frac{\sigma_m}{\sigma_u} = 1 \quad 2.19$$

where σ_a is the stress amplitude, σ_{am} is the fatigue strength for given N_f for zero mean stress, Y is the yield stress, σ_m is the mean stress, and σ_u is the ultimate strength. The relation between σ_a and σ_m for cyclic loading with unequal stresses is indicated in Figure 2.31(c). For most metals, the Soderberg relation yields conservative estimates of critical stress amplitude σ_a (or range of stress $2\sigma_a$). The Goodman relation gives reasonably good results for brittle materials, whereas it is conservative for ductile materials. The Gerber relation yields fairly good estimates for σ_a for ductile materials. The Soderberg relation, the Gerber relation, and the Goodman relation are interpreted in Figure 2.31(d). The dashed line CD is generally used along with the Gerber and Goodman relations since failure by general yielding is assumed to occur along CD [91].

HCF under combined steady and alternating stresses is usually assessed by the modified **Goodman** diagram [26]. Determination of HCF life under varying loading requires the assumption of some damage accumulation law - **Miner's** linear law is still widely used:

$$\sum \left(\frac{n_i}{N_{fi}}\right) = 1 \quad 2.20$$

where N_{fi} = cycles to failure at one applied stress only,

n_i = actual cycles applied at that stress.

The above comments essentially relate to failure, however, the following general desirable properties should be kept in mind when evaluating typical candidate materials as listed in Table 2.10:

- 1) Ratio (strength/weight), or UTS/ρ , should be high to cope with centrifugal loads,
- 2) Ratio (stiffness/weight), or E/ρ , should be high to cope with vibration of blading, in particular, to inhibit flutter, which is dependent on the parameter $(E/\rho)^{1/2}$.
- 3) Limit of blade deflections under foreign object impact, the governing parameter is low value $(E \cdot \rho)^{1/2}$.
- 4) To limit thermal strain effect it is desirable to have low coefficient of thermal expansion and high coefficient of thermal conductivity.

The surface of a turbomachinery blade that had fractured in **high-frequency** fatigue is shown in Figure 2.32(a). The crack progressed in an elliptical pattern from an origin on the blade surface until it covered 40% or more of the blade cross-section. The crack surface is smooth, while the short-term final fracture surface is rough and characteristic of a ductile material as shown in Figure 2.23. The crack surface contains distinctive lines or patterns concentric with the origin, which are known as beachmarks. The beachmarks are associated with propagation of the crack at different rates and stress levels as it extends through the blade cross section [11,18].

Microscopic examination of a surface cracked by fatigue, often reveals the phenomenon of fatigue striations as shown in Figure 2.32(b). These closely spaced parallel lines indicate the cycle progression of a high-cycle fatigue crack in a direction normal to them. Care must be exercised in the identification of high-cycle fatigue striations since there are a number of microscopic features with which they can be confused. One of the most important is **Waller** lines shown in Figure 2.32(c). This structure is characteristic of the fracture of brittle phases in otherwise ductile materials. Fatigue striations differ in that they never cross each other, as can be seen clearly in

Figure 2.32(b), which in general, is their defining characteristic [11,18].

2.8 Vibration in Rotor Blades

A major concern in ensuring the mechanical integrity of a gas turbine is blade vibration. There are two significant vibration problems: resonant vibration and flutter. **Resonant** vibration results whenever an exciting force on the blade coincides with a blade natural frequency. When this happens, the amplitude of vibration will increase without bound and is governed by the amount of damping present in the system. **Flutter** is any self-excited oscillation of an aerodynamically lifting surface [26]. To avoid blade failures it is necessary to predict a safe level of blade vibration. For accurate life predictions, a comprehensive understanding is required of both the material behaviour and the state of stress under the total range of operation as defined by the aircraft mission. The previously accepted ± 10 to 20 percent accuracy standard for stress analysis is no longer adequate since, as illustrated in Figure 2.33, small inaccuracies in calculated stresses can result in large life variations [28,35].

Since HCF in blades invariably involves vibratory resonance, the designer's task is to: 1) determine the natural frequencies, 2) determine stimuli and damping and 3) calculate the stresses. The natural frequencies are properties of the dynamic system established by its mass and stiffness distribution [89]. Calculation of blade frequencies is not simple. The method used must be precise and should include effects such as: varying taper and twist, inertia and flexural axis non-coinciding, stiffening effect due to rotation, coupling effects of shroud and disc flexibility [26].

All systems possessing mass and elasticity are capable of free vibration, or vibration which takes place in the absence of external excitation. The energy principle

(Newton's law of motion, $\Sigma F=ma$) can be used to determine the fundamental frequency of multi-mass system or distributed mass systems, provided the motion of every point in the system is known [89].

In a conservative system, the total energy is constant and the differential equation of motion can be established by the principle of conservation of energy. For the free vibration of an undamped system, (i.e., vibration takes place when a system oscillates under the action of forces inherent in the system itself), the energy system is partly kinetic and partly potential. The kinetic energy (K.E.) is stored in the mass by virtue of its velocity, whereas, the potential energy (P.E.) is stored in the form of strain energy in elastic deformation or work done in a force field such as gravity. The total energy being constant, its rate of change is zero. However, if the system is undergoing harmonic motion, the total kinetic energy of the system is zero at the maximum displacement, but is a maximum at the static equilibrium point. For the total potential energy of the system, on the other hand, the reverse is true. Hence:

$$(K.E.)_{\max} = (P.E.)_{\max} = \text{total energy of the system} \quad 2.21$$

This is known as **Rayleigh's** method and the resulting equation will readily yield the natural frequency of the system [90].

When Rayleigh procedure is applied to a single-span beam of uniform mass and stiffness, the end fixity **F** is defined as the moment developed at the ends, divided by the moment for a perfectly rigid support. For instance, **F=0** for pinned supports, while **F=1** for rigidly clamped supports. Using statistical deflection for any value of **F**, the stiffness and mass of an equivalent spring-mass system can be determined, from which the fundamental frequency can be expressed in the form [89]:

$$f_1 = \frac{\alpha}{2\pi} \sqrt{\frac{EIg}{Wl^3}} \quad 2.22$$

where E = modulus of elasticity, lb/in² (N/m); I = moment of inertia of cross-sectional area about axis, in⁴ (m⁴); W = weight of beam, lb (N); l = length of beam, in (m); g = 386 in/s² (9.81 m/s²); and α = non-dimensional coefficient depending on F . The coefficient α and the equivalent stiffness and mass are plotted in Figure 2.34(a). It is often possible to reduce the system to one of the simple systems shown in Figure 2.34(b) and the equations of the natural frequencies are given in:

$$\omega_n \text{ (rad/sec)} = 2\pi f_n \quad 2.23$$

An expression for the frequency of the first mode of transverse vibration can be derived for a **cantilever** using **Rayleigh's** method [90]. For a cantilever shown in Figure 2.34(c) assume:

$$y = y_l \left(1 - \cos \frac{\pi x}{2l}\right) \quad 2.24$$

This is compatible with zero deflection and slope when $x=0$, and zero shear force and bending moment when $x=l$. Thus:

$$\frac{d^2 y}{dx^2} = y_l \left(\frac{\pi}{2l}\right)^2 \cos \frac{\pi x}{2l} \quad 2.25$$

$$\int_0^l EI \left(\frac{d^2 y}{dx^2}\right)^2 dx = EI \int_0^l y_l^2 \left(\frac{\pi}{2l}\right)^4 \cos^2 \frac{\pi x}{2l} dx \quad 2.26$$

$$=EI.y_l^2(\frac{\pi}{2l})^4.\frac{l}{2}, \quad 2.27$$

$$\int_0^l y^2 dm = \int_0^l y_l^2 (1 - \cos \frac{\pi x}{2l})^2 \frac{m}{l} dx \quad 2.28$$

$$=y_l^2 m (\frac{3}{2} - \frac{4}{\pi}). \quad 2.29$$

Hence, assuming the structure to be conservative, i.e., the total energy remains constant throughout the vibration cycle, thus:

$$\omega^2 = \frac{EI.y_l^2(\frac{\pi}{2l})^4.\frac{l}{2}}{y_l^2 m (\frac{3}{2} - \frac{4}{\pi})} \quad 2.30$$

$$= \frac{EI}{ml^3}.13.4 \quad 2.31$$

$$\omega = 3.66 \sqrt{(\frac{EI}{ml^3})}, \quad 2.32$$

$$f = \frac{3.66}{2\pi} \sqrt{(\frac{EI}{ml^3})} \quad 2.33$$

For blades, complex twisted beam theory computer programs or finite-element method (FEM) are employed for calculation of frequencies and mode shapes and for calculating local stress per unit damping and stimulus. Experimental procedures and methods, on the other hand, perform a critical role in the verification and advancement of analytical techniques by providing steady-state and alternating stress/strain response

measurements in these components. The experimental techniques provide references to which the analytical model can be correlated, and then modified to permit use of the analyses over a broad range of engine operational conditions with good accuracy. For example, a good agreement between the FEM and experimental data can be found for the case of zero centrifugal load, however, increasing centrifugal loading is found to strongly effect the character of some of the analytical models at higher mode shapes [28,35,37].

In the early stages of development, blades or blades models are driven by an electromagnet to excite natural frequencies. The results are used to determine strain distributions for each mode of vibration, while a portable vibration pick-up is set to determine the nodal patterns for the respective modes. In many cases, it is desirable to obtain the actual mode over the entire blade and the need for verification of mode shapes by alternate experimental methods is essential to accurate stress determination. The use of holography, which involves a type of photography where precise images are formed from light waves, has proven to be an accurate method for the overall understanding of mode shapes in airfoil structures. However, holography is not utilized as extensively as strain gauges to measure stress because stress is a function of the second derivative of deflection and is not readily determined by holographic methods without an extremely accurate definition and interpretation of the holography fringes [35,36,37].

Once the blade nodal patterns and frequencies are determined under static conditions, the increase in frequency caused by the rotor centrifugal stiffening effect must be determined and a **Campbell** diagram constructed. This diagram, shown in Figure 2.35(a), is both experimental and theoretical. The blade centrifugal and thermal effects due to rotation are determined from an analytical model which must be refined and modified to have the frequencies at zero speed agree with experimental data. The

crossings of the blade natural frequencies with the engine "per rev" excitations are potential high stress resonances. These regions, circled in Figure 2.35(a), are heavily influenced by design configuration selections such as the number, shape, and proximity of upstream and downstream struts and vanes. The Campbell diagram is important in turbomachinery design to aid the selection of airfoil configurations that avoid high-stress resonances within the engine operating range, further, it also serves as a checklist and road-map for instrumented-engine and component-level bench-testing [35].

The basic scheme shown in Figure 2.35(a), however, the main concern should be to ensure that resonances in the first three or four blade modes do not occur with strong excitations at high speed. The reason for focusing on the first few modes, is that substantial changes in the number of blades or geometry may be required for tuning. The higher frequency modes can usually be tuned with minor changes. Also, one can not calculate the higher modes with sufficient accuracy [26]. With long front stage (fan) blades, strong excitations results from intake inflow distortion. In such cases, excitations can be expected at 1/REV, 2/REV, 3/REV, 4/REV, etc., with the strength of excitation decreasing generally with increase in order. Common design practice on such blades is to set the 2/REVx Mode 1 resonance with a margin of 15% on maximum speed. This leaves the widest possible range free of Mode 1 vibration. The next strongest resonance 3/REV Mode 1 will occur at approximately $0.5 N_{\text{design}}$ where the dynamic excitation force should be low and the steady stresses are reduced by a factor of 4 as shown in Figure 2.35(b) [26].

2.9 Vibration Testing of Rotor Blades

Various techniques are available to bench-test blade fatigue strength relative to

service induced stresses caused by vibratory loads. Recently, the method known simply as the amplitude frequency (*a.f.*) has been favoured as the blade acceptance criteria over the original stress measurement method. The stress method used a strain gauge positioned at a standard position (e.g., determined on standard laboratory fatigue machines) on the blade surface and calibrated against the tip amplitude. The test is then run by controlling the tip amplitude to the desired level, which is necessary as the strain gauge invariably fails before the blade [32]. Over the past years, it was worth considering whether stress on a blade is in fact the most important parameter. It was shown that for a number of types of excitation, the degree of vibration is limited by the magnitude of the blade's motion through the air and not to the actual measured stresses [29]. In addition, if all blades were identical, the stress would be proportional to the amplitude manufacturing variations, i.e., local thickness or fillet radii, trailing edge thickness, slight damage marks [29]. The *af* technique, shows that stress in a vibratory blade is proportional to the product of amplitude (*a*) at a known point, usually blade tip, and natural frequency (*f*) of vibration [17,29].

During an *af* rig fatigue test the blade is clamped at the root with a pre-determined torque in a large block of steel; the size of the block used varies with different sizes of blades. There are several current methods of exciting the blades, such as: an air jet, a crystal pack, and a small electro-magnet with an air gap. The most common, particularly for the larger blades, is a large electro-magnetic exciter with a mechanical coupling to the blade base block. By adjusting the length of the exciter rod and the connecting upright rod, the system can be tuned to the particular natural frequency of the blade; in this way the maximum power of the exciter is utilized and there is maximum deflection of the blade with negligible motion of the block. Having tuned the blade and exciter to the natural frequency (*f*, cycle/second) of the blade in

which failure is required, the power is adjusted to give a tip amplitude ($2a$, inch) such that the quotient af is a certain starting value (value is less than one-half of the failing af level). As the test progresses the natural frequency of the blade changes with accumulated damage. A feedback control system monitoring a maximum tip displacement by adjusting for this change in resonances. Once the test resonance has changed by 2%, to maintain maximum tip displacement, the blade is said to have failed [17].

The OEM procedures for conducting vibration tests to determine the fatigue strength of the compressor blades, vanes, and turbine blades is based on the af method and outlined in Reference 23 and 24. These procedures conform to the Standard Methods of Fatigue and Tension Testing and Analysis (ASTM STP 91-A and ASTM E 8M-89b), outlined in Reference 25 and 44. The test parameters established for the purpose of conducting vibration testing on the EB-Weld repaired first stage titanium rotor fan blades are presented in more detail in Chapter 3.

Chapter 3

Experimental Material and Methods

3.1 Fan Blade and Material

The Ti-6Al-4V material used in this study was obtained from two sources: 1) titanium fan blades provided by Hawker Siddeley Canada Incorporated, Orenda Division, of Mississauga, Ontario and 2) stock material purchased from Titanium Limited of Montreal, Quebec.

Twelve new (baseline) titanium fan blades conforming to the OEM requirements were provided by Orenda. The fan blade is 8.5 inches (21.59 cm) long and 3.75 inches (9.52 cm) wide. The blade airfoil thickness varies from 0.02 inch (0.5 mm) at the leading edge to 0.19 inch (4.8 mm) at the mid-span as shown in Figure 3.1. In addition to the new blades, many unserviceable (i.e., scrapped) fan blades were also made available by Orenda for the study as listed in Table 3.1.

The stock material was obtained in 0.125"x36"x48" (0.3175cmx91cmx122cm) and 0.1875"x36"x48" (0.476cmx91cmx122cm) hot rolled plates with subsequent annealing at $1325^{\circ}\text{F} \pm 25$ ($720^{\circ}\text{C} \pm 15$) and cooled at a rate equivalent to air cool. The chemical composition and mechanical properties of the stock material as quoted by Titanium Limited are presented in Table 3.2 and conform to AMS4911D, AMS2249C, and AMS2380A (references 83,84 & 85).

3.1.1 Pre-Forming and Cutting Operations

A standard rolling technique was used to pre-form the replacement patches. The grain flow direction was maintained in the longitudinal rolling direction of the patch as

shown in Figure 3.2, conforming to OEM specification in references 45 and 46.

The Abrasive Water Jet Cut (AWJC) technique was selected over the laser, the electron discharge machine (EDM) and the mechanical (conventional) cutting techniques for the following advantages: 1) no heat distortion or hardened edges (no HAZ), 2) no compression load on material, and 3) narrow kerf (cut width). The mix of garnet abrasives, water and a computer driven "x-y" gantry table, make for an extremely powerful, precise and affordable (low cost) cutting tool. The AWJC technique was used to cut: 1) the FOD'ed area from the blades before EB-welding, 2) the pre-formed replacement patches, and 3) the run-on/off tabs. The original AWJC parameters were established at the Atomic Energy of Canada Limited (AECL) laboratory and were later modified at RCI Waterjets of Mississauga.

The complete parameters used for the pre-forming and the cutting techniques were considered Canada property and therefore will not be provided in this report.

3.1.2 Machining Operations

The machining operations performed in this study were: 1) machining of weld coupons from Ti-6Al-4V stock plates, 2) machining of EB-weld repaired fan blades to original geometry, and 3) belt grinding and finish polishing EB-weld repaired airfoil sections. Standard milling process using a spindle equipped with carbide coated cutters was used to reduce the plate thickness on the weld coupons to simulate the feather edge of the fan blade. The machining of the EB-weld repaired fan blades was performed using a modern Computer-Numerical-Control (CNC) system, which uses a microcomputer to control the motions of the machine components. The CNC machining was performed at M.B.M. Tool and Machine Company Limited, Downsview, using a Rambda Di Ramnatic DT2 digitising copy milling machine equipped with Fidia CNC

control, 2 heads with 20 HP each. The coordinated participation of computers in all phases of the CNC machining involved the use of Computer-Aided-Design (CAD) combined with Computer-Aided-Manufacturing (CAM) to provide greater productivity, higher accuracy, improved efficiency and reduction in tool design effort and prototype development. A silicon carbide belt was used to grind the leading edge of the welded segment and to finish polish the repaired airfoil section.

3.1.3 Coatings Removal and Alkaline Cleaning

The coatings applied on the blade dovetail and the mid-span dampers were chemically removed or stripped from the processed blades. The coating removal was carried out at Orenda following the approved OEM procedures outlined in [99]. In addition, all parts were alkaline cleaned at various stages of the study in accordance with the approved OEM specification outlined in [63].

3.1.4 Non Destructive Inspection (NDI)

Fluorescent Penetrant Inspection (FPI) and Radiographic Inspection (X-ray) were carried out at Orenda for all the welds in this study following OEM Specifications outlined in [60] and [61]. The FPI and the X-ray inspections were conducted at two stages in the study: 1) following the EB-weld process, and 2) after the patch machining process. The FPI was conducted to detect surface cracks while the X-ray inspection was intended for finding internal defects and weld flaws in three areas shown in Figure 3.3. The OEM EB-Weld porosity limits found in reference 58 were compared with acceptable aerospace standards published in AMS2680A, AMS2681A and Pratt & Whitney technical standard (references 64,65,66). The acceptable aerospace industry standards for the maximum allowable size, frequency and separation of indications in fusion welds are

summarized in Table 3.3. In addition to the limits given in Table 3.3, voids and inclusions were not allowed in the weld for 1.0 inch (2.54 cm) along the weld line, starting at the leading edge.

3.1.5 Microstructural Characterization

Metallographic examination was carried out on weld-coupons and on randomly selected EB-weld repaired fan blades. The weld line was examined at five different locations as shown in Figure 3.4. The EB-weld repaired fan blades were AWJC to smaller pieces as shown in Figure 3.5. These pieces were later prepared using standard metallographic techniques to carry out optical microscopy with the aid of two optical microscopes (Olympus M061-PGM3 and Leitz Weiltzar MM6). The etchant used for optical metallography followed the preferred procedures outlined in AMS 2643A [100].

3.2 Electron Beam Welding

The EB-weld operations in this study were carried out at Nu-Tech Precision Metals Inc. of Arnprior, using a Wentgate 4.2 kW (60kV, 70 mA) electron gun mounted inside an 18 inch³ (46 cm³) vacuum chamber. The EB-weld operation was programable allowing precise control of the welding parameters, while an Allen Bradley CNC capable of simultaneous x and y axis movement was used for positioning the fixture holding the fan blade during welding.

The fixture shown in Figure 3.6 was used to mount the blade in the EB-welding chamber and was made from non-magnetic materials to avoid beam deflection during welding. After the blade and patch were properly aligned and secured in the fixture, the welds were started at the leading edge and finished at the trailing edge of the blade. All

EB-welding operations were conducted under high vacuum of 1×10^{-4} Torr (0.0133 Pa) or greater. A ramped profile of the heat energy input was used to account for the increasing thickness of the blade over the length of the joint. Run-on/off tabs were placed at the start and end of the weld joint to eliminate burn through and undercuts problems. The start and end of the points of the weld were located on the patch. The entry and exit paths were designed to be at a tangent to the mating surfaces to eliminate burn through at the start of the weld and undercut at the exit.

A preliminary set of EB-weld parameters was established initially from welding flat Ti-6Al-4V coupons machined from stock plates with variable cross section. The EB-weld was done from both sides of the joint to produce joints with 75% penetration followed by a de-focused cosmetic weld. The heat input was ramped over the length of the joint during welding both sides of the fan blade. The EB gun-to-piece working distance was kept constant during welding. The welding time for the convex and concave sides was 4 seconds each. The time required to cool down the blades between the weld passes was 20 minutes and the set-up time was not included in the figures. The complete EB-weld parameters used in welding the service exposed fan blades were considered Orenda property, and therefore will not be provided in this report.

3.3 Heat Treatment

The only heat treatment schedule used in this study was the stress relief cycle conforming to OEM Specification outlined in references 45 and 46. The heat treatment was performed at Orenda on processed fan blades (i.e., EB-Weld and patch machined to original geometry). The stress relief cycle was carried out in a vacuum furnace with the blade hanging from a root holding device at a vacuum of 1×10^{-4} Torr (0.013 Pa) or

lower and at a temperature of 1020°F (549°C) for two hours and then furnace cooled at a rate equivalent to air cool.

3.4 Fan Blade Surface Definition

The method used in this study for defining the blade surface geometry was "Reverse Engineering". Reverse engineering refers to the process of creating engineering design data such as cartesian coordinates, surfaces, and orthographic drawings from existing components [86]. Coordinate measuring machines (CMM) are widely used tools for performing fast accurate three-dimensional measurements of mechanical components. A typical CMM uses highly precise linear transducers and a microcomputer-based controller to achieve typical measurement accuracies of ± 0.0002 inch (± 0.005 millimetre). The measurements are transmitted to another computer for further processing. Various geometric calculations can be performed using the measurements to quantify characteristics such as angles, diameters, centres of circles, and deviations such as roundness or perpendicularity [86]. The data is then transferred between the CMM and a CAD/CAM unit using the International Graphic Exchange System (IGES), which is a non-proprietary neutral format for exchanging design data between different CAD systems. An existing drawing on a CAD system can be pre-processed using a software program provided by the CAD system to translate the drawing into IGES format file. The IGES file can be post-processed by a program on a completely different CAD system to convert it to a drawing [86].

The CMM measurements of the first stage titanium rotor fan blades were carried out at the Manufacturing Technology Centre (MTC) of the National Research Council of Canada (NRCC) in Ottawa. Six new (baseline) fan blades identified in Table 3.1 were

measured at different sections as shown in Figure 3.7 using a Brown & Sharpe 8202 coordinate measuring machine. NRC proprietary software programs and the Unigraphics II Version 8 CAD programs were used to average the points measured from the six blades, compensate for the probe radius, distribute the points evenly around the section curves, create surfaces for the airfoil, and model the other features of the airfoil such as the platform and the mid-span dampers. The complete average fan blade CAD model was generated as shown in Figure 3.8. Four different data files were delivered to Orenda on magnetic tape media after being translated into a neutral format using an IGES translator supplied by Unigraphics II. The work performed by MTC/NRCC on the fan blade surface definition is detailed in reference 87. The average CAD model that was developed at MTC/NRCC was later post-processed at M.B.M. Tool & Machine limited company, Downsview, into its Anvil 5000 CAD/CAM system. The data was then transferred to the CAM process and the tool path for the complete blade surface model was successfully generated.

3.5 Fan Blade Finite Element Modelling

The finite element method (FEM) can provide numeric solutions for the stress distribution and dynamic behaviour of a component or an assembly which can not otherwise be solved. The finite element method was applied to analyze: 1) the stress distribution in the rotor fan blade under centrifugal load, and 2) to evaluate the natural frequency of the blade. The FEM system was the Numerically Integrated elements for System Analysis (NISA) developed by EMRC, Torry, MI operated from an Appollo workstation.

The 3D geometric FEM model was built based on the dimensions and inspection

tolerances given in the blade engineering drawings used by the overhaul shop manual at Orenda. The FEM model was established using 3D-hexahedral elements with 20 nodes, however, tetrahedral elements with 15 nodes were used in the transition areas such as the dovetail to platform and weld line to airfoil as shown in Figure 3.9. Each node had 3 translation degrees of freedom (DOF). For both the stress and the natural frequency analysis, the blade was constrained at the dovetail. Two local coordinate systems were defined to simulate the constraints imposed upon the contact surfaces as shown in Figure 3.10. The displacement perpendicular to the contact surface was constrained by equation $U_{z-local} = 0$ to simulate the mating disc slot. The axial movement of the blade was constrained by defining zero-plane displacement for the rear face of the dovetail.

Only the centrifugal loads encountered in service were considered in this study due to lack of design data required for the aerodynamic (gas bending) and centroid offsetting loads (centrifugal bending). The FEM was used to calculate the centrifugal load as a distributed body force from the definition of the axis, speed of rotation and the material density. For each element, the elemental mass was calculated from its volume and density and the overall centrifugal load on each element was calculated as:

$$F_{ele} = \int m\omega^2 r dv \quad 3.1$$

where m is the mass, ω is the angular rotational speed, r is the radius, and dv is the element volume. This force was distributed to the 20-nodes in the element based on the shape function and these nodal forces were assembled in the analysis process to represent the distributed centrifugal load due to rotation and thereby providing the stress distribution. In this study, the speed of rotation used was 13200 RPM corresponding to 100% OEM specified maximum rotor speed and a material density, $\rho_{Ti-6Al-4V}$, 0.160 lb/in³ (4.43 gm/cm³) was used.

3.6 Residual Surface Stress Measurements

The grinding process places a compressive residual stress on the immediate airfoil surface with a slight tensile stress in the subsurface. Conversely, residual stresses in the weld create a deeper zone that may be under high tensile stress. The residual stress measurements were carried out using the Proto stress diffractometer installed at the Canada Centre for Mineral and Energy Technology (CANMET), Ottawa. The equipment was fully automated, and capable of measuring residual stresses, both tensile and compressive, in solid metallic components by evaluating the change in diffraction peak position as a function of crystallographic strain at double and position-tilt angles with respect to the test component with a quoted accuracy of ± 2 ksi (± 15 MPa). The residual stress measurements were conducted on three fan blades conditions: 1) Service exposed (baseline), 2) EB-weld + patch machined, and 3) EB-weld + patch machined + stress relieved. The residual surface stresses were measured at nine locations along the weld line and in the HAZ on each side of the weld. The measurements carried out using the concave side of the fan blade as shown in Figure 3.11. All measurements were made such that the stress reported is perpendicular to the weld line.

3.7 Surface Hardness Tests

Rockwell C hardness tests were carried out on the EB-weld repaired fan blades to compare the weld hardness versus the forged baseline blade surface hardness. The measurements were performed using Clark US 12 tester with a 300 lb (150 kg) load referenced on Rockwell C-scale, R_C , and a diamond Brale indenter. The measurements were taken on both sides of the weld line to include the HAZ and along three planes on

the concave and convex surfaces of the fan blade as shown in Figure 3.12. The ASTM standard, E18-89a (reference 81), for conducting hardness tests was followed. The standard required properly prepared specimens and surfaces perpendicular to the indenter and the measurements were taken at a spacing of no less than the 3 times the indenter diameter using the maximum allowable size of impression/indenter and load available for a given instrument. The fan blades were AWJC at selected sections as shown in Figure 3.5 to achieve accurate hardness readings. The hardness tests were carried out on two EB-Weld repair conditions to determine the residual stress level of: 1) the post-weld machining operation, and 2) the stress relief operation. These measurements were used to verify that the stress relief cycle was successful in reducing the residual stresses from welding and machining.

3.8 Natural Frequency Tests

The natural frequency tests carried out in the study were:

- 1) Simplified FEM model with dovetail constraint of 140 kN (32 ksi)- Calculated;
- 2) Unconstrained (free hanging) blades - Experimental; and
- 3) Blades constrained at dovetail and dampers - Experimental.

The simplified FEM model described in section 3.5 was used to establish the first five frequency modes for the first stage titanium rotor fan blade under simulated centrifugal loads of 32 ksi (140 kN) which represent 100% fan rotor speed.

The experimental natural frequency tests were carried out at the Acoustics Laboratory of the NRC located at Uplands Drive in Ottawa. The test apparatus consisted of a metal tipped impact hammer, a signal amplifier, a signal analyzer with graphic

recorder, a charge amplifier and accelerometer. The fan blades were supported with elastic bands on both ends, as shown in Figure 3.13, during the unconstrained natural frequency tests. A matrix of hammer impact locations were established which provided the best frequency peaks relative to the system coherence and accelerometer location.

The natural frequency tests for constrained fan blades were carried out using the same instruments used for the unconstrained blades. However, the blades were mounted in a fixture capable of the application of controlled loads at the dovetail and mid-span dampers as shown in Figure 3.14.

The estimated loads applied during the constrained frequency tests were calculated for different shaft speeds, N , representing the centrifugal loads during engine takeoff, cruise, and descent operations by using equation 2.4 and the blade's characteristics given in Section 3.1.

The experimentally calibrated load versus voltage relationship for the test fixture is shown in Figure 3.15. The test condition load versus voltage values are given in Table 3.4 for takeoff, cruise and descent. A minimum reproducible mid-span damper contact load of 0.5 ksi (2 kN) was applied to all level of shaft speeds since the service value was unknown. A close-up view of the natural frequency test apparatus for a constrained first stage titanium rotor fan blade is shown in Figure 3.16.

3.9 Vibration Tests

The IAR-NRC vibration test rig installed at Building M-14, Montreal Road, Ottawa, was used to carry out the vibration tests. The vibration test apparatus is shown in Figure 3.17 and consists of a 300 lb (136 kg) shaker table, an amplifier transducer, a Bently Nevada proximeter, an Endevco signal conditioner, a phase meter and a

frequency controller. The IAR vibration test facility did not provide a sufficient tip displacement at any of the higher resonances obtained from the natural frequency tests, or the 1.142 inch (29 mm) double amplitude (peak-to-peak) tip displacement measured at the trailing edge as specified by OEM requirements obtained later in the project. Therefore, the vibration tests were restricted to being carried out at a frequency of 190 Hz (first bending) providing a tip displacement of 0.4 inch (10.16 mm) at the leading edge and 0.28 inch (7.11 mm) at the trailing edge, as shown in Figure 3.18. The fan blade was mounted by the dovetail with a load of 32 ksi (140 kN) applied through three 0.25 inch (6.35 mm) bolts at 2 inches (7.62 cm) from the dovetail base and required a counter balance mass of 0.8 lb (364 grams) when no mid-span support load was applied, as shown in Figure 3.19. Surface strains were measured at three locations along the weld line on the blade convex surface during vibration testing as shown in Figure 3.20.

The following definitions applied during vibration testing of the titanium fan blades conforming to OEM requirements set forth in references 23 and 24:

- 1) Mean fatigue strength is the mean stress which results in 50% failures and 50% runouts in 10^7 cycles.
- 2) The stress is that computed at the maximum stress location from the tip displacement.
- 3) The **clamping** requirement is that the dovetail shall be placed in a slot having the same contour as the disk and loaded radially on the bottom of the dovetail with a clamping load high enough to stabilize the natural frequency of the blade, but not so high as to cause premature failure of the blade. This clamping load shall be within the limits given on the drawing of the blade. **All parts shall be excited at their natural first flexural frequency.** Nothing solid shall touch the airfoil. Excitation by

an air siren may be used with the air blast being applied to the concave side of the airfoil. Excitation by a shaker table may also be used with the clamping fixture mounted on the shaker table.

- 4) Consistency of the excitation method must be maintained on any given stage.
- 5) The frequency shall be detected by a crystal pick-up with a fine wire probe contacting the part near the root of the airfoil, or by any non-contacting probe.
- 6) The frequency shall be measured by an electronic counter accurate to $\pm 0.1\% + 1$ count. The **amplitude** is the peak to peak displacement of the tip of the trailing edge and shall be measured with an accuracy of $\pm 2.5\%$ of the total amplitude by a telemicroscope or non-contacting probe. The amplitude shall be maintained within the limits except that it may temporary fall below so long as the time does not exceed 10% of the total test time.
- 7) The stress on the blade shall be determined from the formula:

$$S_a = KA_{tpp} \quad 3.2$$

where S_a = Single amplitude stress at maximum computed stress location (psi)

A_{tpp} = Trailing edge tip peak to peak displacement (Mils)

K = A constant given on the drawing and obtained from the blade fatigue certification report or by instrumenting 10 blades from the first set tested on a given stage to obtain a calibration or relationship of stress at point of failure to trailing edge tip deflection.

- 8) The first specimen shall be tested at the expected mean fatigue strength. If this specimen fails before 10^7 cycles, the next shall be tested at a lower stress level. Each specimen shall be tested until the frequency decreases 2% or to 10^7 cycles at which time the specimen shall be subjected to non-destructive testing methods inspection. Any indication of a crack is defined as a failure.

3.10 Ballistic Impact Tests

The ballistic impact tests were carried out at the NRC Bird Impact facility, building U-69 located at Uplands Drive in Ottawa. The weld repaired blades were mounted in a fixture shown in Figure 3.21 at a pre-set shooting angle as required for a particular energy level and was positioned just ahead of a sand filled pit which is used to trap the spent projectile and possible blade fragments. During testing a dovetail load of 32 ksi (140 kN) simulating takeoff loads was applied for all tests whereas the snubber blocks provided contact support to the mid-span dampers. Magnum 0.44 and 0.38S calibre revolvers and bullet sizes of 240 and 158 grain (1 grain = 64.8 mg) were used to produce the simulated impact energies. The bullet velocity was measured utilizing a Chronograph system incorporating two photo-electric triggering screens as shown in Figure 3.22. A d.c. voltage is supplied to the foil sheets, and as a bullet passes through the screen, contact is made between the two foil sheets that were separated by a tissue paper insulator. An electrical velocity pulse is thus generated which triggers a timer counter. Bullet velocity in either case is calculated from the measured time interval between the start and stop screen. The accuracy of the system was $\pm 1\text{ft/s}$ (0.3 m/s).

The velocity vectors and associated velocity diagram for a typical compressor

stage are shown in Figure 3.23(a) [88]. The air approaches the rotor with a velocity C_1 at an angle α_1 from the axial direction; combining C_1 vectorially with the blade speed U gives the velocity relative to the blade, V_1 , at an angle β_1 , from the axial direction. The bullet velocity V_b (simulating a bird) was denoted in this study as the relative velocity V_1 and C_1 represented the aircraft speed. It was assumed throughout the ballistic tests that there was no inlet guide vane and the entry velocity was purely axial in direction and the velocity diagram at entry to the rotor was a right-angle triangle without tangential or whirl velocity ($C_{w1}=0$) as shown in Figure 3.23(b). The bullet velocity V_b relative to the rotor is given by:

$$V_b^2 = C_1^2 + U^2 \quad 3.3$$

Using equation 2.6 with target point $r_{\text{target}} = 1.05$ ft (32 cm) located at 1 inch (2.54 cm) below the blade tip and for the fan rotation speeds, N , given in Table 3.5, the values for the rotor velocity components U , was obtained. The total (resultant) bullet velocity was calculated using equation 3.3 and aircraft speeds given in Table 3.5. The shooting angle would have been defined as $\beta_1 = \tan^{-1}(U/C_1)$, but since the blades were assembled in the disc at a serration slot angle of 20° , therefore, the bullet shooting angle was equal to: $\beta_1 - 20^\circ$.

The change in Kinetic Energy, ΔT , for a bullet of mass m , which starts from rest and attains a speed v , in a distance S , travelling at constant acceleration in a rectilinear motion (i.e., motion along a straight line) shown in Figure 3.24(a) can be expressed as follows [93]:

$$\Delta T = \frac{1}{2} m (v_2^2 - v_1^2) \quad 3.4$$

where v_1 is the initial velocity and v_2 is the velocity at impact. When neglecting the air resistance, the forces acting in the movement direction based on Newton's equation of motion as shown in the bullet Free Body Diagram (FBD) in Figure 3.24(b) would give:

$$\sum F = ma \quad 3.5$$

The total work, U_w , done by F during a finite movement, S_b , of the constant mass bullet from point 1 to point 2 is :

$$U_w = \int_{S_{b1}}^{S_{b2}} F \cdot dr = F(S_{b2} - S_{b1}) \quad 3.6$$

The total work done by all forces acting on the bullet during an interval of its motion equals to the corresponding change in kinetic energy of the bullet:

$$U_w = \Delta T \quad 3.7$$

that is:

$$F \cdot S_b = \frac{1}{2} m(v_2^2 - v_1^2)$$

$$ma \cdot S_b = \frac{1}{2} m v_2^2; (v_1 = 0)$$

or,

$$a = \frac{v^2}{2S_b} \quad 3.8$$

It should be noted that the linear impulse momentum $G = mv_2 - mv_1$, illustrated in Figure 3.24(c) could not be readily evaluated for the condition after the impact represented in Figure 3.24(c), since in cases where the bullet did not penetrate the blade, it bounced off in undetermined directions.

For a bullet size of 240 ($m=15.55\text{g}$) and 158 grains ($m=10.23\text{g}$), the energy levels required for the calculated velocities in Table 3.5 could not have been achieved without increasing the shooting angle to 90° . The final ballistic impact test matrix for the different energy levels at the modified shooting angles are given in Table 3.6. A sample of calculation for the ballistic impact energies is given in Appendix A.

Chapter 4

Results and Discussion

4.1 Material Response to Repair Processes

4.1.1 Material Response to Abrasive Water Jet Cutting (AWJC)

The major concerns during the AWJC operation were: (1) control of the kerf size, and (2) perpendicularity of the cut. It was observed that during cutting any change in the surface profile resulted in an increase in the working distance (ie. distance between the AWJC nozzle and the working piece) thereby increasing the kerf width and the cut produced was no longer perpendicular relative to the surface. As a result, a gap of 0.005 inch (0.127 mm) was produced between the mating surfaces during assembly for the EB-Welding process. The cutting program was then modified to maintain the initial working distance and to improve the surface roughness profile. The first stage titanium rotor fan blade after removing the FOD area by AWJC operation is shown in Figure 4.1.

4.1.2 Material Response to EB-Welding

During the EB-Welding trials a number of problems were reported as follows:

- Large porosity due to large assembly gaps.
- Linear indications due to lack of fusion at the thicker section of the fan blade.
- Burn through at the thinner section of the fan blade.
- Undercuts in the run-on and run-off regions.
- Mis-match between blade and patch cut surfaces.
- Mis-alignment between the blade and patch contours.

EB-Weld trials were carried out to improve the parameters and to eliminate the burn through and the undercut. The lack of fusion problem was corrected by: 1) beam

power increase, 2) beam focus modification and 3) beam travel speed control over the thicker section of the blade. The large porosity problem was caused by the large gap due to the mis-match between the blade/patch surfaces. Improvement in the AWJC surface roughness profile reduced the gap from 0.005 inch(0.127 mm) to 0.001 inch (0.025 mm).

It was noted that the blade twist angle varied significantly among blades returning from service which resulted in inadequate alignment between the patch and blade contour, thus producing a large rejection rate for the patches. The yield for the patches was improved to 100% after the following modifications: 1) increasing the patch thickness and 2) introducing three height adjustable support pins in the welding fixture to properly align the patch with the blade contour. Acceptable welds were then produced as confirmed by the radiography results presented in a later section. The list of the first stage titanium rotor fan blades that were subjected to the EB-Welding process is given in Table 4.1. Improvement in the weld quality can be traced to the more recent dates welds. An EB-Weld repaired titanium fan blade in the as welded condition is shown in Figure 4.2.

4.1.3 Material Response to Post-Weld Patch Machining

Initially, the EB-Weld repaired fan blades were manually machined and surface finished to the required contour using a tracer milling machine to copy the surface of an undamaged fan blade which was retired for a reason other than FOD. The weld-induced stresses did not cause surface cracking during the post-weld-patch machining. This observation eliminated the need to stress relieve the EB-Welded blades prior to machining as was initially planned in the study. Later, the CNC machining produced fan blades within the dimensional tolerance of service limits required in [94]. A titanium fan blade subjected to post-weld patch machining process is shown in Figure 4.3.

4.1.4 Optical Metallography

An optical micrograph showing the microstructure of the pre-formed replacement patch is shown in Figure 4.4. The microstructure conforms to AMS2380A standards and consists of (bright) equiaxed alpha (α) with (dark) beta (β) around the α grain boundaries. The grain flow direction was kept in the longitudinal rolling direction to match the grain flow direction in the fan blade after welding as required in Figure 3.2.

The microstructure of the service exposed fan blade material section is shown in Figure 4.5. The microstructure displays an equiaxed alpha phase combined with transgranular alpha grains. Some acicular (transformed beta) formation are also visible.

The microstructure of an as EB-Welded fan blade section is shown in Figure 4.6. The micrographs show the weld fusion zone and the heat affected zone with the beam power at 65% to 75% penetration of the total material thickness. The microstructure displays fine acicular martensitic alpha-prime (α') needles dispersed in prior-beta grains. The HAZ consists of a mixture of martensitic α' and primary α . The fusion zone consisted of small columnar grains that are larger in size than the equiaxed grains in the parent metal. The width of the fusion zone is on the order of 0.098 inch (2.5 mm).

Optical micrographs showing the microstructure of EB-Weld blade section subjected to post-weld stress relief heat treatment cycle are presented in Figure 4.7.

The tensile strength of the as-welded and stress relieved specimens were not evaluated in the study but are expected to be greater than that of the parent metal based on the microstructure and related literature data [97]. The fine acicular martensitic α' in the fusion zone when compared to literature data suggests that the weld may exhibit higher strength than that of the parent metal.

The presence of the larger grains in the fusion zone and residual stresses affect the fatigue properties of the as welded specimens, such that it is suggested that it may

take approximately 2.5 times as many cycles to fail the stress relieved welded specimens as the as-welded specimens. Thus residual welding stresses have a detrimental effect on the fatigue properties of the welds. The stress relief cycle is expected to raise the endurance limit to that of the parent metal [97].

4.1.5 X-Ray Radiography

The x-ray inspections of the initial EB-Weld samples were performed by an NDI specialist at the Structures and Materials Laboratory (SML) of the IAR/NRCC and were later performed at Orenda using OEM approved specifications in [61]. The results of the x-ray inspection of all the EB-Weld fan blades performed in this study are given in Table 4.1. The EB-Weld yield distribution which was based on the industry standards for weld flaws given in Table 3.3 indicates that 59% are within the acceptable limits.

4.2 EB-Weld and Machining Residual Stresses

4.2.1 Calculated Centrifugal Tensile Stresses

The blade tip speed U_t was calculated using equation 2.8 for maximum rotor speed N and blades characteristics given in Table 3.5. The maximum calculated tip speed equals to $U_t = 1451$ ft/sec. The maximum centrifugal *tensile* stress was calculated using equation 2.9 and equals to $(\sigma_{ct})_{\max} = +53.281$ ksi (+367 MPa). A sample calculation is given in Appendix B.

4.2.2 FEM Stress Analysis of Fan Blade Subjected to Centrifugal Loading

The Von Mises results of the static FEM stress analysis of the first stage titanium rotor fan blade model subjected to centrifugal load is shown in Figure 4.8. The photo

shows a Von Mises stress level of -30 ksi (-207 MPa) near the weld region. *The results of the FEM predicted stress distribution validates the FOD repair area limits which were initially based on FOD damage observed on fan blades removed from service.*

4.2.3 X-Ray Diffraction Residual Stress Measurements in the EB-Weld Area

The results of the transverse residual surface stress measurements are compared in Table 4.2 for service exposed, EB-Weld repaired and post-weld stress relieved fan blades. Initial trials performed on service exposed and EB-Weld repaired fan blades indicated high surface *compressive* stress of -525 ksi (-3620 MPa). The high compressive stresses were believed to have been caused by: 1) the post-machining grinding operation in the case of the EB-Weld repaired fan blade, and 2) from sands and gas peening for the service exposed fan blade. The blades were then chemically polished with Kroll's reagent in accordance with AMS 2643A to remove a material thickness of 0.005 inch (0.127 mm) from the blade surface.

The results presented in Table 4.2 indicate that the transverse residual stresses measured on the service exposed blade following etching were negligible since they were within the practical accuracy of the machine of ± 2 ksi (± 15 MPa). The stresses in the as EB-Welded and patch machined blade indicated an average *compressive* stress of -26 ksi (-180 MPa) in the thick section of the blade (i.e., plane 1) and a *tensile* stress level of +4 ksi (+30 MPa) in the feather edge section (i.e., plane 3). However, the stresses are still lower than both the calculated tensile and the FEM predicted stress levels reported in sections 4.2.1 and 4.2.2 above.

The compressive residual stress measured on the as EB-Welded and patch machined fan blade thick section was reduced from -26 ksi (-180 MPa) to -6 ksi (-40 MPa) after carrying out a post-machining stress relief cycle. In addition, a compressive

stress of -16 ksi (-109 MPa) was measured on the thin section instead of the tensile +4 ksi (+30 MPa) measured before the heat treatment. The stresses in the HAZ were also compressive but not significantly lower than those obtained along the weld line (≈ 5.5 ksi (38 MPa) less in the thick section). Following a second polishing process (i.e., removing an additional 0.002 inch (0.05 mm) from the surface of the stress relieved blade), the average compressive stress obtained was -9 ksi (-60 MPa), or 60% reduction in stresses.

The residual stress measurement tests confirmed that the induced surface stresses due to EB-Welding and machining were within the calculated and the established FEM limits. The post-machining stress relief cycle proved to be necessary to further reduce the stresses induced in the welds.

4.3 Surface Hardness Tests

The complete results of the surface hardness tests conducted on baseline and two conditions of EB-Welded blades are presented in Reference 95. The hardness results for service exposed versus the EB-Weld repaired blades are shown in Figure 4.9. The typical Rockwell hardness for Ti-6Al-4V material is 30 R_C [42]. The average value obtained for *all* surface hardness tested blades equals to 32 R_C with a standard deviation of ± 3 as summarized in Table 4.3.

The hardness survey of the as post-weld machined blade in Figure 4.9 shows that there is a constant decrease in hardness from 32 R_C in the parent material to 24 R_C in the fusion zone, to 28 R_C in the annealed replacement patch material. The maximum difference in hardness between the parent metal and the fusion zone is therefore 6 R_C .

The hardness survey of the Post-weld stress relieved blade in Figure 4.9 shows

an increase in hardness from 32 R_C in the parent material to 36 R_C in the fusion zone and there is an increase in microhardness variation for the entire width of the fusion zone.

The results of the surface hardness measurement tests indicate an insignificant change in the surface hardness in the weld and the HAZ regions.

4.4 Natural Frequency Tests

4.4.1 FEM Natural Frequency Analysis

The simplified finite element analysis of the first stage titanium rotor fan blade model described in section 3.5 was evaluated under centrifugal loads of 32 ksi (140 kN) and five frequency modes were established as follows:

Mode 1:	133 Hz	first bending
Mode 2:	493 Hz	second bending
Mode 3:	803 Hz	torsion
Mode 4:	1208 Hz	third bending
Mode 5:	1670 Hz	second bending and torsion

The fan blade deformed geometry models under each mode are shown in Figures 4.10 to 4.14.

4.4.2 Experimental Natural Frequency Tests of Unconstrained Fan Blades

A sample output for a natural frequency test, shown in Figure 4.15, provides details of the apparatus and a plot of four (4) impact signals averaged to show resonance frequency peaks when the blade is impacted at the accelerometer location. The second plot, shown in the lower section of the same figure, compares the resonance frequency peaks to the system coherence or quality of the peaks measured. The flat line coherence close to one represents a quality peak while negative peaks are poor data coherence. It

should be noted that the lower frequencies would represent the blade's rigid body characteristics due to the elastic support system and therefore were not considered. In addition, the time of impact (duration) is inversely proportional to the frequency, therefore, for lower frequencies the required impact duration is not possible. Alternative concepts for measurement of natural frequency include a speaker driver acoustic, a pneumatic push system and a shaker with "dull" or "stinger" impact are more complex, expensive and require proper mounting of the fan blade in a fixture.

The natural frequency peaks measured during the test were found to be consistent for *all* the blade conditions (i.e., new, service exposed and EB-Weld-repaired). The average peaks are summarized in Table 4.4 and the complete plots can be found in Reference 95. The average for the first peak is $428\text{Hz} \pm 7\text{Hz}$ as shown in Figure 4.16 which is comparable to the second bending frequency mode obtained from the FEM analysis.

4.4.3 Experimental Natural Frequency Tests of Constrained Fan Blades

A sample output for a natural frequency test of a constrained blade is shown in Figure 4.17. The natural frequency peaks are summarized in Table 4.4 and compared with those obtained from the FEM model and the **unconstrained** tests. The average for the first peak is $346\text{Hz} \pm 12\text{Hz}$ as shown in Figure 4.18 and as expected is lower than the other two frequencies due to the constraint applied on the dovetail and on the mid-span dampers. **The natural frequency peaks for the constrained fan blades were found to be consistent for *all* blade conditions within acceptable standard deviations.** The complete plots are included in [95].

The natural frequency test results provided valuable guide lines for the vibration (HCF) test selection and confirmed the stability of the fan blade frequency resonances

after the EB-weld-repair application.

4.5 Vibration (HCF) Tests

The restricted vibration (HCF) tests, described in section 3.9, were conducted on two (2) EB-weld repaired fan blades with internal weld defects to represent the worst case scenario. The tests were carried out until 10^8 cycles were completed on each blade without any change in natural frequency or blade failure. The X-Ray radiography of HCF tested blades indicated that there was no change in the internal weld defect following the vibration tests.

The surface strains were measured at three locations transverse to the weld line on the blade convex side during the first bending vibration test as shown in Figure 3.20. The strain test results indicate higher strain in the thicker weld region as given in Table 4.5.

The vibration tests conducted in this study provided insufficient tip displacement which was successfully maintained for 10^8 cycles without apparent damage to the weld area. Failures were not achieved when working at the equipment full capacity, therefore, conclusions will not be made with respect to the HCF strength. The vibration tests must be repeated using a higher capacity shaker table to meet the requirements given in the vibration test specifications presented in [96].

4.6 Ballistic Impact Tests

The six (6) EB-weld repaired fan blades, identified in Table 4.1, were subjected to ballistic impact tests. The damage induced to the fan blades due to the ballistic impact

test is shown in Figure 4.19. The damage induced on the blades produced by the bullet impact can be characterized by penetrating, tearing, bending and localized deformation depending on the bullet size and velocities and impact location on the blade. The test results and the damage characterization are listed in Table 4.6.

The ballistic impact tests were successful since the damage produced at the calculated energies were similar to those induced in service. In addition, the NDI (Visual, FPI and X-Ray) inspection performed after the ballistic tests indicate that there was no cracking associated with the EB Weld-repair due to impact. *This confirms that the EB-weld repair process has no effect on the impact properties of the fan blades at the level of simulated FOD test.*

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

This study has addressed the feasibility of developing an electron beam weld repair for foreign object damaged gas turbine titanium rotor fan blades using 0.187 inch (0.475 cm) Ti-6Al-4V pre-formed patch. The EB-Weld repair process was evaluated through five bench tests, including: 1) the surface residual stress, 2) surface hardness, 3) natural frequency, 4) vibration and 5) ballistic impact. The conclusions for this study are summarized as follows:

- (a) The microstructure of the fusion zone for the as welded and the stress relief EB-Welds consisted of acicular martensitic α' needles dispersed in prior β grains. The HAZ consisted of a mixture of α' and primary α . The parent metal consisted of almost equiaxed α with β around the α grain boundaries.
- (b) The fusion zone consisted of small columnar grains that were larger in size than the equiaxed grains in the parent metal.
- (c) The width of the fusion zone was on the order of 0.098 inch (2.5 mm).
- (d) Nondestructive examination using x-ray techniques revealed 59% of EB-Welds are within acceptable aerospace industry flaw limits.
- (e) Maximum hardness occurred in the fusion zone for post-weld heat treated specimens. Post-weld stress relief tended to increase the hardness in the fusion zone and increase the microhardness variation for the entire width of the fusion zone.

- (f) The overall results of the hardness measurement tests indicate insignificant change in surface hardness in the weld and the HAZ regions.
- (g) Post-machine stress relief cycle is necessary to further reduce the stresses induced in the weld region.
- (h) The residual stress measurement confirmed that the induced surface stresses due to welding and machining are low when compared with the limits established from the FEM analysis.
- (i) The natural frequency peaks measured during testing of constrained and unconstrained fan blades were found to be consistent for all the blade conditions.
- (j) The natural frequency test results confirmed the stability of the fan blade frequency resonances after the EB-Weld repair application.
- (k) The vibration tests conducted in this study provided insufficient tip displacement and conclusions were not established with respect to the HCF strength. The vibration tests must be repeated using a higher capacity shaker table.
- (l) The ballistic impact tests confirmed that the EB-Weld repair process has no effect on the mechanical integrity of the fan blades at the level of simulated FOD test.

Based on the results attained in this study the EB-Weld repair scheme presented in Table 1.1 was deemed viable for the repair of foreign object damaged gas turbine titanium rotor fan blades.

5.2 Recommendations for Future Work

The following recommendations should be considered as future work prior to the application of this repair:

- (a) High cycle fatigue (HCF-vibration) tests should be carried out to determine the HCF strength of the EB-Weld.
- (b) Mechanical coupons testing should be carried out to determine the weld-repair fatigue strength. The influence of the EB-Weld repair on fracture toughness, crack growth rates and tensile properties should be determined.
- (c) The repair cost benefit analysis (CBA), which was conducted during the repair development to ensure cost effectiveness presented in Reference 101, revealed a repair cost of 65% of the new part replacement cost and provides 100% reduction in current FOD rejection rate for the engine and fleet examined. The CBA indicates that an additional 20% reduction in cost can be achieved when considering the following recommendation:
 - i. Use a suitable EB-Welding fixture (production type) and a larger vacuum chamber to improve the weld yield and to process more blades during welding.
 - ii. One side-weld will reduce welding time and cost in half, however, all the qualification and mechanical tests would need to be repeated.
 - iii. Conduct spin-pit test prior to engine test as recommended in qualification methodology for airworthiness certification.
- (d) Perform a damage tolerance assessment of the repaired blade to assess the impact of a weld defect upon the service life and inspection intervals.

REFERENCES

- [1] Patnaik,P.C, Pishva,M.R, Elder,J.E., Doswell,W., & Thamburaj,R., "***Repair and Life Extension of Titanium Alloy Fan Blades In Aircraft Gas Turbines,***" Presented at the Gas Turbine and Aeroengine Congress, Toronto, June 4-8, ASME 89-GT-166, 1989.
- [2] Phipps,B., "***Precision Repairs that Help Cut a Large Fuel Bill,***" Welding & Metal Fabrication Journal, pp.267-269, June 1981.
- [3] Griesheim,M., "***Lufthansa Slashes Repair Costs with Electron Beam Welding,***" Welding Journal, pp.51-53, August 1994.
- [4] Sciaky Bros. Inc., "***Jet Engine Blade Rejects Nosedive Under Electron Beam Welding,***" Welding Journal, pp.47-48, September 1994
- [5] "***Fan Failure in Midland Crash,***" Flight International, pp.2, 25 February 1989.
- [6] Federal Aviation Administration Advisory Circular, "***Turbine Engine Foreign Object Ingestion and Rotor Blade Containment Type Certification Procedures,***" AC No. 33-1 B, Initiated by: FS 140, 22 April 1970.
- [7] Federal Aviation Administration Advisory Circular, "***Turbine and Compressor Rotors Type Certification Substantiation Procedures,***" AC No. 33-3, Initiated by: FS 140, 9 September 1968.
- [8] Federal Aviation Administration Advisory Circular, "***Design Considerations Concerning the Use of Titanium in Aircraft Turbine Engines,***" FAR Guidance Manual, AC No. 33-4, Initiated by: ANE-110, 28 July 1983.
- [9] ***Intentionally Left Blank.***
- [10] Dundas,R.E., "***Investigation of Failures in Gas Turbines: Part 1 - Techniques and Principles of Failure Investigation,***" International Gas Turbine & Aeroengine Congress & Exposition, Cincinnati, Ohio, May 24-27, 1993, ASME 93-GT-83.
- [11] Dundas,R.E., "***Investigation of Failures in Gas Turbines: Part 2 - Engineering and Metallographic Aspects of Failure Investigation,***" International Gas Turbine & Aeroengine Congress & Exposition, Cincinnati, Ohio, May 24-27, 1993, ASME 93-GT-84.
- [12] Colangelo,V.J. and Heiser,F.A., "***Analysis of Metallurgical Failures,***" John Wiley & Sons, New York, 1974.

- [13] ASM Metals handbook, 9th edition, Vol. 12: **"Fractography,"** American Society for Metals, Metals Park, Ohio, 1987.
- [14] **"Federal Aviation Regulations For Aviation Technician"**, 1994, PNR ASA-94-FAR-AMT & Its Equivalence **"Transport Canada Aviation - Airworthiness Manual"**, TP6197E.
- [15] Military Specifications, **"Engines, Aircraft, Turbojet & Turbofan, General Specification For,"** For US-Navy, MIL-E-00507E (AS), 1 Sept. 1983.
- [16] General Electric Aircraft Engine Group, **"F404-GE-400 Engine, Ice Ingestion Test"**, Lynn, MA, R79AEG1015, Class 2, 1979.
- [17] Armstrong, E.K., Crowcroft, R.S., & Hunt, T.M., **"Fatigue Life of Compressor Blading,"** Applied Mechanics Convention, IME, Cambridge, April 1966.
- [18] Marsters, G.F., **"Your Aircraft and Metal Fatigue,"** Canadian Flight, pp.29-32, May-June 1990.
- [19] Edwards, J.L., **"Engine Development in an Operators' Market,"** Aeronautical Journal, pp.42-51, 1970.
- [20] **"Commercial Flight Safety, A Report on Aircraft Fatal Accidents Reported in 1988,"** Flight International, pp.50-57, 21 January 1989.
- [21] **"Fan Cracks Blow To Gripen,"** Flight International, pp.17, 14-20 February 1990.
- [22] Jorgens, W., **"Welding In The Aerospace Industry- Design, Materials, Welding Methods, Maintenance,"** 1st International Conference in Berlin, 7-8 December 1978.
- [23] General Electric Specifications, **"Fatigue Testing - Compressor Blades,"** Flight Propulsion Division, GE Spec.No. E50TF127-S1, March 1976.
- [24] General Electric Specifications, **"Fatigue Testing - Compressor Blades and vanes and Turbine Blades,"** Flight Propulsion Division, GE Spec.No. E50TF39-S1, 3 February 1969.
- [25] ASTM STP91-A, **"A Guide For Fatigue Testing and the Statistical Analysis of Fatigue Data,"** 2nd edition, 1964.
- [26] Saravanamutto, H.I.H., Sjolander, S.A., Straznicky, P.V., & MacIsaac, B.D., **"Gas turbine Performance and Design,"** Course Materials, Department of Mechanical and Aerospace Engineering, Carleton University, 1991.

- [27] Willhem,D.P., "**Fracture Mechanics Guidelines For Aircraft Structural Application**," Northtop Corporation, Hawthorne, California, February 1970.
- [28] Danforth,C.E., "**Blade Vibration: Some Key Elements in Design Verification**," J. Aircraft, Vol. 12, No.4, pp.33- 342, April 1975.
- [29] Clough,H.J., "**Blade Excitation Criteria Developed for Aero Derived Engines in Arctic Alaska**," Presented at the Gas Turbine Conference and Exhibition, Anaheim, CA, May 31- June 4, 1989, ASME 87-GT-104.
- [30] James Jeffers II,D., & Meece Jr.,C.E., "**F100 Fan Flutter Problem Review and Solution**," J. Aircraft, Vol. 12, No.4, pp.350-357, April 1975.
- [31] Covin,G.N., and Falls,J.R., "**Development of a Simulated Bird-Strike Test Method**," Journal of Materials, pp.26 -29, May 1990.
- [32] Hager,R.D., "**Test of a Cracked Compressor Blade Repaired by Electron Beam Welding**," NASA Technical Memorandum, Lewis Research Centre, Cleveland, Ohio, NASA TM X-B41.
- [33] Cox,P.J., "**F4040-GE-400 Turbofan Engine Accident Investigation Procedure**," General Electric Technical Information Series, Lynn. MA. R83AEB-027, September 1983.
- [34] Wassell,A.B., "**The Design and Testing of Aero Engines to Minimize Hazard from Birds**," Symposium on Bird Hazards in Aviation, 14 October. 1987.
- [35] Koff,B.L., "**Aircraft Engine Design using Experimental Stress Analysis Techniques**," General Electric Co. Cincinnati, Ohio, 79-1193. AIAA/SAE/ASME 15th Joint Propulsion Conference, June 18-20, 1979.
- [36] Anderson,D.A., "**Modelling of Gas Turbine Engine Compressor Blades For Vibration Analysis**," J. Aircraft, Vol.12, No.4, pp.357-359, April 1975.
- [37] MacBain,J.C., "**Vibratory Behaviour of Twisted Cantilevered Plates**," J. Aircraft, Vol.12, No.4, pp.343-349, April 1975.
- [38] Donachie,M.J., "**Introduction to Titanium and Titanium Alloys**," Titanium and Titanium Alloys, Source Book, ASM, 1982, pp.3.
- [39] "**Properties of Ti-6Al-4V**," Titanium Engineering Bulletin No.1, Titanium Metals Corporation of America, NY, February 1965.

- [40] **"Room and Elevated Temperature Fatigue Characteristics of Ti-6Al-4V,"** Technical Service Department, Titanium Data, Titanium Metals Corporation of America, NY, December 1957.
- [41] **"Heat Treating of Titanium and Titanium Alloys,"** ASM Committee on Titanium and Titanium Alloys, Non-Ferrous Metals Handbook 1997. pp.763-774.
- [42] Alloy Digest, **"Ti-6Al-4V,"** Filling Code: Ti-66, Titanium Alloy, June 1972, Revised September 1992.
- [43] Martindale, I., **"Bird Ingestion Into Aero Engines,"** Global Gas Turbine News, International Gas Turbine Institute, IGTI, Fall 1994, pp.4-7.
- [44] ASTM E 8M-89b, **"Standard Test Methods for Tension of Metallic Materials ,"** pp. 146-160.
- [45] General Electric Specifications, **"6Al-4V Titanium Base Alloy Compressor Blades and Vanes,"** Flight Propulsion Division, GE Spec.No. C50TF22-S8, 19 April 1991.
- [46] General Electric Specifications, **"6Al-4V Titanium Base Alloy Forged Parts,"** Flight Propulsion Division, GE Spec.No. C50TF12-S11, 25 February 1988.
- [47] Military Specification, **"Ti-6Al-4V,"** MIL-HDBK-5D, Change Notice 1 January 1984, pp. 5-57 to 5-88.
- [48] Wei, R.P., **"Aerospace Material Specification for Ti-6Al-4V,"** CODE 3707, pp. 1-29, Addendum December 1980.
- [49] Kaufman, J.G., **"Fracture Toughness Testing,"** Advanced Testing Techniques, ASTM STP 476, American Society for Testing and Materials, 1970, pp. 96-111.
- [50] Gray, T.G.E., Spence, J., and North, T.H., **"Rational Welding Design,"** Butterworth and Company Publishers, 1975. pp.79.
- [51] Powers, J.W., & Laflamme, G.R., **"Aerospace Applications of Electron Beam Welding,"** Proce. of Conference on the Laser vs. the Electron Beam Welding, ed. by R. Baskin, New Jersey, 1985, pp. 324.
- [52] Powers, D.E., & Laflamme, G.R., **"EBW vs. LBW - A Comparative Look at the Cost and Performance Traits of Both Processes,"** Welding Journal, March 1988, pp. 25-31.

- [53] Gould, J.E., Becker, D.W., & Williams, J.C., "*Microstructural Characterization of Ti-Weldments*," Con. Proce. on Physical Metallurgy of Metal Joining, St-Louis, October 16-17, 1980, pp. 199-221.
- [54] Chesnutt, J.C., Rhodes, C.G., & Williams, J.C., "*Relationships Between Mechanical Properties, Microstructure, and Fracture Topography in Alpha-Beta Titanium Alloys*," Special Technical publication 600, ASTM, pp.99-138.
- [55] Stubbington, C.A., "*Metallurgical Aspects of Fatigue and Fracture in Titanium Alloys*," AGARD Conference Proceedings No. 185.
- [56] Schautz, W., & Oberparleiter, W., "*Influence of Weld Flaws on the Fatigue Strength of Electron Beam Weldments in Ti-6Al-4V*," D8012 Ottabrum, Germany, 1991.
- [57] Goldak, J.A., & Bibby, M.J., "*Notched Toughness Tests for Narrow Zones in Welds*," Con. Proce. on Physical Metallurgy of Metal Joining, St-Louis, October 16-17, 1980, pp. 191-198.
- [58] General Electric Specifications, "*Electron Beam Welding*," Flight Propulsion Division, GE Spec.No. P8TF1-S4, 9 February 1990.
- [59] General Electric Specifications, "*Ultrasonic Inspection*," Flight Propulsion Division, GE Spec.No. P3TF1-S9, 11 March 1977.
- [60] General Electric Specifications, "*Fluorescent Penetrant Inspection*," Flight Propulsion Division, GE Spec.No. P3TF2-S15, 21 March 1991.
- [61] General Electric Specifications, "*Radiographic Inspection*," Flight Propulsion Division, GE Spec.No. P3TF5-S7, 19 January 1990.
- [62] General Electric Specifications, "*Examination of Titanium Alloys for Alpha Case*," Flight Propulsion Division, GE Spec.No. P3TF19-1(T), 21 December 1983.
- [63] General Electric Specifications, "*Cleaning of Titanium*," Flight Propulsion Division, GE Spec.No. P4TF3-S3, 15 April 1989.
- [64] American Materials Society, "*Electron Beam Welding for Fatigue Critical Applications*," AMS 2680A, 1 January 1992.

- [65] American Materials Society, "*Electron Beam Welding*," AMS 2681A, 1 January 1992.
- [66] Pratt & Whitney Canada, Technical Standards, "*Radiographic Inspection Standards for Fusion Weld Repair of Impellers*," CXRS E.13, United Technologies, 11 June 1992.
- [67] Baeslack III, W.A., Becker, D.W., & Froes, F.H., "*Advances In Titanium Alloy Welding Metallurgy*," Journal of Metals, May 1984, pp.46-58.
- [68] Linnert, G., "*Temperature Change in Welding*," Welding Metallurgy, Vol. 1., Welding Workbook, Datasheet No. 171a&b, Welding Journal, May 1994, pp.73-74.
- [69] Baeslack III, W.A., & Banas, C.M., "*A Comparative Evaluation of Laser and Gas Tungsten-Arc Weldments in High Temperature Titanium Alloys*," Welding Journal 60, 1981, pp.121s-130s.
- [70] Mahajan, Y., and Baeslack III, W.A., "*Transgranular Fracture of Heat-Treated Weldments in a High-Strength Alpha-Beta Titanium Alloy*," Scripta Metallurgical 13, 1979, pp.1125-1129.
- [71] Becker, D.W., Mahagan, Y., & Baeslack III, W.A., "*Grain Boundary Deformation in a Metastable Beta Titanium Alloy*," Journal of Materials Science 16, 1980, pp.2031-2035.
- [72] Baeslack III, W.A., & Mahagan, Y., "*Observations of Alpha-Beta Interface Sliding in a Titanium Alloy Weld Metal*," Met. Trans., 11A, 1980, pp.1234-1238.
- [73] Baeslack III, W.A., Becker, D.W., & Froes, F.H., "*Weldability of High a High Toughness Titanium Alloy - A Metallurgical Evaluation*," Titanium '80 - Science and Technology, The Metallurgical Society of AIME, Warrendale, Pennsylvania, 1983, pp.2369-2378.
- [74] ASTM E 8M-89b, "*Standard Test Methods for Tension Testing of Metallic Materials [Metric]*," pp.146-160.
- [75] Thamburaj, R., & Goldak, J.A., "*The Influence of Pre-heating Temperature on Plastic Strain Distributions During Welding*," Materials Science and engineering 67, 1984, pp.137-142.

- [76] Thamburaj,R., Wallace,W., & Goldak,J.A. "***Post-Weld Heat-Treatment Cracking in Superalloys.***" International Metals Reviews, Vol.28, No.1, 1983, pp-1-22.
- [77] Borggreen,K., & Wilson,I., "***Use of Post-Weld Heat Treatments to Improve Ductility in Thin Sheets of Ti-6Al-4V.***" Supplement to the Welding Journal, January 1980, 7-S.
- [78] Baeslack III,W.A., "***Technical Note: Evaluation of Triplex Post-Weld Heat Treatments for Alpha-Beta Titanium Alloys.***" Welding Research Supplement 197-S, 1980.
- [79] Leggatt,R., "***Computer Modelling of Transverse Residual Stresses in Repair Welds.***" Welding Journal, November 1991, Welding Journal Supplement, pp.299-S to 303S.
- [80] Robelotto,R., Lambase,J.M., & Toy,A., "***Residual Stresses in Welded Titanium and their Effects on Mechanical Behaviour.***" Welding Research Supplement 289-S, July 1968.
- [81] ASTM E 18-89a, "***Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials.***" pp.176-188.
- [82] ASTM E140-86, "***Hardness Conversion Tables for Metals.***".
- [83] Aerospace Material Specification, "***Chemical Check Analysis Limits Titanium and Titanium Alloys.***" AMS2249C, 1 October 1985.
- [84] Aerospace Material Specification, "***Titanium Alloy Sheet, Strip, and Plate, 6Al-4V Annealed.***" AMS4911D, 15 January 1977.
- [85] Aerospace Material Specification, "***Approval and Control of Premium-Quality Titanium Alloys.***" AMS2380A, 1 January 1983.
- [86] Kwok,W.L., & Eagle,P.J., "***Reverse Engineering: Extracting CAD Data from Existing Parts.***" Mechanical Engineering, March 1991, pp.52-54.
- [87] Van dan Berg,B., Kowala,S., & Johnston,D., "***F404 Fan Blade Shape Capture.***" NRC, Institute of Mechanical Engineering, Ottawa, 11 February 1992 (Internal Controlled/limited Document).
- [88] Cohen,H., Rogers,G.F.C., Saravanamuttoo,H.I.H., "***Gas Turbine Theory.***" 3rd edition, Longman Scientific & Technical Publisher, England, 1987.

- [89] Avallone.E.A., & Baumeister III,T., "**Mark's Handbook for Mechanical Engineers.**" Mc Graw Hill company, 1987.
- [90] Beards,S.F., "**Vibrations and Control Systems,**" Allis Herwood limited, England, 1988.
- [91] Boresi,A.P., Sidebottom,O.M., Seely,F.B., Smith,J.O., "**Advanced Mechanics of Materials,**" Third edition, John Wiley & Sons Inc., Toronto, 1978.
- [92] Hilley,M.E., Larson,J.A., Jatczak,C.F., Ricklefs,R.E., "**Residual Stress Measurements by X-ray Diffraction,**" SAE J784a, Society of Automotive Engineers Inc., Warrendale, P.A., 1971.
- [93] Meriam,J.L., "**Statics and Dynamics,**" Engineering Mechanics, SI Version, John Wiley & Sons Inc., 1980.
- [94] Canadian Forces Technical Order, "**Intermediate Maintenance for Fan Rotor Assembly,**" CFTO A1-F404-A-MM1-210.
- [95] Orenda Internal Report, "**Electron Beam Weld Repair and Qualification, Phase II,**" Report No. ES92/10.45, 1994.
- [96] Orenda Internal Report, "**Test Specification for High Cycle Fatigue (Vibration) Test,**" Report No. HCF.EBW, Contract No. SV W8477-4-YN02/00/A, June 1995.
- [97] Migliette,W., "**Comparison Between EBW and GTAW for Turmo IV C Compressor Blade Repairs,**" Journal of Engineering for gas Turbines and Power, Vol. 117, July 1995, PP. 545-553.
- [98] Orenda Internal Report, "**Room Temperature- Low Cycle Fatigue Test,**" Report No. RT-LCF.EBW, Contract No. SV W8477-4-YN02/00/A, June 1995.
- [99] Military Support Instruction, "**Removal of DAG & Cu-Ni-In Coatings from Titanium Blades,**" Orenda Internal Instruction, MSI-F404-255.
- [100] Aerospace Material Specification, "**Structural Examination of Titanium Alloys - Chemical Etch Inspection Procedure,**" AMS 2643A, 1 April 1988.
- [101] Orenda Internal Report, "**Qualification Methodology for Advanced Gas Turbine Repairs - Cost Benefit Analysis,**" Contract Number SV.W8477-4-YN01/00/A, December 1995.

TABLES

PROCEDURE	PROCESS
1. Incoming Cleaning/ Damage Classification	
2. Removal of FOD Area	Abrasive Water Jet Cutting (AWJC)
3. Blade geometry Inspection	Geometry & Twist Angle Inspection
4. Preparation of Replacement Patch	Rolling, AWJC
5. Pre-Weld cleaning	Alkaline
6. Welding	Electron Beam weld (EBW)
7. Post-Weld Inspection/ Machining	<ul style="list-style-type: none"> - Visual x10, Fluorescent Penetrant (FPI) - X-ray - NC-milling
8. Post-Machining Inspection/ Cleaning/ Heat treatment	<ul style="list-style-type: none"> - Visual, FPI, X-ray, - Geometry & Twist Angle Inspection - Alkaline - Stress relief
9. Post Heat treat Inspection/ Coating Application	<ul style="list-style-type: none"> - FPI - Shot peen airfoil, dovetail & root - Spray/brush
10. Final Inspection	<ul style="list-style-type: none"> - Chord dimension check - Blade airfoil thickness check - Blade length check - Mid-span dimension check - Angle of twist check - Coating thickness check
11. Re-classification	<ul style="list-style-type: none"> - Moment weight - Stamping as electron beam welded blade (EBWB)

Table 1.1 Electron Beam Weld Repair Scheme for Foreign Object Damaged First Stage Rotor Fan Blade.

Element	Sheet, Strip, Plate & Wire Weight percent	Bar, Billet, Tubing & Extrusion Weight percent
Aluminum	5.5-6.5	5.75-6.75
Vanadium	3.5-4.5	3.5-4.5
Iron	0.25 max	0.25 max
Carbon	0.08 max	0.08 max
Nitrogen	0.05 max	0.05 max
Hydrogen	0.015 max	0.0125 max
Oxygen*	0.20 max	0.20 max

* The maximum oxygen content of the Ti-6Al-4V ELI grade is 0.13 %

Table 2.1 Chemical composition of Ti-6Al-4V [39, 45,46].

Mill Form	Stress Relieving	Annealing	Solution Treating	Aging
Sheet & light plate	1000 to 1200°F 1 to 4 hrs AC	1350 ± 25°F 4 hrs FC to 1050°F AC	1660 to 1700°F 5 to 10 min WQ	1000°F-4 hrs AC
Plate over 1/4 inch	1000 to 1200°F 1 to 4 hrs AC	1350 ± 25°F 4 hrs FC to 1050°F AC	1700 to 1750°F 1/2 hr WQ	1000°F-4 hrs AC
Bar, Forgings and Extrusions	1000 to 1200°F 1 to 4 hrs AC	Same as for sheet and plate except air cool permissible because of slower cooling rate of heavier sections	1750 ± 25°F 2 hrs WQ	1000°F-4 hrs AC

Note: Solution Treating and Aging Cycles may be varied slightly from those for specific applications.

Table 2.2 Recommended heat treatments for Ti-6Al-4V [39].

Heat Treatment	Heat Treatment Schedule	Microstructure
Mill Anneal	732°C/1hr/AC	- Equiaxed alpha with intergranular beta - Some acicular alpha
Recrystallization Anneal	926-955°C/4hr/FC 760°C/AC	- Equiaxed Alpha with intergranular beta
Beta Anneal	1038°C/0.2-1hr/AC + 732°C/2hr/AC	- Coarse acicular alpha
Beat Quench	1038°C/0.2-1hr/WQ + 732°C/2hr/AC	- Fine acicular alpha
Solution Treat and Age	955°C/1hr/WQ + 600°C/4hr/AC	- Equiaxed alpha grains with grains of fine acicular alpha
Solution treat and Overage	955°C/1hr/WQ + 700°C/4hr/AC	- Equiaxed alpha in a matrix of fine acicular alpha
Note: AC - air cool; FC - furnace cool; WQ - water quench.		

Table 2.3 Conventional heat treatment for Ti-6Al-4V [41].

Sheet (up to 0.187 inch)				Plate (0.1875 inch and over)	
Property	Annealed	Solution Treated	Aged	Annealed	Aged
Ultimate tensile Strength -psi Guaranteed Minimum Typical	130,000	---	160,000	130,000	160,000 ⁽⁵⁾
	144,000	152,000	168,000	136,000	Varies with gauge
Yield Strength (0.2% offset)-psi Guaranteed Minimum Typical	120,000	145,000 ⁽⁸⁾	145,000	120,000	145,000 ⁽⁵⁾
	136,000	132,000	154,000	128,000	Varies with gauge
Elongation in 2 inch-Percent Guaranteed Minimum Typical	10 ⁽⁶⁾	8 ⁽³⁾	5 ⁽⁴⁾	10	8 ⁽⁷⁾
	14	12	8	16	15
Reduction in Area, Percent Guaranteed Minimum Typical	---	---	---	20 ⁽²⁾	20 ⁽²⁾
	---	---	---	38	36
Bend radius-Press Brake - 105° Guaranteed Minimum Typical	4.5 ⁽¹⁾	4.5 ⁽¹⁾	---	---	---
	3.3	3.5	---	---	---
(1) For sizes less than 0.070 inch. 5.0 for 0.070 inch and over.					
(2) Reduction in area only on plate sizes 3/8 inch and over.					
(3) For over 0.032 inch. 6% for 0.020 to 0.032 inch.					
(4) For 0.050 inch and over. 4% for 0.033 to 0.049 inch. 3% for 0.020 to 0.032 inch.					
(5) For sizes over 1/4 inch.					
(6) 10% for 0.025 inch and over. 8% for 0.017 to 0.024 inch. 6% for less than 0.017 inch.					
(7) For sizes over 3/8 inch. 5% for 0.1875 to 3/8 inch incl.					
(8) Guaranteed maximum.					

(1) For sizes less than 0.070 inch. 5.0 for 0.070 inch and over.

(2) Reduction in area only on plate sizes 3/8 inch and over.

(3) For over 0.032 inch. 6% for 0.020 to 0.032 inch.

(4) For 0.050 inch and over. 4% for 0.033 to 0.049 inch. 3% for 0.020 to 0.032 inch.

(5) For sizes over 1/4 inch.

(6) 10% for 0.025 inch and over. 8% for 0.017 to 0.024 inch. 6% for less than 0.017 inch.

(7) For sizes over 3/8 inch. 5% for 0.1875 to 3/8 inch incl.

(8) Guaranteed maximum.

Table 2.4 Mechanical properties of Ti-6Al-4V sheet and plate [39].

Weld direction in relation to test condition	Test Temp. (°F)	Bendability R/T	UTS (KSD)	YS (KSD)	EI (%)	NTS $K_t=3$
Longitudinal	R.T.	10.0	147	139	5.0	164
Transverse	R.T.	10.0	140	127	8.0	164
Transverse	600		97	87	6.5	
Transverse	800		91	79	11.0	
Transverse	1000		72	60	17.5	
Longitudinal	1000		82	67	7.0	
Longitudinal	-100		167	155	2.5	180
Longitudinal	-320		221	210	1.5	204
Longitudinal	-423		275	267	1.5	217

Table 2.5 Mechanical properties of as-welded 0.062" Ti-6Al-4V sheet weldments with matching or no filler [39].

Heat Treat Condition	Temperature (°F)	Time (HR)
Ann.	900	20
	1000	2
ST [*]	1100	1
	900	15
STA	1000	4
	900	15
	1000	5

*These cycles will also age the metal.

Table 2.6 Recommended stress relieving times and temperatures for Ti-6Al-4V weldments [39].

Thermal Treatment	UTS (KSI)	YS (KSI)	EI (%)	Failure Location
Weld + 1000°F -24 hr.	141	130	(in 2")	(in 1/8")
Weld + 1150°F -24 hr.	136	126		
Weld + 1350°F -24 hr.	130	125		
STA + Weld	167(93.4)	156(96)		HAZ
ST + Weld + 900°F -4hr.	170(97.2)	159(97.7)	5.7	HAZ
All welds transverse to testing direction			11.3	
Figures in parentheses are joint efficiencies.				

Table 2.7 Room temperature mechanical properties of 0.062" Ti-6Al-4V sheet weldments with matching or no filler at various heat treatment cycles [39].

AIRWORTHINESS STANDARDS: AIRCRAFT ENGINES

FAR 33

AWM CHAPTER 533

Foreign Object	Test Quantity	Speed of Foreign Object	Engine Operation	Ingestion
Birds:				
3-oz. size	One for each 50 sq. in. of inlet area or fraction thereof up to a maximum of 16 birds. 3-oz. bird ingestion not required if a 1 1/2-lb bird will pass the inlet guide vane into the rotor blades.	Liftoff speed	Takeoff.	In rapid sequence to simulate a flock encounter and aimed at selected critical areas.
1 1/2 lb. size	One for the first 300 sq. in. of inlet area, if it can enter the inlet, plus one of each additional 600 sq. in. of inlet area or fraction thereof up to a maximum of 8 birds.	Initial climb speed of typical aircraft.	Takeoff.	In rapid sequence to simulate a flock encounter and aimed at selected critical areas.
4lb. size	One if it can enter the inlet.	Maximum climb of typical aircraft if the engine has inlet guide vanes. Liftoff speed of typical aircraft, if the engine does not have inlet guide vanes.	Maximum cruise Takeoff.	Aimed at critical areas. Aimed at critical areas.
Ice:	Maximum accumulation on a typical inlet cowl and engine face resulting from a 2-minute delay in actuating anti-icing system or a slab of ice which is comparable in weight or thickness for that size engine.	Sucked in.	Maximum cruise.	To simulate a continuous maximum icing encounter at 25 degrees F.
Hail:				
(0.8 to 0.9 specific gravity)	For all engines: with inlet area of not more than 100 sq.in.: one 1-in hailstone. With inlet area of more than 100 sq.in. one 1-in and one 2-in hailstone for each 150 sq.in. of inlet area or fraction thereof. For supersonic engines (in addition): 3 hailstones each having a diameter equal to that in a straight line variation from 1-in at 35,000 ft to 1/4 in. at 60,000 ft. using diameter corresponding to the lowest supersonic cruise altitude expected.	Rough air flight speed of typical aircraft. Supersonic cruise velocity. Alternatively, use subsonic velocities with larger hailstones to give equivalent kinetic energy.	Maximum cruise at 15,000 ft. altitude. Maximum cruise.	In a volley to simulate a hailstone encounter. One half the number of hailstones aimed at random area over the face of the inlet and the other half at the critical face areas. Aimed for critical engine face area.
Water:	At least 4 percent of engine airflow by weight.	Sucked in:	Flight idle, acceleration, takeoff, deceleration.	For 3 minutes each at idle and takeoff, and during acceleration and deceleration in spray to simulate rain.

Note: The term "inlet area" as used in this section means the engine inlet projected area at the front face of the engine. It includes the projected area of any spinner or bullet nose that is provided.

Table 2.8 FAA and TC airworthiness standards for aircraft engines foreign objects ingestion. [14]

Failure Mechanisms of Gas Turbine Components			
		Heavy-Duty Gas Turbines	Aero-derivative Gas Turbines
Compressors	Disks	High-cycle fatigue. Low-cycle fatigue.	High-cycle fatigue. Low-cycle fatigue.
	Blades	High-frequency fatigue due to resonant vibration. High-frequency fatigue due to flutter.	High-frequency fatigue due to resonant vibration. High-frequency fatigue due to flutter.
	Stator Vanes	Clashing and clanging due to surge. Clashing due to surge. High-frequency fatigue (resonant vibration or flutter).	Clashing and clanging due to surge. Clashing due to surge. High-frequency fatigue (resonant vibration or flutter).
Combustors	Liner	Thermal fatigue. Overheating.	Thermal fatigue. Overheating.
Turbines	Disks	Low-cycle fatigue, possibly aggravated by thermal gradients.	Low-cycle fatigue, possibly aggravated by thermal gradients.
	Blades	High-frequency fatigue due to resonant vibration. High-frequency fatigue due to flutter.	Fracture due to embrittlement. High-frequency fatigue due to resonant vibration.
	Nozzle Vanes	Creep-rupture. Thermal fatigue. Creep deflection. Overheating.	Creep-rupture. Thermal fatigue. Overheating.

Table 2.9 Failure mechanisms of gas turbine components [11].

MATERIAL	E	ρ	UTS	UTS/ρ	$(E/\rho)^{1/2}$	$(E\rho)^{1/2}$
Aluminum	10	0.098	55	560	10.1	1.01
Titanium	18	0.163	130	800	10.5	0.58
Steel	30	0.280	140	500	10.4	0.35
Glass Composite	7	0.074	140	1900	9.7	1.39
Carbon-epoxy	25	0.065	150	2300	19.6	0.78
Boron-aluminum	30	0.110	100	900	16.5	0.55

Table 2.10 Comparisons of basic properties - Composites [26].

ITEM #	CONDITION	PROCESS
1	NEW	CR + CMM + NF
2	NEW	CR + CMM + NF
3	NEW	CR + CMM + NF
4	NEW	CR + CMM + NF
5	NEW	CR + CMM + NF
6	NEW	CR + CMM + NF
7	NEW	NF
8	NEW	NF
9	NEW	NF
10	NEW	NF
11	NEW	NF
12	NEW	NF
13	SERVICE EXPOSED	EBW
14	SERVICE EXPOSED	EBW
15	SERVICE EXPOSED	EBW+PM+CR+SR+SP+CA
16	SERVICE EXPOSED	EBW
17	SERVICE EXPOSED	EBW
18	SERVICE EXPOSED	EBW
19	SERVICE EXPOSED	EBW
20	SERVICE EXPOSED	EBW
21	SERVICE EXPOSED	EBW
22	SERVICE EXPOSED	EBW
23	SERVICE EXPOSED	EBW
24	SERVICE EXPOSED	EBW
25	SERVICE EXPOSED	EBW+PM+CR+SR+NF+BI
26	SERVICE EXPOSED	EBW+PM+CR+SR+NF+BI
27	SERVICE EXPOSED	EBW+PM+CR+SR+NF+V
28	SERVICE EXPOSED	EBW+PM+CR+SR+NF+BI
28	SERVICE EXPOSED	EBW+PM+NF+RCH
29	SERVICE EXPOSED	EBW+PM+NF
30	SERVICE EXPOSED	EBW+PM+CR+SR+NF+BI
31	SERVICE EXPOSED	EBW+PM+CR+SR+NF+BI
32	SERVICE EXPOSED	EBW+PM+CR+SR+NF+ET+SSM

Process: CR: Coatings Removal; CMM: Coordinate Measuring Machine; NF: Natural Frequency Test; EBW: Electron Beam weld; PM: Patch Machine; SR: Stress Relief; SP: Shot Peen; CA: Coating Application; BI: Ballistic Impact; RCH: Rockwell Hardness Test; SSM: Surface Stress Measurement Test; ET: Etched.

Table 3.1. List of Fan Blades Used in the Study.

ITEM#	CONDITION	PROCESS
33	SERVICE EXPOSED	EBW+PM+CR+SR+NF
34	SERVICE EXPOSED	EBW+PM+CR+SR+NF
35	SERVICE EXPOSED	EBW+PM+CR+SR
36	SERVICE EXPOSED	EBW+PM+CR+SR+NF+SP+RCH
37	SERVICE EXPOSED	EBW+PM+NF
38	SERVICE EXPOSED	EBW+PM+CR+SR+NF+BI
39	SERVICE EXPOSED	EBW+PM
40	SERVICE EXPOSED	EBW+PM
41	SERVICE EXPOSED	EBW+PM
42	SERVICE EXPOSED	EBW+PM
43	SERVICE EXPOSED	EBW+PM+NF+ET+SSM+RCH
44	SERVICE EXPOSED	EBW+PM
45	SERVICE EXPOSED	EBW+PM
46	SERVICE EXPOSED	EBW+PM
47	SERVICE EXPOSED	EBW+PM+RCH
48	SERVICE EXPOSED	EBW+PM
49	SERVICE EXPOSED	EBW+PM
50	SERVICE EXPOSED	EBW+PM
51	SERVICE EXPOSED	EBW+PM
52	SERVICE EXPOSED	EBW+PM
53	SERVICE EXPOSED	NF+ET+SSM+RCH
54	SERVICE EXPOSED	CR+NF
55	SERVICE EXPOSED	EBW+PM+CR+SR+SP+CA
56	SERVICE EXPOSED	EBW+PM+CR+SR+SP+CA
57	SERVICE EXPOSED	EBW+PM+CR+SR+SP+CA
58	SERVICE EXPOSED	EBW+PM+CR+SR+SP+CA
59	SERVICE EXPOSED	RCH
60	SERVICE EXPOSED	RCH
61	SERVICE EXPOSED	RCH
62	SERVICE EXPOSED	RCH

Process:

CR: Coatings Removal; CMM: Coordinate Measuring Machine; NF: Natural Frequency Test; EBW: Electron Beam weld; PM: Patch Machine; SR: Stress Relief; SP: Shot Peen; CA: Coating Application; BI: Ballistic Impact; RCH: Rockwell Hardness Test; SSM: Surface Stress Measurement Test; ET: Etched.

**Table 3.1. List of Fan Blades Used in the Study.
(Continued).**

TEST REPORT

TITANIUM LIMITED / LIMITEE		DATE AUGUST 7TH 1991	OUR ORDER ITEM NO 26890/1	CUSTOMER ORDER NO 10-737201							
MONTREAL: 5055 rue Levy, St. Laurent, Qc H4R 2N9 Tel.: (514) 334-5781 Fax: (514) 334-3410		VANCOUVER: #175-2251 No. 5 Road, Richmond, B.C. V6X 1S9 Tel.: (604) 276-8433 Fax: (604) 276-8483									
CUSTOMER NAME HAWKER SIDDELEY CANADA INC., ORENDA DIVISION 3160 DERRY ROAD EAST MISSISSAUGA, ONTARIO											
MATERIAL DESCRIPTION		NO PCS	LINEAR FEET WEIGHT	HEAT NO							
.125" X 36" X 48" LG.		1		861929							
SPECIFICATION AMS 4911F 6AL-4V											
CHEMICAL ANALYSIS											
N	C	H	Fe	O ₂	Al	V	Sn	Pd	Mo	Zr	Ni
.011	.01	47 PPM	.17	.121	5.8	3.8					
RESIDUALS EACH	RESIDUALS TOTAL	Ti	Cr	Ta	Cb	Y	O PLUS Fe	Mn	Si	Mg	
		BAL									
MECHANICAL PROPERTIES											
TENSILE STRENGTH KSI	L: 147.6 T: 148	L: T:	HARDNESS								
YIELD STRENGTH KSI	L: 139.4 T: 141.7	L: T:									
% ELONGATION	L: 14 T: 13	L: T:	GRAIN SIZE								
% REDUCTION IN AREA	L: T:	L: T:									
BEND TEST		5.0 TR			OTHER DATA						
STATIC NOTCH STRESS RUPTURE											
ULTRASONIC TEST											
FLARE TEST											
IMPACT TEST											
FLATTENING TEST											
HYDROSTATIC TEST											
EDDY CURRENT TEST											
PNEUMATIC TEST											
REVERSE FLATTENING TEST											
DYE PENETRANT											
RADIOGRAPHIC (X-RAY) TEST											
MICROSTRUCTURE PERFORMED		MEET SPEC. REQUIREMENTS									
MICROSTRUCTURE COMPLIANCE											
MACROSTRUCTURE PERFORMED		MEET SPEC. REQUIREMENTS									
MACROSTRUCTURE COMPLIANCE											
DATE AUGUST 7TH 1991					SIGNED <i>Kia Kary</i>						

THIS IS TO CERTIFY THAT THE ABOVE TEST RESULTS ARE CORRECT AS CONTAINED IN THE RECORDS OF THE COMPANY.

Table 3.2. Chemical composition & mechanical properties of Ti-6Al-4V plates as quoted by Titanium Limited.

TEST REPORT

TITANIUM LIMITED / LIMITEE		DATE	OUR ORDER ITEM NO	CUSTOMER ORDER NO							
		AUGUST 7TH 1991	26890/2	10-737201							
MONTREAL: 5055 rue Levy, St. Laurent, Qc H4R 2N9 Tel: (514) 334-5781 Fax: (514) 334-3410		VANCOUVER: #175-2251 No 5 Road, Richmond, B.C. V6X 1S9 Tel: (604) 276-8433 Fax: (604) 276-8483									
CUSTOMER NAME HAWKER SIDDELEY CANADA INC. ORENADA DIVISION 3160 DERRY ROAD EAST MISSISSAUGA, ONTARIO											
MATERIAL DESCRIPTION		NO	PCS	LINEAR FEET WEIGHT	HEAT NO						
.187" X 36" X 48" LG.		1			T 8798						
SPECIFICATION: 6AL-4V TITANIUM ALLOY PLATE AMS 4911F											
CHEMICAL ANALYSIS											
N	C	F	Fe	O ₂	Al	V	Sn	Pd	Mo	Zr	Ni
.014	.01	.0050	.21	.198	6.07	3.97					
RESIDUALS EACH	RESIDUALS TOTAL	Ti	Cr	Ta	Cb	Y	O Plus Fe	Mn	Si	Mg	
		REM									
MECHANICAL PROPERTIES											
TENSILE STRENGTH KSI	L 178	T 187	HARDNESS								
YIELD STRENGTH KSI	L 170	T 178									
% ELONGATION	L 10	T 10	GRAIN SIZE								
% REDUCTION IN AREA	L 29.5	T 31.5									
OTHER DATA											
BEND TEST											
STATIC NOTCH STRESS RUPTURE											
ULTRASONIC TEST											
FLARE TEST											
IMPACT TEST											
FLATTENING TEST											
HYDROSTATIC TEST											
EDDY CURRENT TEST											
PNEUMATIC TEST											
REVERSE FLATTENING TEST											
DYE PENETRANT											
RADIOGRAPHIC (X-RAY) TEST											
MICROSTRUCTURE PERFORMED											
MICROSTRUCTURE COMPLIANCE											
MACROSTRUCTURE PERFORMED											
MACROSTRUCTURE COMPLIANCE											
THIS IS TO CERTIFY THAT THE ABOVE TEST RESULTS ARE CORRECT AS CONTAINED IN THE RECORDS OF THE COMPANY. SIGNED
DATE AUGUST 7TH 1991											

Table 3.2. Chemical composition & mechanical properties of Ti-6Al-4V plates as quoted by Titanium Limited. (Continued)

SIZE OF INDICATIONS IN WELDS (INCH (mm))	MAXIMUM NUMBER OF INDICATIONS PER INCH OF WELD	MINIMUM SEPARATION BETWEEN ADJACENT INDICATIONS
Greater than 0.020 (0.51) to 0.025 (0.64)	1	6D (see Note)
Greater than 0.015 (0.38) to 0.020 (0.51)	2	6D or 0.100 inches (Whichever is greater)
Greater than 0.010 (0.25) to 0.015 (0.38)	3	0.100 inches
Greater than 0.005 (0.13) to 0.010 (0.25)	5	0.100 inches
Note: D is the greatest dimension of the larger of the two adjacent indications.		

Table 3.3 Industry Standards for EB-Weld Flaw Limits [58 to 66].

<i>SIMULATED AIRCRAFT CONDITION</i>	<i>ENGINE</i>	<i>DOVETAIL LOADS (kN)</i>	<i>STRAIN SENSOR (VOLTS)</i>	<i>DAMPERS LOADS (kN)</i>	<i>STRAIN SENSOR (VOLTS)</i>
TAKEOFF	IRP	140	7.81	2	1
CRUISE	60%IRP	112	6.24	2	1
DESCEND	FI	30	1.67	2	1

Table 3.4 Dovetail Loads Measured during Strain Gauge Calibration.

SIMULATED AIRCRAFT CONDITION	Engine Operating Condition	AIRCRAFT VELOCITY, C_i (ft/sec)	FAN ROTATION SPEED, N (RPM)	BLADE TIP SPEED, U_i (ft/sec)	BULLET VELOCITY, V_i, RELATIVE TO ROTOR SPEED (ft/sec)	KINETIC ENERGY (ft-lb)	CENTRIFUGAL FORCE (lb-ft)	SHOOTING ANGLE (θ, 20°) (DEGREE)
TAKEOFF	Intermediate Rated Power (IRP)	223 (Mach 0.2)	13,200	1451	1468	1151	31.4	61
CRUISE	60%IRP	796 (Mach 0.8)	11,800	1297	1522	1237	25.1	38
DESCEND	FI	408 (Mach 0.38)	6,100	671	785	329	6.71	39

Table 3.5. Parameters for Ballistic Impact Tests.

Blade No.	Bullet Calibre (grain)	Bullet Velocity (ft/sec)	Kinetic Energy (ft-lb)	Shooting Angle (degree)	Number of Shots
1	0.44(240)	1200	767	90	3
2	0.44 (240)	937	470	90	3
3	0.44(240)	494	130	90	3
4	38 S(158)	1200	505	90	3
5	38 S(158)	937	309	90	3
6	38 S(158)	494	86	90	3

Table 3.6 Modified Ballistic Impact Testing Matrix

ITEM #	PROCESS*	DATE PERFORMED	X-RAY RESULTS (REFER TO FIGURE 3.3 FOR DEFINITION OF INSPECTION AREAS 1,2 &3)		
			AREA #1	AREA #2	AREA #3
1	EBW+PM+CR+SR+SP+CA	22 FEB 1993	NIL	NIL	NIL
2	EBW+PM	5 JULY 1993	LACK OF FUSION 0.40" LONG	ONE PORE 0.030" DIA	SCATTER PORES 0.010" DIA
3	EBW+PM	5 JULY 1993	LACK OF FUSION	ONE PORE 0.030" DIA	NIL
4	EBW+PM+CR+SR+SP+CA	15 JULY 1993	SMALL CLUSTER OF PORES	NIL	0.005" DIA PORE
5	EBW+PM+CR+SR+SP+CA	15 JULY 1993	SURFACE INDICATION AT EDGE	0.010" DIA	NIL
6	EBW+PM	15 JULY 1993	LACK OF FUSION	PORES 0.010" DIA	NIL
7	EBW	25 AUG 1993	0.10" LACK OF FUSION AT EDGE NEAR RUN OFF TABS PLUS SCATTER PORES 0.010"	SCATTER POROSITY 0.01" TO 0.02" DIA	SCATTER POROSITY 0.010" TO 0.025" DIA
8	EBW	25 AUG 1993	SCATTER PORES 0.003" TO 0.010"	NIL	NIL
9	EBW+PM+CR+SR+SP+CA	25 AUG 1993	0.15" LACK OF FUSION AT EDGE OF BLADE NEAR RUN OFF TABS	NIL	NIL
10	EBW	25 AUG 1993	SMALL CLUSTER OF PORES 0.010" DIA	TWO PORES 0.010" DIA	SCATTER POROSITY 0.01" TO 0.02" DIA
11	EBW	25 AUG 1993	NIL	NIL	NIL
12	EBW	25 AUG 1993	0.70" LONG LACK OF FUSION	PORES 0.010" TO 0.02" DIA	NIL
13	EBW	25 AUG 1993	0.300" LONG LACK OF FUSION	NIL	NIL
14	EBW	25 AUG 1993	THIN DROP THRU CONVEX SIDE OR MISMATCH	PORES 0.010"	THIN DROP THRU CONVEX SIDE
15	EBW	25 AUG 1993	THIN CAP AT EDGE OF BLADE CONCAVE SIDE OR MISMATCH	TWO 0.010" PORES	NIL
16	EBW	25 AUG 1993	0.125" LONG LACK OF FUSION	SCATTER POROSITY 0.010" TO 0.020" DIA	PORES 0.010" TO 0.030" DIA
17	EBW	25 AUG 1993	NIL	NIL	NIL
18	EBW	25 AUG 1993	PORES 0.010" DIA PLUS ONE PORE 0.040" DIA	SCATTER PORES 0.010" TO 0.025" DIA	ONE PORE 0.035" PLUS SCATTER PORES 0.010" TO 0.020" DIA
19	EBW+PM	13 JAN 1992	NIL	BURN THRU	NIL
20	EBW+PM	24 JAN 1992	LACK OF FUSION	BURN THRU	SCATTER OF PORES 0.015 DIA
21	EBW+PM+RCH	24 JAN 1992	LACK OF FUSION	ONE PORE 0.040" DIA PLUS SCATTER PORES 0.010" DIA	ONE PORE 0.040" DIA PLUS SCATTER PORES 0.015 DIA
22	EBW+PM	11 FEB 1992	NIL	ONE PORE 0.010" DIA	NIL

* CW: Coatings Removal; CMM: Coordinate Measuring Machine; NF: Natural Frequency Test; EBW: Electron Beam weld; PM: Patch Machine; SR: Stress Relief SP: Shot Peen CA: Coating Application; BI: Ballistic Impact; RCH: Rockwell Hardness Test; SSM: Surface Stress Measurement Test; ET: Etched

Table 4.1 List of Service Exposed Titanium Fan Blades Subjected to EB-Welding Repair Process.

ITEM #	PROCESS	DATE PERFORMED	X-RAY RESULTS (REFER TO FIGURE 3.2 FOR DEFINITION OF INSPECTION AREAS 1,2 &3)		
			AREA #1	AREA #2	AREA #3
23	EBW+PM	11 FEB 1992	NIL	NIL	NIL
24	EBW+PM	11 FEB 1992	SCATTER PORES 0.010" TO 0.020"DIA	SCATTER PORES 0.010" TO 0.020"DIA	SCATTER PORES 0.010" TO 0.020"DIA
25	EBW+PM	11 FEB 1992	SCATTER PORES 0.010"DIA	TWO PORES 0.040"DIA	SCATTER PORES 0.020"DIA
26	EBW+PM	13 APR 1992	NIL	NIL	NIL
27	EBW+PM	13 APR 1992	LACK OF FUSION 0.240" LONG PLUS PORES 0.010"DIA	NIL	NIL
28	EBW+PM+CR+SR+NF+BI	26 MAY 1992	NIL	0.020"DIA PORE	NIL
29	EBW+PM+CR+SR+NF+BI	26 MAY 1992	0.025" INDICATION	NIL	NIL
30	EBW+PM+CR+NF+V	26 MAY 1992	CLUSTER OF PORES - 0.080" IN LENGTH FROM EDGE	NIL	NIL
31	EBW+PM+CR+SR+NF+BI	26 MAY 1992	SCATTER PORES OF 0.005" TO 0.020" DIA	NIL	NIL
32	EBW+PM+NF+RCH	26 MAY 1992	0.02"&0.015" PORES -0.080" FROM EDGE OF RUN OFF TAB	0.025" PORE	NIL
33	EBW+PM+NF+CR+SR+CA	26 MAY 1992	0.200" FROM EDGE - 4 INDS LARGEST BEING 0.020"DIA	0.010" PORE PLUS 0.025" 0.015" & 0.010" FROM EDGE OF RUN OFF TAB	NIL
34	EBW+PM+CR+SR+NF+BI	26 MAY 1992	3 INDS LARGEST BEING 0.015"DIA FROM EDGE	0.015" DIA PORE	NIL
35	EBW+PM+CR+SR+NF+BI	26 MAY 1992	0.010" PORE FROM EDGE	3 PORES - 0.010" 0.015" & 0.020"DIA	NIL
36	EBW+PM+CR+SR+NF+ET+SSM	26 MAY 1992	0.030" PORE AT EDGE & 0.020" & 0.015" INDS	NIL	NIL
37	EBW+PM+CR+SR+NF	26 MAY 1992	LINEAR INTERMITTED INDS - 0.375" LONG FROM EDGE	NIL	NIL
38	EBW+PM+CR+SR+NF	26 MAY 1992	0.010" & 0.010" INDS	0.050" PORE	NIL
39	EBW+PM+CR+S	26 MAY 1992	0.010"DIA PORE PLUS 0.015"& 0.010"DIA PORE FROM EDGE	NIL	NIL
40	EBW+PM+CR+SR+NF+SP+RCH	26 MAY 1992	0.015" IND AT EDGE PLUS 0.50" LINEAR INTERMITTED INDS	NIL	NIL
41	EBW+PM+NF+CR+SR+CA	26 MAY 1992	0.025" LONG LINEAR INDICATION FROM EDGE	NIL	NIL
42	EBW+PM+CR+SR+NF+BI	26 MAY 1992	TWO 0.025" INDS& 0.010"DIA PORES AT EDGE	NIL	NIL
43	EBW+PM	24 AUG 1992	LACK OF FUSION 0.30" LONG	LINEAR PORES 0.005" TO 0.020"DIA	LINEAR PORES 0.005" TO 0.020"DIA
44	EBW+PM	9 DEC 1991	SCATTER PORES OF 0.010"DIA	SCATTER PORES 0.010"DIA	SCATTER PORES 0.010"DIA

*: CR: Coatings Removal; CMM: Coordinate Measuring Machine; NF: Natural Frequency Test; EBW: Electron Beam weld; PM: Patch Machine; SR: Stress Relief; SP: Shot Peen; CA: Coating Application; BI: Ballistic Impact; RCH: Rockwell Hardness Test; SSM: Surface Stress Measurement Test; ET: Etched.

Table 4.1 List of Service Exposed Titanium Fan Blades Subjected to EB-Welding Repair Process. (Continued)

SERVICE EXPOSED (BASE LINE) (S/N: GLA 83091)		EB WELDED+PATCH MACHINED+ETCHED (S/N: GLA 78180)				EB-WELDED+PM+SR+SP+ETCHED (S/N: GLA 80035)		
PLANE POSITION	σ_x	PLANE POSITION	σ_x			σ_x		
			@ WELD LINE	@ WELD LINE	@ WELD LINE	@ WELD LINE	@ WELD LINE	@ WELD LINE
PLANE #1 (30.6mm FROM LEADING EDGE 16.0mm FROM TOP)	-21 MPa	PLANE #1 (33.0mm FROM LEADING EDGE 14.1mm FROM TOP)	-180 MPa	-142 MPa	-149 MPa	-40 MPa	34 MPa	-58 MPa
PLANE #2 (19.1mm FROM LEADING EDGE 39.4mm FROM TOP)	-13 MPa	PLANE #2 (20.6mm FROM LEADING EDGE 37.0mm FROM TOP)	-88 MPa	-65 MPa	-121 MPa	-80 MPa	-59 MPa	-50 MPa
PLANE #3 (7.7mm FROM LEADING EDGE 61.9mm FROM TOP)	-10 MPa	PLANE #3 (5.9mm FROM LEADING EDGE 58.3mm FROM TOP)	30 MPa	-50 MPa	-13 MPa	-100 MPa	13 MPa	-110 MPa

• BEST ACCURACY OF THE INSTRUMENT IS QUOTED AT ± 15 MPa
• STRESSES REPORTED ARE PERPENDICULAR TO THE WELD LINE

Table 4.2. Results of Transversal, σ_x , Surface Residual Stress Measurement Tests.

LOCATION	SE	EBW+PM	EBW+PM+SR+SP
CONCAVE	35	33	35
CONVEX	30	31	29

Table 4.3. Results of Surface Hardness Measurement Tests (± 1 D. deviation ± 3).

FINITE ELEMENT METHOD			UNCONSTRAINED				CONSTRAINED			
MODES	FREQUENCY	TYPE	PEAK #	FREQUENCY	S.D.	PEAK #	FREQUENCY	S.D.		
MODE 1	133 HZ.	1ST BENDING	1	428 HZ	7	1	346 HZ	12		
MODE 2	493 HZ	2ND BENDING	2	966 HZ	11	2	1048 HZ	15		
MODE 3	803 HZ	TORSION	3	1173 HZ	33	3	1144 HZ	32		
MODE 4	1208 HZ	3RD BENDING	4	1735 HZ	70	4	1267 HZ	18		
MODE 5	1670 HZ	2ND BENDING + TORSION	5	2036 HZ	44	5	1903 HZ	118		
			6	2160 HZ	74	6	2110 HZ	35		
						7	2447 HZ	39		
						8	2708 HZ	74		

Table 4.4 Results of Natural Frequency Tests.

STRAIN	LOCATION 1 (min/in)	LOCATION 2 (min/in)	LOCATION 3 (min/in)
TEST 1	190	162	33
TEST 2	198	170	34
AVERAGE	194	166	34

Table 4.5. Results of Surface Strains during Vibration Testing.

BLADE #	SHOT #	BULLET MASS	VELOCITY (ft/SEC)	IMPACT ENERGY (ft-lb)	HY-CAM RECORD	DAMAGE MODE
1	1	240 grain	942	473	YES	LOCALIZED DEFORMATION
	2	240 grain	974	505	YES	LOCALIZED DEFORMATION
	3	240 grain	952	483	NO	CUTTING OFF
	4	240 grain	963	494	NO	LOCALIZED DEFORMATION
2	5	240 grain	1309	913	YES	PENETRATING AND TEARING
3	6	240 grain	740	292	YES	LOCALIZED DEFORMATION
	7	240 grain	728	282	YES	BENDING
4	8	158 grain	1395	683	YES	LOCALIZED DEFORMATION
	9	158 grain	1329	620	YES	PENETRATING & CUTTING OFF
	10	158 grain	1337	627	NO	TEARING & CUTTING OFF
	11	158 grain	896	282	YES	MISSED TARGET
5	12	158 grain	915	294	YES	LOCALIZED DEFORMATION
	13	158 grain	917	295	NO	LOCALIZED DEFORMATION
	14	158 grain	767	206	YES	LOCALIZED DEFORMATION
6	15	158 grain	851	254	NO	BENDING

Table 4.6. Results of Ballistic Impact Tests.

FIGURES

Figure 1.1 Photograph of First Stage Rotor Fan Blade Showing Foreign Object Damage and Fretting Fatigue at the Dovetail Pressure Side. The Locations of High Strain Low Cycle Fatigue, and Hammer and Rubbing wear are also Indicated.

Figure 1.2 Repair Process of Foreign Object Damaged Gas Turbine Fan Blade.

Figure 2.1 Phase transformation diagram for Ti-6Al-4V [38].

Figure 2.2 Percent stress relief of Ti-6Al-4V as a function of time and temperature [39].

(a) Acceptable, Fine Primary Alpha in Transformed Beta Matrix

(b) Acceptable, Medium Equiaxed Primary Alpha in Transformed Beta Matrix

(c) Acceptable, Elongated Primary Alpha in Transformed Beta Matrix

(d) Acceptable, Medium Equiaxed Primary Alpha in Transformed Beta Matrix

Figure 2.3 OEM microstructure acceptance standards of annealed Ti-6Al-4V at 100X [85].

Figure 2.4 Microstructure of Ti-6Al-4V solution treated at 1750°F for 1 hour, water quenched and aged for 24 hours at 1000°F. Light areas are primary alpha, dark acicular matrix is age alpha prime and beta [39].

Figure 2.5 Typical stress-strain curves for annealed Ti-6Al-4V sheet [39].

Figure 2.6 Typical stress-strain curves for annealed Ti-6Al-4V bar [39].

Figure 2.7 Effect of ST temperature on the ST tensile properties of Ti-6Al-4V [39].

Figure 2.8 Effect of ST temperature on the STA properties of Ti-6Al-4V [39].

Figure 2.9 Effect of quench delay on tensile properties of Ti-6Al-4V 1/2-inch bar, ST (1750°F, 1 Hr) WQ, aged (900°F 6 Hrs) [39].

Figure 2.10 Effect of quenched section size on the tensile properties of STA Ti-6Al-4V [39].

Figure 2.11 Dynamic modulus of elasticity versus temperature of Ti-6Al-4V [39].

Figure 2.12 Effect of temperature on the Charpy impact strength of annealed and STA sheet and bar [39].

Figure 2.13 Load carrying ability versus remaining area of annealed and STA Ti-6Al-4V [39].

Figure 2.14 Fracture toughness of Ti-6Al-4V at various strength levels [39].

Figure 2.15 High energy density welding process showing deep penetration capabilities [68].

Figure 2.16(a) Plane-strain behaviour (Pictorial) [27].

Figure 2.16(b) Plane-stress behaviour (Pictorial) [27].

Figure 2.17 Temperatures at all points in the vicinity of the weld at different times [68].

Figure 2.18 The temperatures in Figure 2.17 are re-plotted as a function of the time for four different distances [68].

Figure 2.19 Principles of operation of x-ray diffraction [92].

(a) Along the weld centre-line

(b) Perpendicular to weld

Figure 2.20 Residual stresses in as TIG-welded Ti-6Al-4V [80].

Figure 2.21 Effect of thermal treatment on microstructure of Ti-6Al-4V [41].

Figure 2.22 Bent blades due to bird impact [10].

Figure 2.23 Short-time fracture surface of a ductile material (12-Chrome Stainless Steel). (6x) [ASM, 1987, p. 366]

Figure 2.24 Short-time fracture surfaces of ductile materials.
(a) Round specimen of Ti-6Al-4V alloy (6x) [ASM, 1974, p. 274]
(b) Round specimen of Inco 718 alloy (6x) [ASM, 1974, p. 228]
(c) Round specimen of Chrome-moly steel [AMS 4340] (11x)

Figure 2.25 Impact fracture surface of a bar of 12-Chrome stainless steel [ASM, 1974, p. 40].

Figure 2.26 Dimples in a fracture surface of a ductile material [11].

Figure 2.27 Full fan assembly single strike bird ingestion spinning rig test [34].

Figure 2.28 Diagram of Gun used for bird ingestion engine tests [34].

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b) A schematic diagram of the modified strike head impacting the test specimen, showing how striker curvature gives constant moment arm distance [31].

Figure 2.30(a) Blade element force [26].

Figure 2.30(b) Gas bending forces [88].

Figure 2.30(c) Unit height on blade surface [26].

Figure 2.30(d) Offset centroid [88].

Figure 2.31(a) Fatigue regimes [11].

Figure 2.31(b) σ -N Diagram [91].

Figure 2.31(c) Relation between σ_a & σ_m for cyclic loading [91].

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Figure 2.32(a)

High-cycle fatigue fracture of compressor blade of precipitation-hardening stainless steel, showing typical beachmarks [71].

Figure 2.32(b)

High-cycle fatigue striations in Inco 718 nickel-base alloy. (1100X). [ASM, 1974, p. 27].

Figure 2.32(c)

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Figure 2.33 Effect of stress analysis on life [35].

Figure 2.34(a) Plot of coefficient α and the equivalent stiffness & mass [89].

Figure 2.34(b) Natural frequencies for simple systems [89].

Figure 2.34(c) Cantilever beam [89].

(a)

(b)

Figure 2.35 Typical Campbell diagram for blade [26].

Figure 3.1 Schematic of titanium fan blade used in the study.

Figure 3.2 Grain flow direction in replacement patch relative to blade.

Figure 3.3 Locations of inspection areas for x-ray radiography (fan blade).

Figure 3.4 Locations for metallographic examination samples (weld coupon).

Figure 3.5 Location of sections on fan blade for metallographic examinations and for hardness sample preparation.

Figure 3.6 **Electron beam weld fixture.**

Figure 3.7 Blade reference cross-sections for CMM measurements.

(a)

(b)

Figure 3.8 CAD model of fan blade.

- a) Tip section
- b) Dovetail section
- c) Full blade

(c)

Figure 3.8 CAD model of fan blade.

- a) Tip section
- b) Dovetail section
- c) Full blade

Figure 3.9 FEM wire frame representation of fan blade.

Local Coordinate Systems

LCS1: right -side contacting surface on dovetail.

LCS2: left -side contacting surface on dovetail.

LCS3: rear plane surface of the dovetail.

Boundary Conditions at LCS

LCS1: $X1$ $Y1$ free, $Z1=0$

LCS2: $X2$ $Y2$ free, $Z2=0$

LCS3: $X3$ $Y3$ free, $Z3=0$

Loading

Body force due to rotation $N=13200$ rpm.

Figure 3.10 Definition of FEM local coordinate systems, boundary conditions and loading.

Figure 3.11 Locations of residual surface stress measurement points.

Figure 3.12 Locations of surface hardness measurement points.

Figure 3.13 Unconstrained fan blade supported with elastic bands during natural frequency test.

Figure 3.14 Natural frequency test apparatus for constrained fan blades.

Figure 3.15 Dovetail load cell calibration.

Figure 3.16 Close-up of the natural frequency test apparatus for constrained fan blades.

Figure 3.17 NRC vibration test apparatus.

Figure 3.18 Fan blade during a first bending mode vibration test. (Photo showing LE, TE, and TIP displacement).

Figure 3.19 NRC vibration test apparatus. (Photo showing the shaker and the counter mass balance).

Figure 3.20 Fan blade instrumented for surface strain measurements during vibration tests.

Figure 3.21 The fixture used during ballistic impact testing.

Figure 3.22(a) The ballistic impact test apparatus.

Figure 3.22(b) Schematic diagram of the ballistic impact test apparatus.

Figure 3.23 Velocity triangles for one compressor stage.

Figure 3.24(a) rectilinear motion

Figure 3.24(b) Bullet F.B.D.

Figure 3.24(c) Angular momentum due to impact.

Figure 4.1

Titanium fan blade after removal of the FOD area by AWJC process.

Figure 4.2

EB-Weld repaired titanium fan blade showing the as welded condition.

Figure 4.3

EB-Weld repaired titanium fan blade subjected to post-weld patch machining process.

Figure 4.4

Optical micrograph showing microstructure of pre-formed titanium replacement patch.

Figure 4.5 **Optical micrograph showing microstructure of service exposed (baseline) titanium fan blade material section.**

Figure 4.6(a) **Optical micrograph showing the microstructure of the as EB-Welded titanium fan blade material section.**

Figure 4.6(b)

Optical micrograph showing the microstructure of the as EB-Welded titanium fan blade material section.

Figure 4.6(c)

Optical micrograph showing the microstructure of the as EB-Welded titanium fan blade material section.

X200

Figure 4.7

Optical micrograph showing the microstructure of EB-Weld titanium fan blade material section subjected to stress relief cycle.

Figure 4.8 FEM stress analysis for titanium fan blade.

EBW (GLA 73214), Ser.Exp. (GLA 63274)
 EBW + PM + SR + SP (GLA A9468)
 (Concave Surface, Plane 2)

Figure 4.9 Surface hardness surveys for service exposed vs. EB-Weld repaired titanium fan blades.

Figure 4.10 FEM deformed geometry model for titanium fan blade under first bending mode.

Figure 4.11 FEM deformed geometry model for titanium fan blade under second bending.

Figure 4.12 FEM deformed geometry model for titanium fan blade under torsion mode.

Figure 4.13 FEM deformed geometry model for titanium fan blade under third bending mode.

Figure 4.14 FEM deformed geometry model for titanium fan blade under second bending and torsion modes.

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Frequency
Peak

Coherence

Figure 4.15

Sample output of material frequency peaks for unconstrained titanium fan blade.

Figure 4.16 Plot of first natural frequency peaks measured for unconstrained titanium fan blades with different weld conditions.

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W11 FREQ RESP H1 MAG
Y: 227 LIN
X: 0Hz + 3.2kHz
SETUP W11 #A: 4
UNIT Y: 100
UNIT X: 0Hz
TOTAL: 0.008

W11 COHERENCE
Y: 1.00
X: 0Hz + 3.2kHz
SETUP W11 #A: 4
UNIT Y: 0.00
UNIT X: 0Hz

Frequency
Peak

Coherence

Figure 4.17 Sample output of material frequency peaks for constrained titanium fan blade.

Figure 4.18 Plot of first natural frequency peaks measured for constrained titanium fan blades with different weld conditions.

Figure 4.19 Damage induced on titanium fan blades due to ballistic impact tests.

APPENDICES

**Appendix A: Sample Of Calculation For Impact Energies
(Table 3.4)**

Given:

Simulated Aircraft Speed:	Takeoff
Engine Operating Condition:	Intermediate Rated Power (IRP)
Aircraft Velocity, C_1 :	223 ft/sec @ IRP (purely axial)
Fan Rotation Speed, N:	13,200 RPM @ IRP or 1382 rad/sec
Angular Rotational Speed, ω :	$2\pi N$ (1 RPM = 1.047×10^{-1} rad/sec)
Blade Tip Radius, r_t :	12.6 inch or 1.05 ft
Blade Center of Gravity, r_g :	8.0 inch or 0.66 ft
Blade/Disc Serration Angle:	20°
Blade Mass, m:	0.8 lb
Bullet Initial Velocity, V_{bi} :	0 ft/sec
Bullet Mass, m:	240 grain or 1.068×10^{-3} lb.sec ² /ft 1 grain = 64.8 mg; 240 grain = 15.5g = 0.03429 lbf (1 lbf = 4.535×10^{-1} kg) (1 lbf = 1 lb.sec ² /(32.1 lb.ft))

Calculation:

$$\begin{aligned}
 \text{Blade Tip Speed, } U_t &= 2\pi N r_t && \text{(Equation 2.8)} \\
 &= 2\pi/\text{rev} \times (13200 \text{ rev/min} \times 1\text{min}/60 \text{ sec}) \times 1.05 \text{ ft} \\
 &= 1451 \text{ ft/sec.}
 \end{aligned}$$

Assume: - no inlet guide vanes
 - the air entry velocity is purely axial in direction (Figure 3.23)
 - the velocity diagram at entry to the rotor is right-angle triangle without tangential or whirl velocity ($C_{w1} = 0$).

$$\begin{aligned}
 \text{Bullet Impact Velocity, } V_{b2} &= \text{SQRT}(C_1^2 + U^2) && \text{(Equation 3.3)} \\
 &= \text{SQRT}(223^2 + 1451^2) \\
 &= 1468 \text{ ft/sec (relative to rotor speed)}
 \end{aligned}$$

$$\begin{aligned}
 \text{Shooting Angle, } \beta_1 &= \tan^{-1}(U/C_1) - 20^\circ \\
 &= 61.26 \text{ degree}
 \end{aligned}$$

$$\begin{aligned}
 \text{Kinetic Energy, } \Delta T &= (1/2)m(v_{b2}^2 - v_{bi}^2) && \text{(Equation 3.4)} \\
 &= 1/2 \times (1.068 \times 10^{-3} \text{ lb.sec}^2/\text{ft}) \times (1468 \text{ ft/sec})^2 \\
 &= 1151 \text{ ft.lb.}
 \end{aligned}$$

$$\begin{aligned}
 \text{Centrifugal Force, F:} &= m r_g \omega^2 && \text{(Equation 2.4)} \\
 &= 0.8 \text{ lb} \times 0.66 \text{ ft} \times (1382 \text{ rad/sec})^2 \\
 &= 1008440 \text{ lb.ft/sec}^2 \times (1 \text{ lbf.sec}^2/32.1 \text{ lb.ft.}) \\
 &= 31.41 \text{ lbf (140 kN)}
 \end{aligned}$$

Appendix B: Sample of Calculation for Theoretical Centrifugal Tensile Stresses

Given:

Simulated Aircraft Speed:	Takeoff.
Engine Operating Condition:	Intermediate Rated Power (IRP).
Fan Rotation Speed, N:	13,200 RPM @ IRP or 1382 rad/sec.
Blade Tip Radius, r_t :	12.6 inch or 1.05 ft.
Blade Root Radius, r_r :	6.5 inch or 0.54 ft.
Blade Hub-Tip Ratio, r_r/r_t :	0.52.
Blade Material Density, ρ :	0.160 lb/in ³ .

Calculation:

$$\begin{aligned}\text{Blade Tip Speed, } U_t &= 2\pi N r_t && \text{(Equation 2.8)} \\ &= 2\pi/\text{rev} \times (13200 \text{ rev/min} \times 1\text{min}/60 \text{ sec}) \times 1.05 \text{ ft} \\ &= 1451 \text{ ft/sec. or } 17412 \text{ in/sec.}\end{aligned}$$

Maximum Tensile Centrifugal Stresses:

$$\begin{aligned}(\sigma_{ct})_{\max} &= (\rho_b/2) U_t^2 [1-(r_r/r_t)^2] && \text{(Equation 2.9)} \\ &= (0.160/2)(\text{lb/in}^3) \times (17412 \text{ in/sec})^2 \times [1-(0.52)^2] \\ &= 17695878 \text{ lb/in}^2 \cdot \text{sec}^2 \times [(1/32.9)(\text{sec}^2/\text{ft}) \times (1 \text{ ft}/12 \text{ in})] \\ &= 44822 \text{ psi (309 MPa)}.\end{aligned}$$