(Fig. 30c). These flaws are presumed to have formed during the machining and/or shot peening of the dovetail surface. Etched specimens often display grain distortion at these flaws.

Cross-sectional analyses of service exposed stage 1 and stage 2 fan blade dovetails at locations where the coating remained intact indicated that the Ti-6Al-4V pressure face had a surface finish and manufacturing flaws similar to those observed at the pressure faces of the new blade. Due to the similarity of Ti-6Al-4V pressure face flaws between the new and the service exposed blades, it is suggested that these manufacturing defects are not obviously influenced by dovetail shear stresses associated with blade loading conditions. A sub-surface defect that was observed in a service exposed blade dovetail is shown in Figure 31.

The defects which radiate into the Ti-6Al-4V substrate, as shown in Figures 22, 30c and 31 are believed to be deformed material which has etched preferentially. It is unknown if these defects are created as a result of manufacturing or service or a combination of the two. However, it should be noted that the flaw shown in Figure 30c is from a new blade whereas the defect shown in Figure 22 appears to originate from an area where Ti-6Al-4V is under direct fretting action. At this early stage of life it is difficult to predict the level of further in-service degradation which occurs, but it is quite likely that these defects can lead to crack initiation/propagation during service, since the blade dovetail is a highly stressed location.

Ion implantation may be a feasible method to combat fretting damage along the pressure surface of the blades. As reported in section 2.5, ion implantation can improve the fretting fatigue life of Ti-6Al-4V by essentially improving the surface wear properties. It should be noted that to obtain the full potential of ion implantation, the implanted surface must be finished to

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**Investigation of Ion Implantation and Rejuvenation
Treatments for Life Extension of Ti-6Al-4V Fan Blades**

by
Wayne Doswell
B. Eng. (Mechanical)

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

Master of Engineering

Department of
Mechanical and Aeronautical Engineering
Carleton University
Ottawa, Ontario
Canada

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**Investigation of Ion Implantation and Rejuvenation Treatments
for Life Extension of Ti-6Al-4V Fan Blades**

submitted by Wayne Doswell, B. Eng.
in partial fulfilment of the requirements for
the degree of Master of Engineering

A handwritten signature in dark ink, appearing to read "M. C. de Malherbe", is written over a horizontal line. The signature is fluid and cursive.

Dr. M. C. de Malherbe
Thesis Supervisor

A handwritten signature in dark ink, appearing to read "S. J. K.", is written over a horizontal line. The signature is cursive and somewhat stylized.

Chairman, Department of Mechanical
and Aerospace Engineering

Carleton University
July 24, 1989

ABSTRACT

In this thesis, the cumulative damage mechanisms of fretting fatigue and low cycle fatigue occurring in the fan blades of an advanced turbofan engine have been characterized. Ion implantation has been examined as a surface modification technique to minimize the occurrence of fretting at fracture critical locations in the blades. Preliminary investigations have determined that surface modification via ion implantation can improve fretting fatigue properties. In order to investigate the potential of ion implantation processing, a test apparatus has been designed and fabricated to partially simulate the service loading conditions which occur at fracture critical areas of the blades.

Re-heat treatments have been carried out to rejuvenate the microstructure in service exposed fan blades. The goal of this program was to partially anneal dislocation debris from the blade microstructure by thermal treatments. Detailed evaluation of the re-heat treated material has been carried out through transmission electron microscopy and optical microscopy studies.

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CHAPTER 1

INTRODUCTION

Turbofan engine fan blades are highly stressed components and hence, must possess a high level of component integrity (1,2)¹. Also, since fan blades frequently suffer impact from foreign objects such as ice, birds and rocks which can be ingested into the engine during service, the blade airfoils must maintain high impact strength properties. Figure 1 shows the stage 1 and stage 2 fan blades of a turbofan engine. The blade material is the titanium alloy Ti-6Al-4V. The alloy Ti-6Al-4V is widely used for such components because of its high strength to weight ratio (2,3). It should be noted that first stage blades have mid-span dampers to improve rigidity in the assembly and decrease blade vibration (4). These blades are mounted (Fig. 2) on fan disks which are fabricated from the titanium alloy Ti-17. Due to the loading conditions experienced in service, the fan blades are known to accumulate fretting fatigue and low cycle fatigue damage (5). Both of these modes of degradation can limit the service lives of the blades (3-7).

1.1 Fretting Damage

Fretting is a term used to define the wear damage that occurs at the interface of two tightly clamped surfaces that experience relative oscillating motion (8-11). Fretting fatigue refers to a loss in fatigue life of a component as a result of fretting action (8-12). This is because fretting accelerates the initiation of microcracks due to local cyclic stresses that occur with repeated asperity contacts, and due to stress concentrations associated with wear scar formations (10,11,13,14).

¹ Numbers in brackets refer to references

With fretting, the amplitude of motion or slip between the contact surfaces is small enough, generally below 75-150 microns, to restrict the migration of debris away from the wear site (8,12,15). The fretting action is generally enhanced by an oxidation/corrosion phenomenon occurring along the contacting surfaces and within the wear debris (8,10,12,13,16).

Moderate to severe fretting wear has been observed on the pressure surfaces of several first and second stage fan blade dovetails (Fig 3). Currently, the dovetail surfaces of these blades are coated with an anti-fretting Cu-Ni-In coating along with a top layer of MoS_2 , a solid lubricant coating. In spite of these protective coatings, the wear damage has often been observed to progress into the substrate alloy (Ti-6Al-4V) within less than 30% of the established life of these blades (17). A preliminary analysis of the dovetail surface and subsurface regions has revealed the presence of some small crack like defects which have been found on the pressure surface extending into the parent material (17). This type of fretting damage has been associated with service induced slip at the interface between the dovetail pressure surface and the disk rim slot (Fig. 4) (3,6,7). It is believed that if this fretting damage on the pressure surfaces is ignored, cracks will initiate and propagate to sizes that will eventually cause blade separation.

1.2 LCF Damage

Essentially, fatigue is a damage accumulation process occurring in the presence of cyclic loading (18-20). After a sufficient number of cycles, a certain maximum tolerable amount of damage is incurred in the material, leading to crack initiation (18,19,21,22). It is known that dislocation densities increase as the fatigue damage accumulation process progresses (18,20,21). Fatigue cracks usually nucleate at discontinuities on or near the surface or at defects within the material (18,21,22). Various dislocation mechanisms have been proposed to explain the fatigue

crack nucleation process. A model recently proposed by Kramer et. al. (22) involves the generation of dislocations near the surface as a result of cyclic loading. As the dislocation density increases, dislocation pile-ups are created within the near surface material. Stress concentrations associated with these pile-ups are thought to provide the necessary conditions for the nucleation of cracks. Once a crack has initiated, further fatigue loadings may propagate the crack to a critical size where component failure may occur (18-22). Low cycle fatigue is generally defined as fatigue which occurs under large cyclic strains at relatively low frequencies (21). With LCF loadings, components typically fail in under 50,000 cycles (21).

During engine start-up/shut down and significant thrust changes, rotating components are subjected to low cycle fatigue. The number of equivalent low cycle fatigue (ELCF) cycles the engine receives is recorded by special instrumentation in most advanced aircraft. Fan blades are sensitive to LCF damage and consequently, the service lives have been set in terms of an ELCF limit. The LCF damage mechanism involves the introduction of microstrains within the components with the degree of damage dependent primarily on the load range, peak loads, stress concentrations, and number of cycles (18). The area of the blade believed to be most prone to LCF damage is located within the shank, just below the trailing edge of the blade airfoil (Fig. 1).

1.3 Life Extension Schemes

A component life extension program can have strong economic benefits as a result of substantially reduced component replacement costs. However, life extension must not infringe on the components reliability to operate in a safe manner. The work conducted in this research is an exploratory study of the feasibility of life extension of fan blades through ion implantation and re-heat treatments.

1.3.1 Ion Implantation

Ion implantation has emerged as a promising technique for improving the surface properties of a material and so far a number of commercial applications have been reported (23-26). A detailed review of earlier work on ion implantation with respect to fretting is presented in a later section of this thesis. In this process, a beam of high energy ions is accelerated to a target surface and after a number of collisions, the ions come to rest just below the surface (27,28). The affected layer is characterized by a disrupted crystal structure with increased number of interstitials, vacancies, and dislocations (29-31). Under certain circumstances, ion beams can promote the formation of phases with structure and composition that generally cannot be achieved by traditional metallurgical techniques (28,29,32). The depth of ion implantation is typically within the range of 100-1000 nm and thus this process is only effective against surface sensitive material properties including hardness, wear, fatigue, oxidation and corrosion (24,27,29,33). Preliminary research has indicated that implantation of nitrogen and carbon ions can be quite effective in terms of improving fretting fatigue life in Ti-6Al-4V (30,34).

One of the objectives of this study is to design and fabricate a test rig which could be used for determining the effectiveness of ion implantation in improving surface properties. In order to quantify the effectiveness of the processing technique, one set of ion implanted coupons and one set of unimplanted coupons will undergo fretting fatigue testing. The fretting test rig to be used has been designed to partially simulate the actual fretting environment on the fan blade pressure surfaces.

1.3.2 Rejuvenation

In the case of LCF damage, an effective rejuvenation treatment should restore the mechanical properties of LCF damaged components to a state which is close to those of the original material (35). This may be accomplished through furnace re-heat treatment (36,37). Surface cracks cannot be healed by re-heat treatments alone, without the superimposed application of pressure, and thus components which exhibit surface flaws are much more difficult to rejuvenate (35). It should be noted that such re-heat treatment procedures must not cause distortion in the component (35,36,37).

Within the scope of this research, rejuvenation by re-heat treatment will be investigated as a possible method to alleviate LCF damage in fan blades. Heat treatments used are those that appear most suitable for fan blade rejuvenation on the basis of an in-depth literature review. Firstly, rejuvenation treatment must achieve LCF damage relief. Secondly, the treatment must promote a microstructure which provides similar or improved mechanical properties as compared to the pre-service blade condition. The extent of LCF damage relief introduced through annealing will be associated with the reduction of dislocation debris within the microstructure (21). Dislocation removal may be a sign of full rejuvenation of LCF properties, provided the grain size and other microstructural parameters have not changed substantially.

1.4 Objectives

The principal objectives of this study are as follows:

- A. Fretting fatigue life improvement; (i) Conduct a surface and sub-surface examination of service exposed stage 1 and stage 2 fan blade dovetail pressure surfaces to characterize fretting damage. (ii) Design and fabricate a fretting fatigue test rig

which partially simulates service conditions. (iii) Generate and compare fretting fatigue data for ion implanted and unimplanted Ti-6Al-4V specimens.

B. LCF life improvement, (i) Perform complete microstructural analysis of service exposed fan blade material. (ii) Assess the LCF damage relief and microstructure of fan blade material after rejuvenation by heat treatment and assess the prospects for practical application to service exposed parts.

CHAPTER 2

LITERATURE REVIEW

2.1 Fretting Fatigue

Fretting fatigue may be defined as the reduction in fatigue life of a component as a direct result of fretting damage (8-14,38-41). Figure 5 illustrates the typical losses in fatigue life of Ti-6Al-4V due to fretting (41). Other classifications of fretting are fretting wear and fretting corrosion (8,12,41). Fretting wear is the removal of material from the contacting surfaces during fretting (8,10,12). The consequences of this action include a loss of tolerances at critical locations (8,10,12). Fretting corrosion refers to the form of damage resulting from chemical interaction between the environment and material at the fretting interface (8,12,40,41). Most often this process is oxidative (8,12,40,41).

Before analyzing the mechanisms of fretting fatigue, it is important to review the surface degradation process incurred as a result of fretting. It is generally accepted that there are three stages of fretting, namely (a) initial adhesion and metal transfer; (b) the production of debris, and (c) a steady state wear condition (12,39,42). It is established that fretting commences with adhesion between the contacting surfaces (10,12,39,42). The nature of the adhesion may involve the mechanisms of welding and mechanical interlocking of surface asperities (10,42). Subsequent fretting action results in fracture of the surface layers of the material (10,42). The wear particles that form during fretting oxidize and because of the small slip amplitudes associated with fretting (section 1.1), the wear debris remains trapped at the fretting interface (10,12,39,42). This debris often results in further damage by acting as an abrasive media (39,42). A steady state wear process may occur which involves the scraping away of surface oxides by

abrasive debris, re-oxidizing of freshly exposed material, and subsequent abrasive wear to the newly established coating (10,12). As well, the steady state wear mechanism may include/involve a "delamination" process which describes a situation in which metal platelets fail due to surface adhesion, sub-surface fatigue, and possibly environmental effects (10,12,13).

The mechanisms of fretting fatigue have been discussed by a number of investigators. There is however no universal model that covers all cases (43). The main factors for fretting fatigue degradation have been associated with alternating shear stresses in the contact areas arising from the frictional stresses between the surfaces (8,9,42). Crack initiation has been found to occur at points of maximum stress (12,44). Frequently, crack initiation occurs at boundaries between slip and non-slip regions at or near the outer contact boundary where high stress concentrations are known to exist (44). Also, wear grooves and wear pits produced during fretting act as sites for crack initiation as a result of their tendency to introduce stress concentrations (9,14,44). It has been suggested that surface fatigue generated through repeated asperity contacts is likely to be a driving force in the initiation of fatigue cracks (Fig. 6) (9,10,16,43).

Crack propagation rates under fretting fatigue are known to be initially increased by fretting (9,13,39,42). As a crack propagates beyond the state of stress associated with fretting, propagation occurs predominantly through a conventional fatigue mechanism (9,16,39,42,45). It has been suggested that fretting debris forced into cracks may accelerate propagation rates (9). It should be noted that a universal relationship between crack propagation, the fretting process, and cyclic loading has never been established (9,16,39).

Failures due to fretting fatigue have been increasingly more evident (40). The reason for the increased incidence of fretting fatigue failures has been associated with ever increasing demands on component performance and tolerances as well as due to higher awareness in identifying fretting initiated fatigue failures (12,40). In the design stage of components it is difficult to predict the level of fretting damage (13,40). Often fretting effects are encountered in the field long after a design has been well established and components have been produced (12,40). The damage incurred frequently restricts the operation and safety of components (39,40,45).

Methods to overcome fretting on components include introducing new component designs to modify the contacting surfaces (12,13,40). Modifying the dimensions of a system to avoid fretting is generally impractical or impossible due to design constraints (12,40). Therefore it is necessary to alter the nature of the fretting action along the contacting surfaces via lubricants or coatings (12,13,40). Since fretting fatigue cracks initiate at the interface of the contacting bodies, the surface condition is an important consideration in fretting fatigue life improvement (6,8,12,39,40). Any alteration in surface properties brings about a change in the fretting fatigue characteristics of a material (8,13,40,44).

2.2 Factors Influencing Fretting Fatigue

In this section, the main factors which determine the severity of fretting fatigue will be examined. The parameters of concern are the cyclic load, normal load, amplitude of slip, number of cycles, environment, and surface finish (8,44). For each case, the influence of the factors on fretting fatigue behavior will be reviewed in general. When available, information relevant to the fan blade material Ti-6Al-4V and other tita-

nium alloys will be presented. Work referred to in this section pertains to testing under ambient conditions unless otherwise stated.

2.2.1 Cyclic Load

Cyclic load can lead to fretting in systems by providing sufficient energy to create relative motion between the loaded material and unloaded material in contact with it (12,47). Also the bulk stresses from cyclic loading can combine with localized fretting damage to promote the premature nucleation and propagation of fatigue cracks (Section 2.1). It is therefore apparent that the fretting fatigue life of a component is dependent on the cyclic loading conditions (12,47,48). Increasing the magnitude of the cyclic loads has the effect of decreasing the fretting fatigue strength as a result of accelerated nucleation and propagation of cracks (12,49). A decrease in frequency of the cyclic loads decreases component fretting fatigue life, in terms of number of cycles to failure, as a result of additional time available between cycles for chemical interactions to occur at the fretting interface (6,8,15,49,50). The influence of cyclic stresses on the fretting fatigue strength of Ti-6Al-4V under constant fretting conditions is documented in Figure 5 (30). From Figure 5 it is apparent that the fatigue strength of Ti-6Al-4V is very sensitive to fretting.

2.2.2 Slip Amplitude

The slip amplitude is a significant variable in fretting induced degradation (8,13,49). The amplitude of slip may be a result of the applied cyclic load but is dependent on the system arrangement, normal load, and coefficient of friction at the slip interface (8,12). It is often reported that increasing slip magnitude increases fretting rates (6,8,15,49). Waterhouse (45) has

found that fretting fatigue life of materials generally decreases with increases in slip amplitude up to 20 microns but was less sensitive to slip beyond 20 microns.

2.2.3 Normal Load

The normal load provides the contact stresses which create the surface degradation due to fretting. The general fretting trend, under constant slip amplitude, is that increasing normal stresses increases the rate of fretting damage (6,15,49,50,51). Shown in Figure 7 is the relationship between the normal load and fretting fatigue properties of various materials including titanium (16).

2.2.4 Number of Cycles

It is well established that fretting damage increases with the number of cycles (6,8,9,49). It has been reported that under fretting conditions, the fatigue strength of Ti-6Al-4V is not apparently affected until a threshold is crossed (52). Beyond the threshold limit, the fretting fatigue strength has been found to rapidly degrade with number of fretting cycles (52).

2.2.5 Environment

Environmental factors are known to influence fretting at ambient temperatures (13,14,44). The extent of environmental effects upon fretting is somewhat dependent on the materials involved in the fretting process (50,53). In vacuum, fretting effects are moderated because of lack of oxygen which allows the formation of abrasive oxides (13,16,50). Figure 8 shows the effects of different atmospheres on the fretting fatigue strength of Ti-6Al-4V (54). From Figure 8 it is apparent that relative humidity has influence on the fretting fatigue life of Ti-6Al-4V. Humidity effects are very complex and are likely associated with

chemical interaction rates, physical characteristics of the debris, and possibly effects upon the surface mechanical properties of the contacting materials (8).

2.2.6 Surface Finish

Generally, the smoother the contacting surfaces, the greater the damage accumulation (42,50). This is believed to occur with smoother surfaces as a result of more restrictive debris escape routes (8,12,49). As well, the larger asperities associated with rough surfaces may be more resilient to slip by elastic deformation (48,54).

2.3 Fretting Fatigue Testing

The purpose of this section is to provide an overview of fretting fatigue test guidelines. Section 2.4 will describe four fretting fatigue test rigs which have been used by other investigators. So far no standardized test methods or specimen configurations have been established for fretting fatigue testing. Fretting fatigue is controlled by a number of parameters which combine to promote a characteristic degradation phenomenon. As a result, experimental work should be performed in a manner which simulates the specific service conditions. However, due to economic and time constraints, evaluation is usually carried out on test facilities which are acceptable, inexpensive, and require short term attention (12).

Fretting fatigue testing is usually conducted on conventional fatigue test specimens fabricated with parallel flat surfaces to which fretting pads are clamped by a normal load (Fig. 9) (47,50). During testing, specimens are subjected to an axial cyclic load which results in alternating slip at the specimen/pad interfaces (41,47). Slip occurs as a result of strain elongation that is introduced above the fretting pads (Fig. 9). Fretting

fatigue tests are often carried out at accelerated frequencies (relative to service conditions) to reduce testing time (6,12,50). The primary means of evaluating fretting fatigue is by measuring the extent of fatigue life degradation incurred by the fretting action (12). Fretting fatigue results are compared to baseline data which is typically generated by fatigue life testing (in the absence of fretting) on the same test apparatus and specimen configuration as used in the fretting fatigue experimental work (12,47). Results are usually presented graphically in the form of a S/N curves with both fretting fatigue data and baseline fatigue data being presented (12,41,47,50). In addition, investigators often include macroscopic examination of the fretting damage and sometimes crack growth studies. Variables in experimental techniques include cyclic load conditions, normal load, environment, slip amplitude and component geometry (both fatigue specimen and fretting pads).

The influence of cyclic loading conditions, normal load and environment on fretting fatigue has been reviewed in section 2.2. Cyclic loads are generally applied via hydraulic actuators, whereas the constant normal clamping load is typically applied by bolted arrangements (12,47). For both cases it is important to monitor the loads, as the normal load may vary with time because of wear or the build up of wear debris (47,48,49). Environmental chambers are frequently used for fretting fatigue testing at elevated temperature or in corrosive liquids or gases (12,47). It is also advisable for specimens tested at ambient conditions to be suitably enclosed to control humidity which may otherwise vary with time (6,42).

The amplitude of slip is dependent on the cyclic loading conditions, normal load, coefficient of friction between fretting surfaces and strain elongation which occurs above the fretting pads (Fig. 9). For set cyclic and normal loading conditions, the magnitude of slip can be varied by shifting the pad position relative to the coupon (10,47,48). Therefore, increasing the

length of specimen positioned above the fretting pad increases the elongation and the slip amplitude proportionally (10,41,47,48).

The geometry of the mating components determines the state of stress in components and therefore has significant influence on the fretting process (12,44,49). Most investigators have utilized flat plate or cylindrical coupons which have been machined with parallel flat surfaces (12,47). Depending on the design, one or two pad arrangements may be used on each side of the specimen to introduce fretting. Two pad arrangements are commonly referred to as fretting bridges. The bridge design must be rigid enough to resist excessive deformation in the bridge pads (47,54). Also, the area of contact must be large enough to retain the wear debris within the fretting region (47,54).

2.4 Test Facilities

In this section, four different test facilities used for fretting fatigue testing will be examined. Three of the test facilities are typical systems which cover a range of designs reported in the literature. The fourth facility has been designed to partially simulate fretting fatigue on dovetail sections of gas turbine blades.

Figure 10 shows a test apparatus used by Duquette and Gaul (13). In this design, fretting pads are rigidly connected to pad supports which in turn are fixed to the upper grip (Fig. 10). The pad supports are flexible in length such that fretting pads can be located at any point along the specimen gage length. This allows for control of slip amplitude since the magnitude of slip varies with the length of specimen available for strain elongation as described in section 2.3. Although not shown in Figure 10, the normal load was applied through two sets of circular disk springs. In order to determine the magnitude of slip, plastic

replica scales and pointers were fixed to the specimens and fretting pads, respectively. Accurate measurements were completed with the aid of an optical microscope and a stroboscope.

A schematic used by Hoeppe et. al. (9) is shown in Figure 11. The interesting aspect of this system is that only one side of the test specimen is subjected to fretting. The normal load is reacted by a rolling support which is free to move in the direction of specimen elastic deformation (Fig. 11). Apparatus design has included a relatively large, low friction, contact area at the specimen/rolling support interface to avoid fretting at this particular location. A design of this nature was developed to restrict damage to only one side of the specimen which was believed to be more representative of most actual situations.

Exposing two sides of a specimen to fretting creates a complex stress state within the specimen making the application of fracture mechanics to the mechanisms of fretting more difficult. The advantages of the system are the flexibility in obtaining a wide range of slip amplitudes and ease with which the normal load may be applied. The magnitude of slip can be controlled by varying the stiffness of the rod linking the specimen to the frame. Difficulties may however exist in establishing proper alignment within the system as a result of bending in the specimen due to the normal load compressing the rolling support (9,49).

A system used for environmental studies by Waterhouse et. al. (53) is illustrated in Figure 12. In this case, the normal load is applied by a screw/proving ring arrangement through fretting bridges. Bridges are commonly used in fretting fatigue testing and consist of two feet which act as pads. Slip amplitude is essentially regulated by the length of specimen which lies between the bridge feet.

During the design stage of a fretting fatigue apparatus, investigators must usually choose between a fretting bridge (two pads) or a single pad arrangement. Both systems are susceptible to pad deformation (Fig. 13) (47,49,54). These deformations can lead to a heterogeneous normal stress distribution and possibly loss of debris during testing. It should be noted that with proper design, the extent of these deformations may be limited. The advantages of a bridge arrangement are the reproducibility of slip amplitude, simplicity and stability. However, because the slip magnitude is dependent on the distance between the pads of the bridge, bridge arrangements are less flexible in obtaining a wide range of slip amplitudes.

In the literature, a few novel test facilities have been reported which have been developed to provide accurate simulation of actual service situations. One of the test facilities (7) has been produced to assess the influence of fretting on the reduction in fatigue life in dovetails of gas turbine blades (Fig. 14). The driving force behind the development of such a facility stems from the costly and time consuming spin pit tests which are traditionally used. The components of the apparatus were designed to reproduce the state of stress which exists during service in blade dovetails. Components include a rectangular sheet specimen which models a disk and three pairs of blades that are mounted on the sheet specimen (Fig. 14). During testing, the rig is biaxially stressed with loads applied across each set of blades and along the rectangular sheet (Fig. 15). In order to confine failure to the central set of blades, the outer blades received approximately 10% less loads than the central blades. Under the experimental arrangement, a simulated stress state was produced at the blade dovetail as verified by a photoelastic model. It was established through studies using the rig that fretting had a significant effect in degrading the fatigue life of blades.

2.5 Ion Implantation

2.5.1 Introduction

The process of ion implantation offers some unique advantages over other surface modification practices. By controlling ion species and implantation parameters, the implanted zone can be optimized in terms of chemistry and structure to best suit the property requirements (25,30,32,55). Ion implantation does not affect surface dimensions or finish and a zone of residual compressive stress may be introduced within the affected zone (25,56). In addition, no interface is created between unimplanted and implanted material because of the gradual decrease of ion concentration into the bulk material (29,33,55,56). For surface enhancement, ion implantation is recommended for components where high dimensional tolerances restrict the application of thin films or where a possibility of coating delamination rules out the use of conventional coatings (23,25,57). The market applications best suited for ion implantation include medical implants and tooling, critical aerospace components, and precision tooling such as molds, dies and punches (23,25,58). Materials in which ion implantation techniques have proved effective include the alloys of nickel, beryllium, titanium, zirconium and various types of stainless and tool steels (23).

A number of investigators have applied ion implantation processing to titanium alloys to improve surface properties (23,24,55). Most documented work has involved implanting the ion species of nitrogen and carbon into titanium alloys in order to initiate the formation of ultrahard nitrides and carbides to enhance wear and corrosion properties (59-61). Other ions used for surface modification of titanium alloys which have received limited attention in the literature are B^+ , Al^+ , Ba^+ , Cs^+ , Sr^+ , Sn^+ and Yb^+ (34,62,63).

2.5.2 Implantation Processing

The source of ions used in implantation processing is a plasma which can be produced from a dissociated gas or by the practice of evaporating/sputtering solid elements (30,57). During ion implantation, ions are accelerated in vacuum by a bias voltage, typically 10-200 keV, then directed to a target material (25,29,30). After a series of energy dissipating collisions with the host atoms, the ions come to rest resulting in a concentration profile roughly fitting a Gaussian distribution (25,27,30). The penetration depth is dependent on the bias voltage, ion energy (mass and velocity), the target chemistry and crystalline structure (27,29,57,59). The total depth of ion implantation generally ranges from hundreds to several thousand angstroms (27,29). For the case of high energy implantation, the target surface will be affected by erosion and sputtering (29,57,59). With implantation of light atoms such as nitrogen and carbon, there is negligible sputtering (30). While the concentration of implanted ions, or fluence, is typically in the range of $(0.1 \text{ to } 15) \times 10^{17} \text{ ions/cm}^2$, the actual dose is dependent on the sputtering yield. A substrate current regulates the rate of implantation and the extent of target substrate heating (23,57).

During ion implantation, the target surface receives significant heat input which may be dissipated to prevent overheating or controlled to enhance chemical interactions between the ions and substrate (25,57). For "cold" processing it is important to select a low substrate current density and/or reduce the time the beam is on the target, and a heat sink must be introduced as well. Heat removal is a major obstacle restricting high substrate current processing required for large scale production (12). Implantation at certain elevated temperatures can aid in the formation of new second phases (57). However post implant heat treatments can be used to have similar effects in a more

controlled manner (27,29). Elevated temperature implantation may also result in dimensional or surface changes of the product (27,58).

2.5.3 Influence of Ion Implantation on Fretting Fatigue

The main mechanical properties which govern the extent of fretting fatigue damage to a material are essentially hardness, wear, oxidation/corrosion and fatigue strength. A few studies have indicated that ion implantation can enhance the fretting fatigue life of Ti-6Al-4V (30,34,59,63). To best understand the nature of fretting fatigue life improvement via ion implantation, the mechanism by which ion implantation influences these above properties must be examined. It has been reported that fretting fatigue life improvements by ion implantation of Ti-6Al-4V mainly results from enhanced wear resistance rather than improved fatigue properties (6,25).

The hardness of a material is a very important parameter governing wear resistance of materials (25,30). For C^+ or N^+ implanted titanium alloys, solid solution hardening and/or the formation of ultrahard carbides and nitrides provides the increased surface microhardness (25,58). Measuring the hardness of implanted metal surfaces is difficult as a result of the shallowness of the implanted layer. Nevertheless, measurements have been completed indicating that implantation can have significant effect on the surface microhardness. In one investigation it was observed that nitrogen and carbon implantation can improve the surface hardness of Ti-6Al-4V by 40-50% or higher (61).

Titanium alloys are generally fairly resistant to oxidation because of the formation of a stable oxide film. However, at elevated temperatures significant diffusion of oxygen can occur (34,59,62). Ion implantation can reduce the oxidation of titanium alloy components without affecting tolerances (34,62). Ions with low electronegativity have proved most effective because

they "trap migrating oxygen" which serves to restrict further migration (34,61). Ions of calcium, phosphorus, tin, and barium have all been reported to improve the oxidation properties of titanium alloys (34). Barium and tin are believed to react chemically with the diffusing oxygen to form BaTiO_3 and SnO_2 respectively (59,61,62). Once formed, these products generate a localized compressive stress within the titanium lattice which block further oxygen diffusion (34,59,61,62).

Fatigue may involve the initiation and propagation of cracks in a material under the application of cyclic stresses. Since crack initiation is often surface sensitive, this stage can be influenced by ion implantation. However, once a crack has propagated beyond the implanted layer, the crack growth is dependent on the properties of the bulk material (64). A number of investigations have studied the effects of ion implantation on fatigue for a wide range of materials. It has been determined that ion implantation can be effective in improving high cycle fatigue properties for titanium alloys (24,30,64). Under low cycle loading conditions the life enhancements are not as pronounced (59,64). The exact reason for life improvements are not well understood but it appears that ion implantation changes the nature of near surface slip (30,33). It is believed that precipitation hardening, solid solution strengthening and compressive stresses can combine to cause the improvements (30,65). Solid solution strengthening involves mobile interstitials diffusing to dislocations or other defects to resist dislocation motion. Precipitation strengthening leads to the interference of dislocation movement by second phase formations.

Titanium alloys generally display poor wear resistance because they are prone to adhesive wear and abrasive wear by particles of wear debris (26,55,64,66,67). In terms of wear improvement, ion implantation may enhance surface hardness which in turn reduces the surface coefficient of friction (55,56,67). A hardened surface generally decreases surface adhesion and

ploughing of micro-asperities during wear (33,55,56,67). For titanium alloys, nitrogen and carbon ions have been found to introduce a transition in the wear mechanism from one of severe abrasion/adhesion to a mild oxidative mode (25,55,59,67,68). The process of stress-induced nitrogen migration where nitrogen atoms diffuse ahead of the advancing wear surface, imparting improved wear resistance beyond the implanted layer has been proposed for some materials, but not well documented in the case of Ti-6Al-4V (25,63).

Very little literature is available on fretting fatigue life improvement of Ti-6Al-4V via ion implantation. Carbon atoms at the implantation conditions of 2×10^{17} ions/cm² at 75 KeV were found to increase the fretting fatigue life as shown in Figure 16 (30). Gains in life were thought to be a result of slowing of debris formation and subsequent damage to the surface. It was reported the increase in life was due to the increased wear resistance of the surface (6).

Syers and Dearnaley (34) have examined the effects of implanting the ions Ba⁺, Cs⁺, Sr⁺, and Yb⁺ into Ti-6Al-4V coupons for fretting fatigue testing. These ions are thought to concentrate at dislocations, which are believed to be the oxygen diffusion paths in titanium alloys. It was noted that there was a direct correlation between fretting fatigue performance and oxidation behavior at 600°C for these implanted ions. Shown in Figure 17 is the fretting fatigue improvement for specimens implanted with barium, the most effective ion species studied, combined with shot peening. In the absence of a shot peened surface modification, barium implanted Ti-6Al-4V increased life up to 50% (34,63).

2.6 Microstructure and Mechanical Properties of Ti-6Al-4V

2.6.1 Physical Metallurgy of Ti-6Al-4V

Titanium and its alloys are classified into 3 major categories depending on the microstructural phases present: alpha, beta and alpha-beta (2,69-71). Pure titanium undergoes a transformation from alpha (hcp structure) to beta (bcc) as its temperature is raised through approximately 882°C (2). Addition of alloying elements may either favour the formation of alpha or beta phases or have no effect. Alpha stabilizers are generally simple metals or interstitial elements which include Al, O, C and N. Beta stabilizers are typically transition metals such as Cu, Cr, Nb, Fe, Ta and V. Alpha alloys are characterized by satisfactory strength, toughness, creep resistance and weldability (69,71). Also, alpha alloys are not significantly influenced by heat treatment and compared to beta alloys are more resistant to oxidation but harder to form (2,71). Beta alloys require a high alloy content such that the beta phase can be retained at room temperature and as a result, beta alloys are denser than other titanium alloys. Beta alloys are often chosen for applications which require a high formability material or superior strength capabilities which can be obtained through appropriate aging schemes (71).

The third class of titanium is alpha plus beta alloys which account for 70% of all titanium in use (70,71). These alloys are formulated such that both the alpha and beta phase co-exist at room temperature (69,71). A wide range of mechanical properties can be achieved in alpha-beta alloys by varying the material chemistry or by altering the microstructure via processing and subsequent heat treatment (69-71). Ti-6Al-4V is the most common alpha-beta alloy in use today (2). 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 18 (2). It

should be noted that for Ti-6Al-4V, the actual response to heat treatment varies from heat to heat as a result of processing history, chemistry and section size (70-74).

Heat treatments for Ti-6Al-4V usually involve cooling the alloy from an annealing temperature in the alpha/beta region or above the beta transus (Fig. 18) (2,70,72-76). These solution treatments are sometimes followed by an intermediate age to produce an appropriate mixture of alpha and transformed beta products (2,70,71,73). Heat treating above the beta transus temperature and cooling leads to the nucleation of alpha phase in plate form starting from beta grain boundaries (Fig. 19a). The resulting lamellar or Widmanstatten transformed beta product can be coarse if slow cooling is utilized. A fine alpha plate size may be produced if faster cooling rates are adopted. Equiaxed microstructures are obtained by mechanical working in the alpha/beta phase region. Subsequent annealing within the alpha/beta phase field produces equiaxed alpha with intergranular beta (Fig. 19b) and/or a matrix of lamellar acicular alpha (Fig. 19c) (76). By increasing the annealing temperature within the alpha/beta field increases the volume fraction of the beta phase (Fig. 18) (2,70,72,77).

The mechanical properties of Ti-6Al-4V are known to be very dependent on the microstructure (ie. phase morphology, grain size and texture) (77-79). These microstructural aspects can be controlled by processing and heat treatment, therefore a wide range of mechanical properties can be obtained in Ti-6Al-4V products (74,79). However, it should be mentioned that improving one specific mechanical property by microstructural modification might cause a loss of other properties (74,79). Textures are created in titanium alloys during processing as a result of plastic deformation (74,80,81). Various textures may arise depending on deformation mode and on processing temperature (78-80).

Textured Ti-6Al-4V exhibits property anisotropy with one direction possessing a stronger, stiffer and more fatigue crack initiation resistant condition compared to other plane directions (74,81). Property anisotropy is associated with the crystallographic orientation of the alpha phase in the hcp lattice structure (74,81). Creating a transformed beta microstructure by heat treating above the beta transus will randomize the texture (74,81). The mechanical properties of Ti-6Al-4V in the different conventional heat treated conditions will be reviewed in the following section.

2.6.2 Conventional Heat Treatments

Table 1 presents the main conventional heat treatment schedules for Ti-6Al-4V and a description of the resulting microstructures for the different conditions (72,73,80,82,83). The six treatments of Table 1 are the mill anneal (MA), recrystallization anneal (RA), solution treat and age (STA), solution treat and overage (STOA), beta anneal (BA), and beta quench (BQ). The BA and BQ treatments utilize anneals above the beta transus, whereas the RA, STA, and STOA treatments use annealing temperatures in the alpha/beta regime of Figure 18. The MA represents a partial anneal which may leave traces of cold or warm work stresses within the final product (72,73). These six treatments of Table 1 produce a variety of microstructures which in turn are associated with a wide range of mechanical properties. The mechanical properties reported for Ti-6Al-4V microstructures in the conventional heat treated conditions often vary between published investigations. These variances are likely a result of differences in as-received material and specimen fabrication methods (72,84).

Tensile Properties

In order to maintain high strength in Ti-6Al-4V components, manufacturers have traditionally utilized a mill anneal (MA) condition. The improved tensile properties of the MA condition have been associated with its relatively fine grain size (72,73). The other conventional heat treatments utilize solution anneals which coarsen the microstructures. Table 2 compares the tensile properties of a fine equiaxed grain structure ($2\text{ }\mu\text{m}$) to a coarser grained equiaxed material ($12\text{ }\mu\text{m}$) and a bi-modal structure consisting of equiaxed alpha in a matrix of fine lamellar alpha/beta (81). The grain size of the bi-modal material was reported to be $6\text{ }\mu\text{m}$. It can be seen from Table 2 that a reduced Ti-6Al-4V grain size can have a pronounced affect on tensile properties (81). Comparative tensile strength data for material in the different conventional heat treatment conditions is reported in Table 3 (73,81). From Table 3 it is difficult to discern any trends in terms of tensile strength. It has been reported that tensile strength is not sensitive to the phase morphology (72,78,83). However it can be seen that ductility decreases with conditions involving anneals above the beta transus temperature (Table 3).

Fatigue Strength

In order to attain high fatigue strength it is necessary to prevent or delay crack initiation (74). In Ti-6Al-4V, crack initiation is dependent on the microstructure and loading conditions. It should be noted that in Ti-6Al-4V components, the total fatigue life is dominated by factors affecting the time until crack initiation rather than crack propagation rates (74,78). Under high cycle fatigue loading conditions crack initiation has been found to occur along alpha/beta interfaces (74,80,85). Under low cycle fatigue loading conditions, crack initiation generally occurs along slip bands within the alpha grains (74,81,85). For both cases, a fine grained microstructure

is beneficial to restrict the localized size of the alpha/beta interface and the length of slip bands available for crack initiation within the alpha grains (74,80,81). The influence of grain size on high cycle fatigue life of Ti-6Al-4V is depicted in Figure 20 (81). It can be seen from Figure 20 that a fine equiaxed structure is preferable in both air and vacuum compared to a coarse grained, equiaxed structure. A fine bi-modal structure was found to perform better than the fine grained equiaxed structure in air but not in vacuum. It was noted that the fatigue strengths of equiaxed microstructures were more sensitive to air compared to structures with a matrix of lamellar alpha/beta (81). Good low cycle fatigue strength has been obtained when microstructures contain a lamellar alpha/beta structure (74,85). However this microstructure does not improve high cycle fatigue crack initiation life (74,85). Although no comparative fatigue life data was available for the different conventional heat treatments, it is likely that the STA which creates a bi-modal structure and the MA heat treatment which produces an equiaxed structure would have good fatigue strength because of their fine microstructures (80,85).

Fatigue crack propagation (FCP) in Ti-6Al-4V at room temperature is known to be significantly affected by microstructure (83,86,87). Microstructures that cause tortuous crack paths and crack branching have been found to yield the lowest FCP rates (78,83,86). The degree of crack path tortuosity increases with the coarseness of the microstructure and is more significant with a lamellar morphology compared with an equiaxed microstructure (83,87). Figures 22a (73) and 22b (86) relate the different FCP rates to the microstructures of the conventional heat treatments. From Figure 22a and 22b it is apparent that the MA, STA, and STOA all display relatively poor FCP rates which is a result of their high volume fraction of equiaxed alpha phase (83,88). Although both the STA and STOA contain lamellar alpha plus beta, the acicular alpha platelets are fine and do not apparently introduce any significant secondary cracking or an irregular crack path

(86,88). Intermediate FCP rates occur with the RA microstructure. The RA microstructure is characterized by an equiaxed alpha plus beta structure and moderate FCP rates have been associated with the formations of secondary cracking which absorb energy and reduce energy available for propagation of the main crack (73,86). Relatively low FCP rates occur in the BA and BQ microstructures as a result of the lamellar structures which make the crack route more tortuous (73). It was noted that the FCP rates in equiaxed structures are somewhat dependent on the extent of texture (74,78,86).

Fracture Toughness

Fracture toughness is an assessment of a materials resistance to fracture (18). The fracture toughness of Ti-6Al-4V is sensitive to microstructure and material processed in the beta solvus field and displaying a coarse lamellar alpha/beta structure typically exhibits the best fracture toughness values (73,74,77,86,89). The microstructural features which best enhance fracture toughness are those which impart crack blunting by causing cracks to branch in directions parallel to the stress axis (77,89). Table 4 presents fracture toughness data from two different references for material in the conventional heat treated conditions (83,88). From table 4 it can be seen that the BA and RA conditions provide the highest fracture toughness values. Significant secondary cracking is introduced in the plate-like alpha in the lamellar structure of the BA condition. The lamellar structures created by quenching plus age as with the STA, STOA, and BQ display relatively poor fracture toughness values because the alpha plates are fine and do not promote significant crack tip blunting (73,80,88). The high fracture toughness values for the RA condition maybe due to multiple cracking in the alpha grains and at the alpha/beta interfaces (73). The mill anneal material displays poor fracture toughness, probably a result of residual stresses from processing combining with the applied stresses (72,73). Thus lower applied stresses are

required for failure. It should be noted that the mill anneal only provides a partial stress relief of as-processed material and therefore extensive dislocation debris is present even in the heat treated condition (72,73).

2.6.3 An Alternative heat Treatment For Stage 1 Fan Blades

During the course of recent years the performance of the Rolls Royce RB-211 aero gas turbine engine has been improved substantially through design alterations. In order to meet the increased service stresses in present day engines the mechanical properties of the stage 1 Ti-6Al-4V fan blades were enhanced by a modified treatment. The original heat treatment (700°C/1 hr.) was essentially a mill anneal. The modified treatment is similar to the solution treat and age (STA) and involves a partial solution treatment (940°C/1 hr.) with a fast cooling, plus a 700°C age. An alpha beta morphology with 50 percent alpha phase was the target. The increases in mechanical properties of the stage 1 fan blades, which were achieved by the modified treatment, are presented in Table 5. As shown in Table 5, according to Rolls Royce, this heat treatment leads to substantial increases in tensile strength, fatigue strength, and fracture toughness. The test data of Table 5 was established by performing 15 tests on material from the dovetail portion of the blades. It should be noted that in this study the importance of creating a grain texture along the stress axis of the blades was emphasized (1).

2.6.4 Rejuvenation Treatments for Ti-6Al-4V

Two important investigations have been carried out which concern rejuvenation of fatigue damaged Ti-6Al-4V (36,37). In both cases, HIPing was utilized in an effort to close surface cracks. Although only limited success was achieved in bridging the defects, many important guidelines for rejuvenation of Ti-6Al-4V by reheat treatment were discussed in these reports. It should be emphasized that in this thesis the type of rejuvenation

being carried out is the annealing of internal LCF induced microstructural damage rather than the healing of macroscopic surface cracks.

An investigation to relieve or minimize fatigue damage in Ti-6Al-4V was carried out by the Battelle-Columbus Laboratories (36). The heat treated material examined was the beta solution treatment and overaged condition. A thermal treatment at 954°C for one hour was found to cause considerable coarsening of the grain structure and elongated grains to become equiaxed. To minimize microstructural coarsening, it was suggested to limit the rejuvenation temperatures to below 870°C and annealing times to a few hours.

In this study, mechanical testing included subjecting specimens to low cycle fatigue loadings to a condition just before cracks had initiated. After the damage was incurred and specimens examined by non-destructive inspection techniques, the specimens were re-heat treated in an attempt to rejuvenate the LCF properties. Under total strain range testing, improvements of up to 69% were found, whereas under plastic strain range testing the maximum rejuvenation achieved was 15%. The overall rejuvenation results showed improvements but these were often modest with the data showing high scatter and not always consistent (36).

HIP rejuvenation of service exposed Ti-6Al-4V turbine disks in the mill annealed condition has been investigated by AirResearch Manufacturing Company (37). It was reported that the rejuvenation temperatures utilized by government and private research labs has ranged from 845-955°C, with 900°C most commonly used. In this investigation it was established that temperatures above 900°C introduce microstructural coarsening and can possibly cause component distortion. Annealing at 845°C was found to retain a microstructure similar to the initial mill annealed condition. An 845°C/4hr HIP treatment was deemed best suited for a

turbine disk rejuvenation treatment. This heat treatment schedule was found to reduce the dislocation density within disk material from approximately 10^9 - 10^{10} per square centimeter to approximately 10^7 - 10^8 per square centimeter. However, all eight disks of a batch HIPed following the above rejuvenation schedule were unacceptable in terms of tolerance because of warpage. It was suggested that proper fixtures within the HIP facility may minimize component distortion.

Room temperature tensile and low cycle fatigue tests were conducted on serviced exposed disk material and service exposed plus HIPed disk material. The results of the tensile tests are shown in Table 6. It can be seen that the rejuvenation HIP treatment ($845^{\circ}\text{C}/4$ hours) resulted in only minimal loss in strength with the strength values of HIPed disk material remaining above specification minimum. It was noted that the cooling rate influenced the tensile strength and high strength was retained by utilizing a very slow cool ($\sim 70^{\circ}\text{C}/\text{hour}$). The low cycle fatigue properties of the HIPed disk material were better than the un-HIPed material, but not by a significant amount (Table 6).

It is felt that the primary reason for the failure of these rejuvenation treatments to produce substantial improvements is due to the fact that the solution treatment temperatures chosen are too low to cause sufficient recrystallization. It has been shown that a recrystallization anneal enhances mechanical properties as a result of the recrystallized grain structure being capable of absorbing more deformation prior to failure than the as-worked grains structure. Also, recrystallizing the grain structure may have the result of annealing-out microstructural damage introduced during early stages of the LCF cycling (35,36,37,73).

Chapter 3

Analyses of Fretting Damage in Stage 1 and Stage 2 Fan Blades

Moderate to severe fretting wear damage has been observed on the pressure surfaces of several stage 1 and stage 2 fan blade dovetails of an advanced turbofan engine (Fig. 3). Small crack like defects have been found on the pressure faces extending into the parent material (Fig. 22). As a result of the fretting action, the pressure face material/coatings may have to be modified in order to minimize blade degradation. This investigation has been carried out in order to establish the consequences of the fretting damage which occurs on the blades by documenting the various surface and sub-surface defects present in the service exposed blades. Fan blade operating conditions which cause fretting damage on dovetail pressure surfaces has been analyzed. It was of interest to evaluate the performance of the MoS_2 and Cu-Ni-In coatings which are applied to the pressure faces of the dovetails. Also, the possible impact of the defects on flight safety has been discussed within this study.

In this research, ten stage 1 and ten stage 2 service exposed fan blades which had been retired because of minor FOD (foreign object damage) as well as a new second stage blade have been examined. In the case of the first stage blades, blades with various service histories were selected. Their service lives are listed in Table 7. The service histories of retired second stage blades were unknown and therefore blades which appeared to have sustained the worst possible fretting damage were considered. It should be noted that the selected first stage blades had consumed less than 30% of their established design lives. It is likely that the second stage blades had only been in service for a short time as well. In the analyses, the fretting damage in both first and second stage blades is discussed together unless otherwise specified.

The evaluation of the fan blades has included both optical and scanning electron microscopy of the blade pressure surfaces and dovetail cross-sections. At least five cross-sections have been prepared metallographically (mounted and polished). Dovetail cross-sections have been examined in the etched and unetched conditions. The etchant used was a 93% H_2O , 2% HF and 5% HNO_3 solution. Examination of the dovetails has been completed with the use of a Leitz mm6 microscope and a Novascan 30 scanning electron microscope.

3.1 Characterization of Fretting Damage in Fan Blades

The fan blade operating loads which produce fretting degradation of dovetail pressure surfaces are shown in Figure 4. The centrifugal loads which develop within the blades are a result of high engine rotational speeds and are transferred to the disk via dovetail pressure surfaces. This load transfer produces high normal pressures along the pressure surfaces of the fan blades. As a result of dovetail design configuration, high shear stresses develop in material beneath the pressure surfaces (Fig. 23). In the case of relative movement (slip) between disk/fan blade pressure surfaces during service, the magnitude of the shear stress is dependent on the localized normal pressures and the coefficient of friction between the contacting surfaces. Shear stresses will dissipate with depth from the blades pressure surfaces (Fig. 23).

Fretting is produced during service on dovetail pressure surfaces as a consequence of high normal pressures and the occurrence of relative movement at the disk /blade interface. Variations in centrifugal force caused by engine start-up/shut-down and major throttle excursions cause the blades to shift axially within their mounts (Fig. 24a). Slip is also known to occur as a result of natural blade vibration which causes blades to rotate back and forth within their mounts (Fig. 24b). Slip amplitudes associated with the blade natural frequencies are much smaller as compared to the slip magnitudes which occur during

engine start-up/shut-down. However, natural blade vibration occurs at a very high frequency whereas only a limited number of fretting fatigue cycles associated with changes in centrifugal forces will occur during a single mission. Fretting degradation on fan blade dovetail pressure surfaces is therefore influenced by two different conditions acting simultaneously. It is unclear at this time which of these effects dominates the overall fretting degradation mechanism.

Shown in Figures 3a and 3b are two typical damaged pressure surfaces of the first and second stage blades, respectively. It can be observed that in both cases wear scars have formed parallel to the longitudinal axis of the blade. With regards to fretting damage accumulation on first stage pressure surfaces, it appeared that the degree of damage increased with blade service exposure hours. It is necessary that blades with even higher service exposure times than those available for this study must be tracked in order to build up a sufficient data base such that a trend between fretting damage and service exposure can be established.

It appears that the severity of the fretting action varies with location since fretting damage on the blades occurs randomly along the pressure faces of the stage 1 and 2 blades. Fretting damage kinetics are believed to be accentuated at areas where high localized contact pressures exist as a result of surface mismatches and micro-roughness (asperities) between the pressure surfaces of the blade and disk slot. Once fretting has commenced, wear debris is generated and is entrapped at these high contact pressure locations and thus a condition of high localized contact pressure is maintained. It is also possible that the pressure may actually increase with service exposure at these localized areas as a result of an increase in debris volume associated with oxidation.

From an optical examination of a number of retired stage 1 and 2 blades it was quite apparent that the dovetail pressure surfaces of second stage blades were subject to more severe fretting wear conditions. This observation is likely a result of the second stage blades having an increased freedom to vibrate since these blades do not have mid-span dampers which are employed on stage 1 blades to reduce blade flutter. All second stage blades examined were also found prone to fretting damage at a particular end location of a pressure face as shown by arrows in Figure 25. This may be a result of a deficiency in the design or in the manufacturing process which creates a localized, high contact stress state at this particular location during service. Also, it may be a result of inhomogeneous slip along the dovetail pressure surfaces. In other words, the fretting damage which occurs commonly on stage 2 fan blades is likely due to the area on the dovetail being subjected to a relatively higher magnitude of slip or pressure than other regions.

In terms of coating performance, the molybdenum disulphide (MoS_2) solid lubricant coating was present only in limited quantities on the pressure surfaces of stage 1 blades serviced for 333.8, 600.5, 838.1, and 847.1 (Table 7) and all second stage blades. Exceptions included stage 1 blades in service for 94 and 407 hours where up to approximately 30% of the pressure surface area still contained the MoS_2 coating. When present, MoS_2 appears as a black and smooth layer which may be continuous with new blades or cracked with serviced blades (Fig. 26). The failure mechanism for the MoS_2 coating was determined to be delamination at the $\text{MoS}_2/\text{Cu-Ni-In}$ interface (Fig. 26). Although the molybdenum disulfide solid lubricant coating adhered poorly, the MoS_2 coating may moderate the fretting action by mixing with or coating the abrasive debris. As well, it may act as a buffer zone to accommodate local micro-roughness between the contacting surfaces and therefore create a more homogeneous stress state along the pressure face.

Fretting action on the soft Cu-Ni-In coating was found to result in a material removal process consisting of a crumbling action (Fig. 27). Plasma sprayed layers which are common to the Cu-Ni-In coating (as shown by arrows in Figure 28) may also fail by delamination. It did not appear that delamination readily occurs at the Cu-Ni-In/Ti-6Al-4V interface. The crumbling process is believed to be associated with failure at discontinuities within the coating or by surface embrittlement due to oxidation. Note that the Cu-Ni-In is a soft coating and serves to hinder fretting by reducing the shear loads which are transmitted to the surface of the Ti-6Al-4V from the fretting motion and to dampen vibration.

Examination of the sample service exposed blades (Table 7) by scanning electron microscopy indicated that very little Ti-6Al-4V was directly attacked by the fretting action. Fretted Ti-6Al-4V has a smooth and an almost smeared appearance (Fig. 29) whereas Cu-Ni-In is much rougher and less continuous. From Figure 29 it is apparent that abrasion plays a significant role in the surface degradation. Although not very clear, it appears that adhesion may also be a factor in the fretting degradation of Ti-6Al-4V. Since very little Ti-6Al-4V was revealed by the fretting, the coatings have performed adequately over the early portions of the blade lives. However, future studies on blades with even higher exposure times than those available in this study may find that the coatings are not effective over the entire service lives of the blades. Therefore, the blade dovetail pressure surfaces may require attention in terms of stripping and recoating or possibly utilizing an alternative coating.

Dovetail cross-sectional analysis of a new second stage blade revealed that the parent alloy underlying the coating has a poor surface finish in some locations (Fig. 30a). The manufacturing process appears to have introduced many pressure face flaws (Fig. 30b) that on occasion occur along with sub-surface defects

(Fig. 30c). These flaws are presumed to have formed during the machining and/or shot peening of the dovetail surface. Etched specimens often display grain distortion at these flaws.

Cross-sectional analyses of service exposed stage 1 and stage 2 fan blade dovetails at locations where the coating remained intact indicated that the Ti-6Al-4V pressure face had a surface finish and manufacturing flaws similar to those observed at the pressure faces of the new blade. Due to the similarity of Ti-6Al-4V pressure face flaws between the new and the service exposed blades, it is suggested that these manufacturing defects are not obviously influenced by dovetail shear stresses associated with blade loading conditions. A sub-surface defect that was observed in a service exposed blade dovetail is shown in Figure 31.

The defects which radiate into the Ti-6Al-4V substrate, as shown in Figures 22, 30c and 31 are believed to be deformed material which has etched preferentially. It is unknown if these defects are created as a result of manufacturing or service or a combination of the two. However, it should be noted that the flaw shown in Figure 30c is from a new blade whereas the defect shown in Figure 22 appears to originate from an area where Ti-6Al-4V is under direct fretting action. At this early stage of life it is difficult to predict the level of further in-service degradation which occurs, but it is quite likely that these defects can lead to crack initiation/propagation during service, since the blade dovetail is a highly stressed location.

Ion implantation may be a feasible method to combat fretting damage along the pressure surface of the blades. As reported in section 2.5, ion implantation can improve the fretting fatigue life of Ti-6Al-4V by essentially improving the surface wear properties. It should be noted that to obtain the full potential of ion implantation, the implanted surface must be finished to

relatively high quality. Therefore blades receiving ion implantation processing will have to have a much improved surface finish as compared to the quality of contemporary finishes.

Improving the surface finish may also have adverse effects with regard to the adherence of the coating to the Ti-6Al-4V substrate. The full benefit of ion implantation can only be determined through extensive mechanical testing because of the complex component arrangement and stress-state.

Chapter 4

Experimental Procedure

4.1 Fretting Fatigue Testing

4.1.1 Test Rig Design

A fretting fatigue test facility shown in Figure 32, was designed for preliminary assessment of ion implanted material. Complete drawings of all components used in the apparatus can be found in Appendix D. The fretting bridge arrangement which was used provides a relatively inexpensive means of inducing fretting and has been used by other research groups (10,54). The fretting fatigue test apparatus shown in Figure 33 was originally employed but later modified since it was determined that normal clamping loads, between fretting bridges and fatigue specimen, varied with pad location. Component drawings for this apparatus are included in Appendix E.

The flat plate fatigue specimens used in this investigation are similar to those employed by other research groups (Fig. 34) (54). Specimens have been machined from flat plate Ti-6Al-4V in the mill anneal condition. According to the supplier, the yield strength of the plate material was 810 MPa. Specimens were polished to a one micron diamond level in order to facilitate ion implantation processing. During testing, each specimen (Fig. 34) was simultaneously subjected to an axial cyclic fatigue loading and a constant normal load applied through two fretting bridges (Fig. 35) by means of 4 clamping bolts. Fretting damage was introduced to four different locations on the specimens. The fretting bridge pads were ground to a 600 grit level and polished to a nine micron level. It should be noted that a new set of fretting bridges were used for each test. The material of the fretting bridge is the disk alloy Ti-17. Ti-17, like Ti-6Al-4V

is an alpha-beta alloy which has an approximate composition of Ti-5Al-2Sn-2Zr-4Mo-4Cr (70). The main advantage of Ti-17 is it's ability to have uniform strength in large sections (70).

The complete test facility which includes the fretting fatigue test apparatus, MTS 250 KN servo hydraulic test frame, MTS 810 material test system and a Hewlett Packard Data Acquisition/Control Unit (Model 3497A) is shown in Figure 36. The fretting fatigue test apparatus is enclosed in a chamber such that testing could be completed in dry air. Humidity effects are known to influence fretting wear and due to the fact that significant variations in humidity can exist between seasons, it was deemed necessary to control this parameter while testing. During testing, compressed air was passed through desiccants before being bled into the chamber. Testing was carried out at room temperature since fan blades operate at ambient temperatures.

The test apparatus was calibrated with regards to normal load. The normal load was produced by tightening the four clamping bolts and was measured through the use of a calibrated load cell (Fig. 32). The load cell in this case is a strain gauged aluminum cylinder. In order to generate an output voltage from the load cell, an Accudata bridge amplifier (model 218) was employed. A Fluke 73 Multimeter was used to measure the output voltage. The calibration curve for amplifier output voltage versus applied load is shown in Figure 37. In order to ensure the normal pressure was homogeneous between fretting bridge and specimen, each specimen was strain gaged as shown in Figure 38. In each case the gages were calibrated through the use of a shunt resistor. Testing was suspended at regular intervals in order to measure the microstrain output. Strains were monitored through the use of the Hewlett Packard Data Acquisition/Control Unit. Two different strain gage types were used in this study (types EA-06-062EN-350 and EA-06-090EF-120) because of availability problems. The characteristics of these gage types are listed in Table 8.

4.1.2 Test Parameters and Conditions

The controlling variables that influence the fretting degradation on fan blade dovetails were analyzed in Chapter 3. It was noted in section 3.1 that the fretting action was a consequence of relative slip and high normal contact loads which exist at fan blade pressure surface/disk interfaces during service. Slip is influenced by both fluctuating centrifugal blade forces and natural blade vibration. Since both centrifugal blade forces and blade vibration vary with engine RPM and flight conditions, a wide range of fretting conditions will exist during a single mission. It should also be noted that very little information is available regarding the specifics of fretting conditions which occur on blade dovetails during service. In this study only one set of fretting conditions has been examined experimentally. Fretting fatigue testing has been carried out under normal loads of 50 MPa and a cyclic fatigue load of 560 MPa. The R ratio (minimum stress over maximum stress) used was 0.25. The frequency employed for the testing was 4 Hertz. In this experimental investigation, testing has been conducted with the materials used in actual components.

The test matrix employed in this study is summarized in Table 9. Within this investigation a carbon implantation treatment and a nitrogen plus carbon ion implantation treatment were examined. The implant conditions used for the fretting coupons were established through an in-depth literature review and TEM study (6). Specimens receiving ion implantation processing were treated on two opposing sides of the specimen along the gage length. For comparative purposes it was required to complete fretting fatigue and baseline fatigue (without fretting) tests on unimplanted coupons. Testing was also carried out on two specimens that had received a shot peening treatment. Shot peening is a common treatment used to improve fretting fatigue properties of components and is used on fan blade dovetail pressure surfaces. In one investigation, shot peened Ti-6Al-4V specimens

showed a high resistance to fretting fatigue, with test results being only slightly below those of specimens that were polished and tested under fatigue conditions but not fretted (Fig. 39) (90). Another investigation reported that the fretting fatigue limit at 10^7 cycles of Ti-6Al-4V specimens was improved by more than a factor of two as compared to untreated milled specimens by shot peening (91). The shot peening parameters examined within this investigation included a 110 shot size of hardness R_C 42-52, and a peening intensity of 4 to 6 Almen. A Leitz microhardness test unit was used to compare the surface hardness values of implanted, shot peened and unimplanted material.

4.2 Characterization of Fan Blade Material in Re-heat Treated Conditions

A goal of this investigation was to find potential re-heat treatments which can rejuvenate uncracked fan blade material which has suffered service induced microstructural damage due to LCF. This rejuvenation of fatigue damaged material may be accomplished by annealing-out the dislocation debris and other similar effects of LCF. This heat treatment must produce a microstructure which provides similar or improved mechanical properties as compared to the original mill anneal condition. As illustrated in Section 2.6.2, the mill anneal condition provides high strength and resistance to crack initiation but relatively poor fracture toughness and crack propagation properties. Since fatigue life in Ti-6Al-4V components is very dependent on the time to crack initiation, the heat treated condition must lead to a high resistance to crack initiation as well as good strength properties. In this study the materials have been evaluated microstructurally.

Prior to attempting re-heat treatments on service exposed fan blades, a few guidelines were established with regard to the

heat treatment schedules. It was believed that treatments utilizing annealing temperatures above the beta solvus (approximately 985°C) or quenching would introduce significant component distortion. As well, obtaining a complete microstructural rejuvenation might require anneals which recrystallize the microstructure. Four different heat treatments have been carried out on dovetail material from stage 1 fan blades service exposed for 333.3 hours or 948 ELCF's. The schedules of the heat treatments examined and the designation of each condition (heat) are listed in Table 10. Although treatments 1 and 2 (Table 10) do not employ annealing temperatures which will promote recrystallization (section 2.6.4), they were included within this study to establish their influence on the blade material microstructure. A stage 1 fan blade and an airfoil from a stage 2 fan blade were heat treated to condition 4 and 5 respectively (Table 10) to determine the consequences of a recrystallization anneal with respect to component distortion.

4.2.1 Optical Microscopy

Sections of service exposed fan blades in the mill anneal condition and re-heat treated conditions (Table 10) were mounted, polished and etched using standard metallographic techniques. Grain size measurements were completed using the mean linear intercept method, ASTM standard E 112-82.

4.2.2 Transmission Electron Microscopy

Shank sections from service exposed stage 1 fan blades were heat treated following the schedules in Table 10. Three millimeter rods were carefully machined from the shank sections in a region below the trailing edge (Fig. 40). This area is believed to be a critical location for LCF damage because of stress concentration factors associated with the geometry. Foils with an approximate thickness of 200 microns were cut from the rods with the use of a diamond saw and subsequently ground to an

approximate thickness of 100 microns. Thinning was completed in a Struers jet polisher with a 94% acetic/6% perchloric acid solution. A Philips model type EM 201 TEM was used in the investigation.

Chapter 5

Results

5.1 Fretting Fatigue Testing

The surface appearance of carbon implanted, nitrogen plus carbon implanted, as-polished and shot peened Ti-6Al-4V fatigue specimens are shown in Figure 41. It can be seen that nitrogen plus carbon implantation treatment has caused surface pitting. Under high magnification (Fig. 42a) it is evident that the pit sizes are typically 1 micron across and shallow in depth. Surface pitting was not evident on the carbon implanted specimens (Fig. 42b). The depth of the pits likely corresponds to the thickness of the implanted layer (0.2-0.3 microns in depth). Visually, the nitrogen plus carbon implanted specimens were bronze tarnished whereas the carbon implanted specimens were only slightly tinted. Shot peened Ti-6Al-4V specimens displayed a surface that was smeared and roughened as shown in Figure 43.

Micro-hardness test results of implanted and polished Ti-6Al-4V surface material from failed test specimens revealed that under low indenter loads (15 grams) the nitrogen plus carbon implanted material and the carbon implanted material had average Vickers hardness values of 459 and 422, respectively, as compared to 393 for the polished material (Fig. 44). Under higher indenter loads (25, 50 and 100 grams) the surface hardness of the nitrogen plus carbon implanted material was not as pronounced (Fig. 44). The microhardness values of the carbon implanted material were similar under indenter weights of 15, 25, 50, and 100 grams. No significant difference in surface hardness was evident between the implanted and polished materials when a 200

gram indenter test weight was employed. It is apparent that under a 200 gram indenter test weight, the bulk material properties are being measured rather than the surface properties.

Fretting fatigue tests were initially carried out on the apparatus as shown in Figure 32. However it was later observed that the normal load distribution between specimen and fretting bridge pads varied between tests due to machining tolerances and the tightening of the clamping bolts. As a result, test data was scattered and inconsistent. Therefore, a modified test apparatus was designed and built (Fig. 31). Precautions were taken in the design stage to ensure that the normal clamping stress would be homogeneous. It was observed that for each test run with the modified test apparatus, similar levels of fretting wear damage were introduced on the specimen at the four bridge pad/specimen contact areas.

The fatigue/fretting fatigue test results are listed in Table 11 and presented graphically in Figure 45. Fretting fatigue tests carried out on polished Ti-6Al-4V specimens lasted 39,370 and 52,434 cycles before failing. The two baseline fatigue tests were discontinued after the specimens had accumulated one million cycles. One million cycles was used as an upper limit because it provided sufficient differences in test data to draw conclusions between fatigue and fretting fatigue lives of Ti-6Al-4V testing. Continued fatigue testing under the 4 Hz test frequency would have prolonged testing unnecessarily. By comparing the baseline fatigue data to the fretting fatigue tests results it can be seen that the fatigue life of Ti-6Al-4V is severely degraded by fretting under the test conditions examined within this investigation. The two nitrogen plus carbon ion implanted specimens lasted 67,438 and 49,067 cycles, whereas the two carbon implanted specimens lasted 114,438 and 94,670 cycles before failing. Shot peened coupons were found to have the best fretting fatigue properties with one coupon lasting 1

million plus cycles and the second specimen failing after 276,754 cycles. Width measurements of wear scars on the failed specimens and fretting bridges revealed that the slip amplitude was in the order of 5-7 microns during testing.

Scanning electron microscopy of fretting wear scars showed that the fretting wear process which occurred on the polished and ion implanted specimens were similar. It was noted that two distinct wear mechanisms were present in each wear scar (Fig. 46). An oxidative wear process was found to occur at the edges of the wear scars and sporadically throughout the wear damaged areas (Fig. 46). Over most of the wear scars, a wear mechanism involving a surface galling process prevailed (Fig. 46,47). Fretting was found to cause surface cracking and the delamination of metal platelets which upon separation would smear the surface (Fig. 47). During cross-section analyses of the fretting wear scars, surface delamination was found to occur up to depths of 10 microns (Fig.48). From Figure 46 it can be seen that the worst case of oxidative damage occurs at the outer edge of the wear scar whereas oxidative wear damage on the inside edge is less severe. Figure 49 shows the morphology associated with the oxidative wear process. It can be seen from Figure 49 that the wear process involves the removal of small surface particles which likely fracture from the surface upon oxidizing. The oxidation process also appears to occur in conjunction with a galling process as cracks can often be seen within the oxidized material (Fig. 50). However, it appears that the galling process, which occurs in combination with the oxidative wear is a milder process as compared to the predominant galling process.

SEM examination of the failed specimens revealed considerable secondary cracking in the surface material of the nitrogen plus carbon implanted specimen near the onset of a wear scar (Fig. 51). It appears that the cracking is associated with the surface pitting found only in the nitrogen plus carbon implanted

specimens (Fig. 42). Since many of the pits have a square cross-section, it is possible that cubic particles which formed during processing may have a tendency to lift out. Secondary cracking of this nature was not observed in the polished or carbon ion implanted specimens.

It was noted that for the cases of polished and nitrogen plus carbon implanted specimens, that cracks which had propagated to failure had initiated from within the wear scars but at areas which were in close proximity to the interface between undamaged and fretting damaged material (Fig. 52). The crack propagation route on the wear surface was found to follow very close to the outer limits of the wear scars which corresponded to the band of oxidative wear degradation (Fig. 46,52). For the case of carbon ion implanted specimens, cracks had initiated from areas close to the boundary between damaged/undamaged material but in locations where the dominant wear mechanism was a galling process (Fig. 53). It was interesting to note that for these tests crack propagation routes on the fretting surface were unpredictable and appeared to be influenced by wear damage (Fig. 53). Usually a semi-elliptical crack propagates from the initiation site, in a direction perpendicular to the surface (Fig. 54). For all cases, final specimens failure was due to overload along shear planes, after the crack covered approximately 60-70% of the specimen cross-section.

With regards to the shot peened specimens, the wear degradation process involved both a coarse galling process and combined oxidative/mild galling processes (Fig. 55). As compared to the polished and ion implanted material, the oxidative/mild galling process was much more prevalent on the shot peened specimens. It was noted that the crack initiation site, for the shot peened specimen which failed, was located in a central region of the

fretting wear scar where significant galling damage was present (Fig. 56). It was also noted that the fretting wear damage which occurred on the two shot peened specimens appeared similar.

5.2 Fan Blade Re-Heat Treatments

5.2.1 Optical Microscopy

Shown in Figure 57a is the typical microstructure of untreated fan blade material from the dovetail section. The microstructure displays an equiaxed alpha phase combined with transgranular beta grains. Some acicular alpha (transformed beta) formations are also visible. Figure 58 shows the elongated grain structure which exists in the fan blade dovetail as a result of deformation stresses that occur with processing.

The microstructures of heat treatment numbers 1-4 are shown in Figures 57b-57e. Both heat 1 ($700^{\circ}\text{C}/4\text{hr}/\text{AC}$) and heat 3 ($926^{\circ}\text{C}/2\text{hr}/\text{AC}$) display an equiaxed alpha phase combined with transformed beta grains (Fig. 57b, 57d), whereas the microstructure of heat treatment number 2 ($800^{\circ}\text{C}/2\text{hr}/\text{AC}$) consists of almost all equiaxed alpha and intergranular beta with some dispersed transformed beta grains (Fig. 57c). The microstructure of the recrystallized anneal condition, heat treatment number 4, exhibits strictly equiaxed alpha with intergranular beta (Fig. 57e).

Table 12 documents the average grain sizes for the four heat treated and the untreated blade material. During measurements the transformed beta formations were considered as grains. Also, the intergranular beta formations were regarded as separate grains for the case of heat treatment number 4 (the RA condition). From Table 12 it can be seen that very little difference in average grain diameter existed between the untreated material (9.29 microns), heat treatment number 1 (9.42 microns) and heat treatment number 2 (9.07 microns). It is therefore evident that

the grain growth kinetics are very slow in the temperature range of 700-800° C, although transformed beta grains appear to grow at the expense of the equiaxed alpha grains with 700° C annealing. Rapid grain coarsening is evident when annealing at 926° C as for the case of heat treatment numbers 3 and 4. The average grain size of heat treatment number 4 (12.02 microns) is somewhat larger than the grain size of heat treatment number 3 (10.62 microns). This difference in grain size between heat treatment numbers 3 and 4 is a direct result of the extra annealing time in heat 4 schedule (Table 10).

From the heat treated dovetail samples it was observed that the mild elongated grain structure which is evident in etched dovetail cross-sections of untreated blades (Fig. 58) is also present in material of heat treatment numbers 1 and 2. However heat treatment numbers 3 and 4 fail to display this common grain pattern. Figure 59 shows typical texture patterns in an untreated fan blade airfoil and an airfoil segment in heat treatment number 5 (Table 1) along the planes LT and ST of Figure 60. It can be seen that the marked grain structure of the untreated airfoil is not apparent in heat treatment number 5 as a result of the 926° C annealing treatment. As well, considerable grain growth has been incurred in heat treatment number 5 by the thermal treatment. It was also observed that the heat treatment number 5 schedule introduced obvious distortion within the airfoil section. As a result of the distortions, which were introduced to the blade airfoil, a complete stage 1 blade was heat treated following schedule 4 of Table 10. The airfoil of the blade was obviously warped by the thermal treatment but the shank area did not appear to have been deformed. It was noted that a likely driving force behind blade distortion was the positioning of the blade in the furnace because the airfoil appeared to "bend" under the influence of temperature and gravity.

5.2.2 Transmission Electron Microscopy

TEM analysis was completed on untreated service exposed material and material from heat treatment numbers 1 to 4. TEM micrographs of these are shown in Figures 61-66. Extensive dislocation networks are evident in the untreated blade material (Fig. 61a,b,c) as well as within heat treatment numbers 1 and 2 (Fig. 62,63). The TEM microstructures of heat treatment numbers 1 and 2 as well as the untreated condition appeared similar (Fig. 61-63). As a result of the similarity, it is apparent that neither the 700° C nor the 800° C anneals had an effect on the microstructural damage. The microstructures of the heat treatment numbers 3 and 4 material are much cleaner, in terms of dislocation debris, as compared to heat treatment numbers 1 and 2 and the untreated material conditions (Fig. 64,65). Heat treatment number 3 possesses a moderate number of dislocations which are mostly located in or near the acicular alpha formations (Fig. 64b,c). Usually the equiaxed alpha grains appeared dislocation free. In heat treatment number 4 material, dislocations appeared most often within the intergranular beta (Fig. 65c). Some of these dislocations carry on into the alpha phase (Fig. 62c). It should however be noted that for the case of heat 4 it was difficult to analyze the beta phase because of preferential etching of the alpha phase during jet thinning. Figure 66 shows a TEM micrograph of untreated fan blade material taken from a location in the dovetail where a lower stress state is known to exist. Comparing Figures 61 and 66 it can be seen that similar dislocation networks exist in material from fracture critical areas and material which is subjected to much lower service stresses.

Chapter 6

Discussion

6.1 Fretting Fatigue Testing

6.1.1 Test Apparatus

Fretting fatigue tests were initially carried out on the test apparatus shown in Figure 33. With this apparatus, the fretting bridges were rigidly fixed to the upper pull rod. Higher slip amplitudes could be obtained with this design as compared to traditional fretting bridge test systems because the amount of slip was dependent on the length of specimen between the fretting bridge pads as well as the length of specimen above the fretting bridges. During test set up, precautions were taken to ensure that the testing was conducted in an axial manner and clamping bolts were evenly tightened. It was noted that fretting conditions which occur between the bridge pads and specimen were sensitive to component tolerances as a result of the rigid apparatus design, and the tightening of the four clamping bolts. Uneven bolt tightening and/or poor matching between specimen/fretting bridges were found to cause heterogeneous stress distributions at the fretting interface. This may have resulted in local stress concentrations that can accelerate initiation of cracks and cause increased scatter in the data.

Due to the problems associated with this design a modified fretting fatigue test apparatus was employed. The bridges in this case were unconstrained and supported through the application of the normal load. The main design consideration with this rig was to ensure an even normal stress distribution between the fretting bridges and the specimen. Two spherical ball joints were incorporated (in the design) in order to align the normal load which was produced by tightening the four clamping bolts.

Each specimen was strain gaged at four locations (Fig. 39) to ensure that the compressive strains that occurred in the specimen were equal. An indication that an even distribution of normal loads was achieved for each fretting fatigue test was the fact that similar levels of fretting damage was introduced on the specimen at the four bridge pad/specimen contact areas.

6.1.2 Fretting Damage Process

In this section the fretting degradation processes which occurred on test specimens are analyzed. To support fretting degradation theories, TEM micrographs of the fretting damaged areas are examined and discussed. The fretting process which occurs on fan blade dovetail pressure surfaces has been detailed in chapter 3. Examination of dovetail pressure surfaces revealed that the fretting process on Ti-6Al-4V caused surface smearing and possibly some surface galling (Fig. 29). The exact wear mechanisms were difficult to assess because of the difficulty in distinguishing the fretted appearances of coating and Ti-6Al-4V substrate.

SEM analysis of polished and ion implanted specimens showed that the fretting wear mechanism was mostly a surface adhesion or galling process (Fig. 47). The fretting wear process of galling appears to introduce the formation of surface cracks which propagate parallel to the surface. As a result, material undergoes delamination which was found to occur up to depths of approximately 10 microns (Fig. 48). This cracking is most likely a result of alternating shear stresses which develop in the near surface material because of adhesion and friction occurring between the bridge pads and specimen. Fretting was also found to cause some smearing of the surface (Fig. 47). Surface smearing is caused by metal platelets, which have separated from the surface, plowing into the wear surface. It is believed that a sur-

face galling process is sustained during testing because debris has a tendency to migrate outwards thus allowing adhesion between the contacting surfaces to persist.

Along with a surface galling process, polished and ion implanted specimens were found to undergo an oxidative wear process (Fig. 49). The wear process was found to occur sporadically within the fretting scars and almost continuously along a thin band at the outer edges of the wear scars (Fig. 46). This wear process is most likely associated with wear debris acting in an abrasive scrubbing fashion removing surface oxides. It is believed that initially these outside regions experience a coarse galling process but as wear debris builds up the wear mechanism switches to a oxidative process. The build up of debris at these localized areas is believed to be a result of edge effects of the bridge on the specimen. The accumulation of wear debris is likely accentuated by the migration of wear debris from the central regions of the wear scar. This migration appears to be motivated by debris moving to lower normal stress states.

The wear mechanisms that occurred on the shot peened specimens were a combination of oxidative/mild galling and a coarse galling process (Fig. 55). As compared to the polished and ion implanted specimens, shot peened specimens received considerably more oxidative/mild galling wear degradation. This observation can be explained by the fact that the tests ran much longer and therefore there was more time for wear debris to generate within the fretting wear scars. Surface galling is likely to occur on the asperities of the shot peened surfaces since these areas would be in direct contact with the bridge pad material.

The crack initiation sites for the polished and nitrogen plus carbon implanted specimens occurred within the oxidative/mild galling wear band (Fig. 49,53). As mentioned above, the fretting degradation process which occurs along the outer edges of the wear scars is enhanced by the edges of the fretting

bridges. These edge effects are likely associated with the localized entrapment of debris. It should also be noted that the crack initiation sites are also in close proximity to the boundary between damaged material and undamaged material. High stress concentrations are known to exist at these areas because it is an interface between material under tensile and alternating shear stresses (44). Therefore, for the case of polished and nitrogen plus carbon implanted specimens, crack initiation appears to be motivated by fretting bridge edge effects and stress concentrations which develop at the interface between material undergoing fretting and undamaged material.

The two carbon implanted specimens had crack initiation sites close to the boundary between fretting damaged/undamaged material. However, the initiation sites did not occur within the band of oxidative wear damage but in areas where a coarse galling wear mode was predominate (Fig. 53). The likely reason for these crack initiation sites is that the carbon ion implantation treatment has reduced or delayed the generation of debris within the wear scar. By reducing the amount of debris within the wear scar, less debris will be trapped under the edges of the fretting bridges and the rate of fretting damage accumulation would be slower. Therefore the fretting bridge edge effects have been moderated by the carbon implantation treatment. As a result, the crack initiation site for carbon implanted specimens has been shifted from the oxidative/mild galling wear band to locations which have received a galling wear degradation process.

6.1.3 Fatigue/Fretting Fatigue Test Results

The experimental fatigue/fretting fatigue test results are listed in Table 11. It can be seen from Table 11 that fretting reduces the fatigue life of polished Ti-6Al-4V specimens under the test conditions by a factor of at least 20. It should be noted that the two fatigue tests on polished specimens were stopped after one million cycles. Actual lives would have been

much higher if testing had been allowed to continue until specimen failure. The fretting fatigue test results show that nitrogen plus carbon implanted specimens performed slightly better than the polished specimens (Table 11). The carbon ion implantation treatment was found to essentially double fretting fatigue life as compared to polished and nitrogen plus carbon implanted specimens. Shot peened specimens were found to have the best fretting fatigue properties with one test lasting one million cycles and the second test lasting 276,567 cycles. It should be noted that only two samples were tested for each test condition and further testing is required to build up a data base for a proper statistical analysis.

For the implanted coupons, the carbon treatment proved to be better than the carbon plus nitrogen treatment. Microhardness tests revealed that the nitrogen plus carbon treatment produced a slightly harder surface layer as compared to the carbon ion implantation treatment (Fig. 44). Generally a harder surface is preferable with regards to improving wear properties of a component (25,30). These results appear to be the consequence of the nitrogen plus carbon implant producing a layer which was more brittle as compared to the carbon implant. Figure 51 shows the nitrogen and carbon implanted surface layer severely cracked near the onset of a wear scar. This cracking appears to be associated with the surface pitting which was observed on the nitrogen plus carbon implanted specimens (Fig. 42a). Since the carbon implanted specimens did not appear to have this surface pitting (Fig. 42b), it is likely that these surface defects were introduced during the nitrogen ion implantation treatment, possibly as a result of surface sputtering. Thus, for the case of nitrogen plus carbon implanted specimens, it appears that the hardened surface layer has a tendency to crack and delaminate (thus giving rise to more debris) before the benefits of the treatments are achieved. The build of debris appears to be a driving force for

crack initiation at wear scar edge locations. Test results indicate that improvements in fretting fatigue life of Ti-6Al-4V specimens introduced by the nitrogen plus carbon treatment are only slight if any at all.

The crack initiation site for carbon implanted specimens occurred in locations which had received a galling wear process (Fig. 53), whereas polished and nitrogen plus carbon implanted specimens had crack initiation sites restricted to the band of oxidative wear as shown in Figure 52. Carbon implantation has had the influence of shifting the crack initiation site from the band of oxidative wear to locations where a predominantly galling wear process occurred. As mentioned in the previous section, this can be explained by the fact that carbon implantation treatment has likely reduced the rate of debris generation which is required for the oxidative wear process. Therefore, the increase in fretting fatigue lifetime by carbon ion implantation is likely associated with a delaying in the generation of debris and subsequent damage to the hardened surface layer.

Shot peened specimens proved to have the best fretting fatigue characteristics as compared to implanted and polished specimens. The improvement in fretting fatigue properties by shot peening has been attributed to surface compressive stress strengthening and increased surface roughness. Compressive stresses are produced in the near surface material during the shot peening process which impair the early growth of fatigue cracks (33). Increasing surface roughness has beneficial effects on fretting because surface valleys on the surface provide free space to accommodate wear debris (Section 2.2.6). Also, only surface asperities (peaks) come into contact and they can tolerate small slip displacements by elastic deformation.

With regard to shot peened test results, considerable differences were found between the two tests with one suspended after one million cycles and the second test failing after

265,456 cycles. During SEM analyses it did not appear that the specimen which failed after 265,456 cycles had received a more severe fretting wear degradation process. It did appear that the likely reason for failure is that debris built up at an outside wear location is quite substantial, producing more severe fretting conditions at this particular location. In the work of Lutynski et. al. (90), the life of shot peened specimens tested under fatigue varied from 1800 to 9600 cycles under the peak stress conditions of 828 MPa. Under a peak stress of 759 MPa, the fatigue test data for shot peened specimens varied from 86,000 to 420,000 cycles. It can be seen that wide scatter in data can occur when shot peened specimens are tested under fatigue conditions and scatter of a similar nature would likely occur under fretting fatigue test conditions. Therefore the differences in fretting fatigue lifetime are believed to be a result of intrinsic scatter in test data. More tests should be conducted on shot peened specimens to establish the magnitude of the scatter such that standard deviations can be established.

A carbon ion implantation treatment has been shown to improve fretting fatigue properties of Ti-6Al-4V plate as compared to polished material (Section 6.1). It should be noted that only one set of fretting condition has been examined experimentally and for full appraisal of ion implantation surface treatments would require testing under a wide range of fretting conditions which simulate service. Unfortunately, the fretting conditions which exist on fan blade pressure surfaces are not well understood, and thus an in-depth analyses is required to determine service fretting parameters.

Also, other ion implantation treatments which utilize different ion species and/or implant conditions may prove to be superior to the carbon treatment examined within this study. Further, it may be possible to incorporate a shot peening plus ion implantation treatment to fan blades. This combination of

surface treatments has received very little attention in the literature. Ion implantation would most likely have to be carried out after shot peening, otherwise the implanted layer would be severely damaged. Shot peened surfaces are likely to be too rough to effectively ion implant as many the ions would be sputtered. Therefore the shot peened surface will probably have to be polished, conceivably electrolytically, to create a surface more suitable for ion implantation processing. It should be noted that a rough surface is beneficial because it improves surface fretting properties and is important for coating adherence. The extent of polishing would have to be optimized with regards to creating a polished surface to suite ion implantation treatment while leaving some roughness for coating adherence.

6.2 Characterization of Re-heat Treatments for Fan Blade Material

TEM analyses of service exposed (untreated) stage 1 fan blade material from locations believed critical to LCF damage revealed that extensive dislocation debris is present within the microstructure (Fig. 61). Similar dislocation networks were found in untreated fan blade material which was likely subjected to a less severe stresses during service (Fig. 66). In all likelihood, the dislocations debris is common to the mill anneal condition and was present prior to service. Some microdamage may have been incurred during service but damage of this nature is not readily distinguishable as compared to dislocations which are generated during manufacturing. To confirm this will require comparing material from a new and service exposed fan blade in order to establish if dislocations densities increase with service at the critical blade dislocations.

From the TEM study it was apparent that only the thermal treatments used for heat treatment numbers 3 and 4 are potential fatigue rejuvenation treatments. The heat treatments associated with heat treatment numbers 1 and 2 failed to remove the dislocation debris which is common to untreated blades and therefore are

unacceptable for LCF damage relief schemes (Fig. 62,63). Some dislocations were present in the heat 3 condition and to a lesser extent heat treatment number 4. It is believed that many of these dislocations are created during cooling as a result of differences in thermal expansion properties between the alpha and beta phases. Also some dislocations may be created during the mechanical grinding process which each foil must receive prior to jet thinning. For material in the heat treatment numbers 3 and 4 conditions, LCF microdamage present prior to re-heat treatment is most likely being healed by the 926°C anneal.

Pre-crack initiation fatigue damage which is incurred during service in Ti-6Al-4V fan blades in the mill anneal condition is likely to build up at alpha/beta interfaces or grain boundaries as reported in section 2.6.2. Grain growth through re-heat treatments may change or remove the induced dislocation pile-ups as a result of recrystallization. The actual extent of rejuvenation can only be established by mechanical testing. It should be noted that re-heat treatments cannot heal fatigue damage which has progressed beyond the crack initiation stage if cracks are surface connected and blades displaying cracks in critical areas should be retired.

It is well known that the fatigue life of titanium alloys is dependent on the crack initiation stage. Problems may exist for the fan blades in heat treatment numbers 3 and 4 because of lower fatigue properties as compared to pre-serviced fan blades in the mill anneal condition. The modification of mechanical properties of material in heat treatment numbers 3 and 4 condition would be likely more a result of grain coarsening rather than due to the alterations in phase morphologies. Increasing the grain size has the general effect of increasing fracture toughness and decreasing crack propagation rates, however at the expense of fatigue crack initiation properties (section 2.6.2). Also, the deformed grain structure which is present in untreated blades has been randomized by the heat treatments used for heat treatment numbers

3 and 4 material. Although a textured cell structure will remain within the recrystallized grains of heat treatment numbers 3 and 4, the loss of grain orientation may accentuate the effects of a coarsened grain structure. It should also be noted that for material in the heat treatment number 3 condition the coarse acicular alpha/transformed beta grains may be vulnerable to crack initiation.

An area of concern with 926°C anneals (heat treatment numbers 3 and 4) is the potential for fan blade distortion. Rejuvenation treatments must not impart blade distortion because of the need for high tolerance levels at critical areas such as at the dovetail pressure surfaces. Therefore special precautions will have to be taken such that distortion effects can be avoided. One possible method involves shielding the airfoil section from the heat treatment via insulators or special furnace arrangements. This would be practical because areas critical to LCF damage lie in the shank area of the blade rather than in the airfoil. The shank section could therefore be subjected to heat treatments which relieve LCF damage. By maintaining the airfoil at lower temperatures the regular mechanical properties within the airfoil might be retained. Caution would have to be undertaken to ensure that the airfoil remains below recrystallization temperatures and that shank distortion is limited. It may also be possible to fabricate special fixtures which can prevent distortion during thermal treatments. The fixture material would have to possess good high temperature properties and similar thermal expansion coefficients as Ti-6Al-4V.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

This research has addressed the feasibility of ion implantation and re-heat treatments for gas turbine fan blade life extension. Ion implantation was examined as a treatment to improve the fretting fatigue behavior of fan blade pressure faces. Re-heat treatments have been investigated as a possible means of alleviating low cycle fatigue damage in fan blades. The major results, observations and conclusions from this research are summarized below.

7.1.1 Fretting Fatigue Life Improvement

- Fan blades were found to have received moderate service induced fretting damage on the dovetail pressure surfaces. The fretting wear degradation process to fan blades was difficult to assess because of the difficulty in distinguishing the fretted appearances of coating and Ti-6Al-4V substrate. It appeared that service induced wear caused surface smearing and some surface galling to the substrate Ti-6Al-4V. Some near surface defects were observed in the blade dovetail material which may have been incurred as a result of service. From the analysis of fan blade pressure surfaces it was initially thought that ion implantation could be an effective treatment to improve the fretting fatigue characteristics of the blades.
- Mechanical testing revealed that fretting fatigue causes a definite reduction in the life of polished Ti-6Al-4V specimens as compared to fatigue alone. A nitrogen plus carbon ion implantation treatment was found to provide only limited

improvements in the fretting fatigue lives of polished specimens. However, a carbon ion implantation treatment was found to increase the fretting fatigue life of Ti-6Al-4V by a factor of two. Shot peening proved to be the best process for improving the fretting fatigue behaviour of Ti-6Al-4V, under the test conditions employed in this study.

- Differences in the fretting degradation processes between polished and nitrogen plus carbon implanted specimens were not apparent. The carbon implantation was found to alter the fretting fatigue crack initiation process. The increase in the fretting fatigue lifetime by carbon ion implantation was associated with a delaying in the generation of debris and
- subsequent damage to the hardened surface layer. The improvement in fretting fatigue properties by shot peening was attributed to compressive stress strengthening and a roughened surface that was able to accommodate wear debris and delay the onset of abrasive wear damage.
- It was concluded that a combination of shot peening (which is generally carried out as a regular process for fan blades) plus ion implantation may provide superior fretting fatigue properties for the component.

7.1.2 Fatigue Life Improvement

- Transmission electron microscopy studies on fan blade material from fracture critical areas revealed that extensive dislocation debris was present in the microstructure. It is believed that the dislocation debris was common to the material condition and was present prior to service. It was noted that service induced damage was not readily distinguishable as compared to processing damage.

- Two different heat treatments which utilize 926° C anneals were found to remove dislocation debris from the microstructure. It was believed that fatigue microdamage could be healed by these treatment. The mechanical properties of the re-heat treated conditions are believed to be similar to the pre-service blade condition. Some modification in properties may be incurred as a result of grain coarsening and texture effects.
- Re-heat treatments must not impart blade distortion because of the need for high tolerances at critical areas such as dovetail pressure surfaces. Blade distortion could be overcome by re-heat treating in specially designed fixtures or by using localized heat treatments.

7.2 Recommendations

7.2.1 Fretting Fatigue Testing

- In order to provide an accurate quantitative assessment of ion implantation on fretting fatigue of Ti-6Al-4V, further testing is required at various test conditions. A variety of ion implantation conditions should be examined as well as other ion species. Test matrices should be set up such that optimum implant conditions/species can be determined. Implant conditions which prove best suited to improving the fretting fatigue behavior of Ti-6Al-4V should also be combined with shot peening process to determine possible benefits of a combination surface treatment.
- Work should also be carried out on fan blades to quantify service loading conditions and the fretting degradation processes which occur on dovetail pressure surfaces. Without this information, accurate simulation of service fretting conditions cannot be completed experimentally.

7.2.2 Fatigue Life Improvement

- Mechanical testing should be carried out on service exposed fan blade material in re-heat conditions to determine the extent of fatigue rejuvenation. The influence of the re-heat treatments on fracture toughness, crack growth rates and tensile properties should be determined. Potential problems with fan blade distortion should be addressed through the use of suitable fixtures.

Appendix A

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Appendix B

Tables

Table 1

Conventional Heat treatments for Ti-6Al-4V

Heat Treatment	Heat Treatment Schedule	Microstructure
Mill Anneal	732 °C/1hr/AC	<ul style="list-style-type: none"> - Equiaxed alpha with intragranular beta - Some acicular alpha
Recrystallization Anneal	926-955 °C/4hr/FC 760 °C/AC	<ul style="list-style-type: none"> - Equiaxed Alpha with intragranular beta
Beta Anneal	1038 °C/.2-1hr/AC + 732 °C/2hr/AC	<ul style="list-style-type: none"> - Coarse acicular alpha
Beta Quench	1038 °C/.2-1hr/WQ + 732 °C/2hr/AC	<ul style="list-style-type: none"> - Fine acicular alpha
Solution Treat and Age	955 °C/1hr/WQ + 600 °C/4hr/AC	<ul style="list-style-type: none"> - Equiaxed alpha grains with grains of fine acicular alpha
Solution Treat and Overage	955 °C/1hr/WQ + 700 °C/4hr/AC	<ul style="list-style-type: none"> - Equiaxed alpha in a matrix of fine acicular alpha

Note: AC - air cool
 FC - furnace cool
 hr - hours
 WQ - water quench

Table 2
Influence of Grain Size on
Tensile Properties of Ti-6Al-4V (81)

	Yield Strength (MPa)	Ultimate Strength (MPa)	Strain Elong. (%)
Fine Equiaxed	1120	1505	7.0
Coarse Equiaxed	1030	1370	5.6
Bi-Modal	1005	1455	6.1

Table 3
Tensile Properties of Conventionally
Heat Treated Ti-6Al-4V

Reference	Yield Strength MPa		Ultimate Srength MPa		R. of Area %	
	73	83	73	83	73	83
MA	1103	/	1172	/	30	/
RA	1048	707	1145	873	21	36
BA	1034	774	1103	853	23	23
BQ	/	862	/	931	/	6
STA	/	877	/	939	/	34
STOA	1103	908	1131	974	30	47

MA - Mill Anneal
RA - Recrystallization Anneal
BA - Beta Anneal
BQ - Beta Quench
STA - Solution Treat and Age
STOA - Solution Treat and Overage

Table 4

Fracture Toughness of Conventionally
Heat Treated Ti-6Al-4V

Treatment	Fracture Toughness (K_{Ic}) MPa·m ^{1/2}	
	Ref. [73]	Ref. [83]
MA	36	/
RA	63	120
BA	90	118
BQ	/	100
STA	/	84
STOA	47	76

Table 5
Mechanical Properties of Fan Blades in two Conditions (1)

Characteristic	Unit	Condition A	Condition B
Tensile Strength	N/mm ²	945	985
Fatigue Strength	N/mm ²	490	540
Low Cycle Fatigue	N/mm ²	855	875
Fracture Toughness	N·mm ^{3/2}	1735	1978

Condition A - 700 C/1 hr./Air Cool

Condition B - 940 C/1 hr./Quench + 700 C/1 hr./Air Cool

Table 6
Rejuvenation Results (36)

Test Method	Maximum Rejuvenation Achieved (%)	
	Level 1*	Level 2**
Total Strain Range	69 ¹ - 112 ²	32 - 60 ³
Plastic Strain Range	15 ¹ - 33 ²	68 ³

* Pre-crack Initiation Damage

** Crack Initiation Damage

1 Rejuvenated Without Coating

2 Rejuvenated with Coating

3 Specimens Which Did Not Fail At A Visible Preexisting Crack (Mapped Cracks Bridged)

Table 7

Investigated First Stage Fan Blades

Serial Number	Service Life Hours	Service Life ELCF
83598	94.4	332.07
85238	333.8	1106.28
85235	333.8	1106.28
76049	407.5	1424.07
59667	600.5	2091.24
59842	838.1	3241.98
69782	847.1	3056.39
69796	847.1	3056.39
70252	847.1	3056.39
85315	unknown	unknown

Table 8
Strain Gage Characteristics

Gage Type	Resistance (Ohms)	Gage Factor at 75 ⁰ F
EA-06-090EF-120	120.0 ± 0.15%	2.05 ± 0.5%
EA-06-062EN-350	350.0 ± 0.15%	2.065 ± 0.5%

Table 9
Test Program

Number of coupons	Test Type/Test Conditions
2	Polished Specimens for Baseline Fatigue Testing (no fretting)
2	Polished Specimens for Fretting Fatigue Testing
2	Nitrogen plus Carbon Implanted Specimens for Fretting Fatigue Testing
2	Carbon Implanted Specimens for Fretting Fatigue Testing
2	Shot Peened Specimens for Fretting Fatigue Testing

Table 10
Rejuvenation Heat Treatment Schedules

Heat	Schedule
1	700° C/4hr./AC*
2	800° C/2hr./AC
-	926° C/2hr./AC
4	926° C/4hr./FC** ---> 760° C/AC (Recrystallization Anneal)
5	926° C/1.5hr./FC ---> 760° C/AC (Treatment for Airfoil)
	* AC - Air Cool
	** FC - Furnace Cool

Table 11
Fatigue/Fretting Fatigue Test Results

Condition	Test Type	Test 1	Test 2
Polished	Baseline Fatigue	1,000,000 ¹	1,000,000 ¹
Polished	Fretting Fatigue	39,730	52,434
N ⁺ + C ⁺ Implanted	Fretting Fatigue	74,371	49,067
C ⁺ Implanted	Fretting Fatigue	114,438	94,670
Shot Peened	Fretting Fatigue	1,000,000 ¹	267,451

Note; 1- test suspended after 1 million cycles

Table 12
Average Grain Size Measurements

Treatment Condition	Average Grain Diameter (μm)	ASTM Grain Size Number (G)
Untreated	9.29	10.55
1	9.42	10.48
2	9.07	10.61
3	10.62	10.14
4	12.02	9.74

Appendix C

Figures

Figure 1 Stage 1 (left) and Stage 2 (right) Fan Blades of an Advanced Aero Engine

Figure 2 Dovetail Mount Arrangement for Fan Blade/Disk (28)

2

OF/DE

2

MicroD

Figure 3 Typical Fretting Damage (as shown by arrows) which occurs on the Dovetail Pressure Surfaces of Stage 1 (top) and Stage 2 (bottom) Fan Blades

Centrifugal Blade Load

Figure 4 Operating Loads which cause Fretting

Figure 5 S/N Curves for Baseline and Fretting Fatigue of Ti-6Al-4V

Figure 6 A Model for Fretting Fatigue Degradation (9)

Figure 7 Influence of Clamping Pressure on the Fatigue Strength of Various Materials (16)

Figure 8 Effect of Relative Humidity on the Fretting Fatigue Strength of Ti-6Al-4V (54)

* - Length X represents material which will elongate under the applied cyclic load to provide slip at the bridge/specimen interface.

Figure 9 Schematic of Simplified Fretting Fatigue Test Arrangement

Figure 10 Diagram of Duquette and Gual's Fretting Test Facility (13)

Figure 11 A Schematic of a Test Facility used by Hoeppner (9)

Figure 12 Diagram of an Environmentally Controlled Test Facility Used by Waterhouse (53)

Figure 13 Exaggerated Deformation which may occur in Fretting Pads during Testing

Figure 14 Specimen Arrangement used by Boddington for Simulating Fretting in Dovetail Joints (7)

Figure 15 Bi-Axial Loading Condition used in Boddington's Fretting Fatigue Tests (7)

Figure 16 Influence of Carbon Ion Implantation on Ti-6Al-4V Fretting Fatigue Life at Ambient Conditions (30)

Figure 17 The Improvement in Fretting Fatigue Life of Ti-6Al-4V at Ambient Conditions Introduced Through Barium Ion Implantation (34)

Figure 18 Phase Transformation Diagram for Ti-6Al-4V Alloy (2)

Figure 19 Typical Microstructures of Ti-6Al-4V (800x) (76):
 (a) Platelike Alpha (light) and Intergranular Beta
 (dark)
 (b) Equiaxed Alpha (light) and Intergranular Beta
 (c) Grains of Equiaxed Alpha (light) in a matrix of
 Transformed Beta containing Acicular Beta

Figure 19

Figure 20 The Influence of Grain Size and Microstructure on Fatigue Properties of Ti-6Al-4V (61)

Figure 21 Crack Propagation Rates of Various Heat Treated Conditions of Ti-6Al-4V (73,86)

Figure 22 A Cross-Section of a First Stage Fan Blade Dovetail Showing a Crack Like Defect

Figure 23 Location of Shear Stresses which develop in Fan Blade Dovetails during Service

Figure 24 Fan blade dovetail displacements which cause fretting as a result of (a) alternating centrifugal forces and (b) natural blade vibration

Figure 25 Location of Severe Wear Damage on Stage 2 Fan Blades

Figure 26 Delamination of MoS₂ Coating on a Stage 1 Blade Serviced for 407 Hours

Figure 27 Typical Appearance of Fretting Wear Damage on Cu-Ni-In Coating for a Stage 2 Fan Blade

Figure 28 Discontinuities within Plasma Sprayed Cu-Ni-In Coating (Cross-Section) of a Stage 1 Fan Blade Serviced for 98 Hours

Figure 29 Typical Appearance of Fretting Damage on the Substrate Ti-6Al-4V.

Figure 30 Typical Flaws Observed within a
New Second Stage Blade on the
Ti-6Al-4V Pressure Face
(a) Surface Roughness
(b) Machining Flaws
(c) Crack like Defect

Figure 31 A Sub-Surface Crack Like Defect Observed in a Stage 2 Fan Blade (Cross-Section)

ITEM NO	DESCRIPTION
1	CLAMPING BOLT, HEX HD WITH NUT, STEEL 3125-18UNC-2A x 6 OLG
2	LOAD CELL SUPPORT
3	LOAD CELL
4	BALL JOINT SUPPORT
5	BRIDGE SUPPORT
6	CAP SCREW, HEX. SOC. HD. 112-40 UNC-2A x .6 LG.
7	FRETTING BRIDGE
8	SPECIMEN
9	BALL JOINT END SUPPORT
10	WASHER STEEL 5/16 NOM.
11	BALL JOINT 750 SPHER DIA STEEL

Figure 32 Schematic of the Modified Fretting Fatigue Test Apparatus

ITEM NO.	DESCRIPTION
1	LOWER PULL ROD 1.0 DIA WITH 1.00-8 UNC-2A END
2	SPECIMEN
3	FRETTING BRIDGE
4	LOAD CELL 1.00 INCH DIA
5	CLAMPING PLATE
6	SUPPORT COLUMN
7	LOAD PIN, DOWEL .500 DIA. = 4.5 LG.
8	BOLT, HEX. HD WITH NUT .500-13 UNC-2A = 4.5 LG.
9	RIG SUPPORT
10	UPPER PULL ROD .75 DIA. WITH .75-10 UNC-2A END
11	THREADED ROD 1.00-8 UNC-2A = 3.5 LG.
12	GRIPS
13	CLAMPING BOLT, HEX. HD. WITH NUT .750-10 UNC-2A = 6.5 LG.
14	CAP SCREW, HEX. SOC. HD. .250-20 UNC-2A = .875 LG.
15	CAP SCREW HEX. SOC. HD. .190(NO.10)-24 UNC-2A = .600 LG.
16	BRIDGE SUPPORT

Figure 33 Schematic of the Original Fretting Fatigue Apparatus

Figure 34 Fretting Fatigue Test Specimen

Figure 35 Fretting Bridge

1. Test Apparatus
2. Data Acquisition System
3. Test Frame
4. Test Console

Figure 36 Fretting Fatigue Test Console

Ampl. Output Volts.

Figure 37 Calibration Curve for Normal Load
Note: 1 Newton is equal to .2248 LBs

Figure 38 Location of Strain Gages on Specimen with Respect to Fretting Bridges

Figure 39 Fatigue/Fretting Fatigue Test Results for Shot Peened and Polished Specimens (90)

Figure 40 Schematic of the 3mm Rod Extraction Process from Fan Blades

Figure 41 Typical Appearances of Ti-6Al-4V Specimens in;
 (a) Polished Condition
 (b) Carbon Implanted Condition
 (c) Nitrogen plus Carbon Implanted
 (d) Shot Peened Condition

Figure 42 The Typical Surface Appearance of Nitrogen plus Carbon Ion Implanted Material (left) and Carbon Implanted Material (right)

Figure 43 SEM Micrograph of a Shot Peened Surface

Figure 44 Microhardness Values for Polished and Implanted Material Under Different Penetrator Loading Conditions

Figure 45 Fatigue/Fretting Fatigue Test Results

Figure 46 The Typical Appearance of a Fretting Wear Scar Introduced on Test Specimens

← Direction of Slip →

Figure 47 Typical Appearances of Material Degraded Through a Galling Wear Process (Top) and Metal Platelet Drift Causing Surface Smearing (Bottom)

100

40

Figure 48 Near Surface Cracking which Results in Platelet Delamination

Direction of Slip

Figure 49 Typical Appearance of Material Damaged Through an Oxidative Wear Process

← Direction of Slip →

Figure 50 Appearance of Surface Cracks which were Evident in Material Damaged by an Oxidative Wear Mode

Figure 51 Secondary Cracking Observed in Nitrogen plus Carbon Implanted Specimens

Figure 52 Tendencies in Fracture for Polished and Nitrogen plus Carbon Implanted Specimens showing;
 (a) Crack Propagation Route Near Damaged/Undamaged Material
 (b) Oxidative Wear Damage along Crack Propagation Route

Figure 53 Typical Appearances of Failed Carbon Implanted Specimens showing;
 (a) Crack Propagation Route on Wear Scar Surface
 (b) Galling Wear Damage along Crack Propagation Route

Figure 54 Typical Appearance of a Fracture Surface from a Specimen Failed under Fretting Fatigue Conditions

Figure 55 Fretting Wear Damage on Shot Peened Specimens
 (a) Galling Wear Damage
 (b) Oxidative Wear Damage

Figure 56 Surface Galling Damage near the Crack Initiation Site
for the Shot Peened Specimen which Failed after
267,451 Cycles

Figure 57 Microstructures of Fan Blade Ti-6Al-4V in the following Conditions (Note all micrographs 800x);

(a)	Untreated Material	
(b)	Heat 1 - 700°C/4 hr/AC	
(c)	Heat 2 - 800°C/4 hr/AC	
(d)	Heat 3 - 926°C/4 hr/AC	780°C/AC
(e)	Heat 4 - 926°C/4 hr/FC	

Figure 58 Mild Elongated Grain Structure present in Untreated Fan Blade Material

Figure 59 Grain Structure in Blade Airfoil (500x);
 (a) Untreated Blade Material; Plane LT (See Fig. 60)
 (b) Untreated Blade Material; Plane ST
 (c) Heat 5 Condition; Plane LT
 (d) Heat 5 Condition; Plane ST

Note: LT - longitudinal traverse
ST - short traverse

Figure 60 Designation of planes used for airfoil segments.

Figure 61 TEM Micrographs of
Serviced (untreated)
Fan Blade Material

Figure 62 TEM Micrographs of Heat 1
Material (700°C/4 hr/AC)

Figure 63 TEM Micrographs of Heat 2
Material (800°C/4 hr/AC)

Figure 64 TEM Micrographs of Heat 3
Material (926°C/4 hr/AC)

Figure 65 TEM Micrographs of Heat 4 Material
(926°C/4 hr/FC → 780°C/AC)

Figure 66 A TEM Micrograph of Untreated Fan Blade Material which was taken from a location within the Blade Where Moderate Stress Levels are known to Exist

Appendix D

Modified Test Apparatus Drawings

NOTE: FOR PARTS LIST SEE SHEET I.

FRETTING TEST ASSEMBLY		MAT.	SCALE	1 : 1
		DRAWN	M.S.	NO.
		89-06-20		331K00009

(SHEET NO. 2 OF 2)

ITEM NO.	DWG. NO.	DESCRIPTION	QTY. REQ.
1	—	CLAMPING BOLT, HEX. HD. WITH NUT, STEEL 3/25-10UNC-2A x 6.0LG.	4
2	33IK00013	LOAD CELL SUPPORT	1
3	—	LOAD CELL	1
4	33IK00012	BALL JOINT SUPPORT	1
5	33IK00011	BRIDGE SUPPORT	2
6	—	CAP SCREW, HEX. SOC. HD. 1/2-40 UNC-2A x .4 LG.	2
7	33IK00010	FRETTING BRIDGE	2
8	—	SPECIMEN	1
9	33IK00014	BALL JOINT END SUPPORT	1
10	—	WASHER STEEL 5/16 NOM.	4
11	—	BALL JOINT .750 SPHER. DIA. STEEL	2

**FRETTING TEST,
ASSEMBLY**

(PARTS LIST)

SCALE

DRAWN

89-06-20

M.S.

NO. 33IK00009

(SHEET NO. 1 OF 2)

SECT. A-A

NOTE: ALL DIMENSIONS ARE IN INCHES.

FRETTING BRIDGE	MAT. Ti-17 DRAWN 89-06-20	SCALE 2:1
	M.S.	NO. 33IK00010

NOTE: ALL DIMENSIONS ARE IN INCHES.

BRIDGE SUPPORT		MAT. STAINL. STEEL	SCALE 1 : 1
DRAWN 89-06-20		M.S.	NO. 33IK00011

SECT. A-A

NOTE: ALL DIMENSIONS ARE IN INCHES.

BALL JOINT END SUPPORT	MAT. STAINL. STEEL DRAWN 89-06-20 M.S.	SCALE 1:1 NO 33IK00014
-----------------------------------	---	---

.343 DIA.
4 HOLES

SECT. A-A

NOTE: ALL DIMENSIONS ARE IN INCHES.

**BALL JOINT
SUPPORT**

MAT.
STAINL. STEEL

SCALE

1:1

DRAWN
89-06-20

M.S.

NO. 331K00012

Appendix E

Original Test Apparatus Drawings

SECT. A-A

NOTE: ALL DIMENSIONS ARE IN INCHES.

LOAD CELL SUPPORT	MAT. STAINL. STEEL	SCALE 1 : 1
	DRAWN 09-06-20 M.S.	NO. 33IK00013

(SHEET NO. 2 OF 2)

ITEM NO.	DWG. NO.	DESCRIPTION	QTY. REQ.
1	—	LOWER PULL ROD 1.0 DIA. WITH 100-8 UNC-2A END	1
2	331K00002	SPECIMEN	1
3	331K00004	FRETTING BRIDGE	2
4	—	LOAD CELL 1.00 INCH DIA.	1
5	331K00008	CLAMPING PLATE	1
6	331K00006	SUPPORT COLUMN	2
7	—	LOAD PIN, DOWEL .500 DIA. x 4.5 LG.	2
8	—	BOLT, HEX. HD. WITH NUT .500-13 UNC-2A x 4.5 LG.	4
9	331K00007	RIG SUPPORT	1
10	—	UPPER PULL ROD .75 DIA. WITH .75-10 UNC-2A END	1
11	—	THREADED ROD 1.00-8 UNC-2A x 2.5 LG.	1
12	331K00003	GRIPS	2
13	—	CLAMPING BOLT, HEX. HD. WITH NUT .750-10 UNC-2A x 6.5 LG.	4
14	—	CAP SCREW, HEX. SOC. HD. .250-20 UNC-2A x .875 LG.	8
15	—	CAP SCREW HEX. SOC. HD. .190(NO.10)-24 UNC-2A x .680 LG.	4
16	331K00005	BRIDGE SUPPORT	2

**FRETTING TEST
APPARATUS**

SCALE

(PARTS LIST)

DRAWN 89-02-15 M.S.

DWG. NO. **331K00001**

(SHEET NO. 1 OF 2)

6.35 mm THICK
(.250" THICK)

SPECIMEN	MAT. Ti-6Al-4V	SCALE 1:1
	DRAWN 09-02-15 PLG	NO. 33IK00002

NOTES: ALL DIMENSIONS ARE IN INCHES.

BRIDGE SUPPORT	MAT.	SCALE 1:1
DRAWN 89-02-13 M.S.	DWS.NO.	33IK00005

NOTES: ALL DIMENSIONS ARE IN INCHES.

RIG SUPPORT	MAT.	SCALE 1:1	DRAWN 89-02-13 M.S.
DWG NO 331K00007

.375 INCH THICK

NOTES: ALL DIMENSIONS ARE IN INCHES.

SUPPORT COLUMN	MAT: STEEL PLATE 12=6=3/8 THICK	SCALE 1:2
	DRAWN 89-02-18 M.S.	DWG. NO. 331K000006

NOTES: ALL DIMENSIONS ARE IN INCHES.

CLAMPING PLATE	MAT. STEEL PLATE 5x5x1/2 THICK	SCALE 1:2
	DRAWN 89-02-13 M.S.	DWG. NO. 331K000008

END

1|4|09|90

FIN