Determination of Fretting Fatigue Behavior in Titanium Alloy Ti-6Al-4V: A review

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Abstract-Fretting fatigue is an important concern in the structures and machine parts that are subjected to repeated relative movements between them. In current study a review of the work done by various researchers related to the evaluation of fretting fatigue response of Ti-6Al-4V has been presented. Effects of surface treatments, crack growth, heat treatments, types of loading, contact pad configuration on the fretting fatigue life have been presented. Life prediction models developed by various researchers have also been discussed.

Keywords-fretting fatigue, review, Ti-6Al-4V, crack growth, heat treatment.

I. INTRODUCTION

Fretting fatigue failure is a type of failure which occurs in structures and machine parts, typically in gas turbine disc and blade joints, due to vibration between them. Titanium after being alloyed with aluminum, vanadium and other elements is highly suitable to be used in aircraft, naval ships, armor plating, missiles and aircrafts because of high strength to weight ratio, higher capability to resist corrosion. Most importantly it resists the crack growth and creep elongation even at high temperatures. Ti-6Al-4V is the mostly used alloy in aircraft applications, almost 50% of all alloys [1]. Composition of Ti-6Al-4V alloy and its physical, mechanical, electrical and thermal properties are given in Table I and Table II respectively.

TABLE I
COMPOSITION OF TI-6AL-4V. [2]

Component	Weight (%)
Al	6
Fe	Max 0.25
O	Max 0.2
Ti	90
V	4

TABLE II
PHYSICAL, MECHANICAL, ELECTRICAL AND THERMAL PROPERTIES OF TI-6AL-4V. [2]

Physical Properties	Metric	Imperial
Density	4.43 g/cc	0.16 lb/in³
Mechanical Properties		
Hardness, Brinell	334	334
Hardness, Knoop	363	363
Hardness, Rockwell C	36	36
Hardness, Vickers	349	349
Tensile Strength, Ultimate	950 MPa	138000 psi
Tensile Strength, Yield	880 MPa	128000 psi
Modulus of Elasticity	113.8 GPa	16500 ksi
Compressive Yield Strength	970 MPa	141000 psi
Notched Tensile Strength	1450 MPa	210000 psi
Ultimate Bearing Strength	1860 MPa	270000 psi
Poisson's Ratio	0.342	0.342
Charpy Impact	17J	12.5 ft-lb
Fracture Toughness	75 MPa-m½	68.3 ksi-in½
Shear Strength	550 MPa	79800 psi
Shear Modulus	44 GPa	6380 ksi
Electrical Properties		
Electrical Resistivity	0.000178 ohm-cm	0.000178 ohm-cm
Magnetic Permeability	1.00005	1.00005
Magnetic Susceptibility	3.3e-006	3.3e-006
Thermal Properties		
Thermal Conductivity	6.7 W/m-k	46.5 BTU-in/hr-ft²-°F
Specific Heat Capacity	0.5263 J/g-°C	0.126 BTU/lb-°F
Melting Point	1604-1660 °C	2920-3020 °F

II. REVIEW

2.1 Surface Treatments

The purpose of surface finishing/ treatments is to acquire desired improved properties in the manufactured parts like wear and damage resistance, resistance to corrosion, reducing stress concentration, hardness, appearance and increasing the total life of the part.

Reference [3] found that by the application of different coating processes and surface treatments: shot peening, ion-beam-enhanced deposition (IBED) CrN films, shot-peening + IBED CrN films and IBED CuNiIn films on Ti-6Al-4V specimens, their resistance to fretting wear damage and fatigue strength can be enhanced as shown in Fig. 1 and Fig. 2. They found that IBED CrN films exhibit the highest resistance to fretting fatigue however duplex treatment by shot-peening/IBED CrN exhibit superior resistance towards fretting wear.

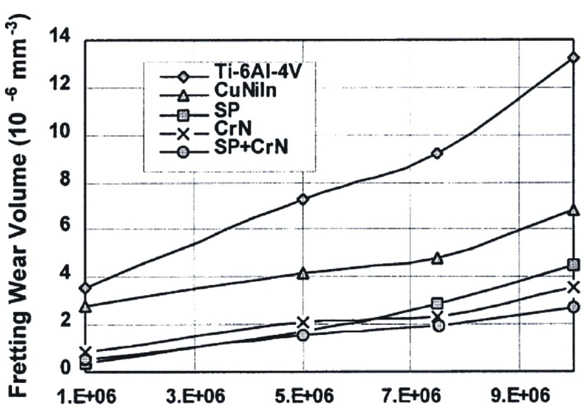

Fig. 1. Graph showing the comparison of the fretting wear volume for various surface treatments at 20 N load and 50 μm slip amplitude. [3]

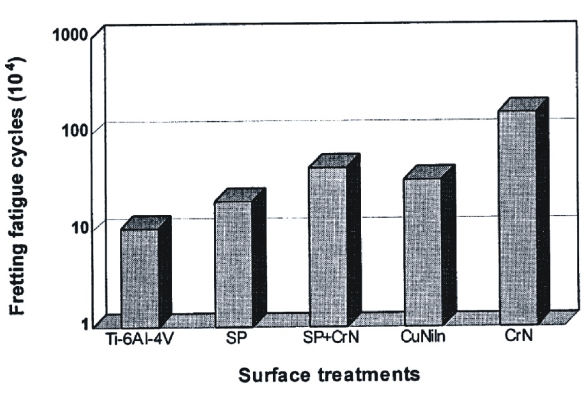

Fig. 2. Comparison of fretting fatigue strength by the application of different surface treatments. [3]

Reference [4] conducted an experimental study to analyze the response of Ti-6Al-4V specimen in contact with pads under four surface conditions: Ti-6Al-4V (bare) with highly polished surface, Ti-6Al-4V (bare) grit blasted to RMS #64, Ti-6Al-4V polished to RMS #8 and Ti-6Al-4V plasma spray coated with Cu-Ni. 20-25% increase in fretting fatigue strength was found for Cu-Ni plasma spray coated specimens as compare to those polished to RMS #8. The response of Ti-6Al-4V specimens against above four treatments was also evaluated using fatigue tests and S-N curves. It was found that the mechanism responsible for improving fretting fatigue strength was surface roughness rather than material of the parts in contact with each other.

Reference [5] studied the effect of re-shot peening on fretting fatigue strength of forged and previously shot-peened Ti-6Al-4V specimens at room temperature and at elevated temperatures. Relaxed residual stresses were found to be successfully recovered to a level of initial shot peening by the re-shot peening process. 20-25% residual stress relaxation was induced by the conditions applied during their study. Further re-shot peening eliminated the effects of any damage caused by fretting fatigue after initial shot peening.

Reference [6] studied the potential of four coating systems (TiCN, CrN+MoS_2, Cu-Al and Ag+ irradiated layer) towards enhancing the fretting fatigue strength of Ti-6Al-4V specimens. Fretting lives and coefficient of friction of both coated and without coating were compared as shown in Fig. 3 and Fig. 4 respectively. Finally the tested specimens were analyzed using Scanning Electron Microscope (SEM) and energy dispersive spectrometry for understanding the microstructural information about coating degradation process.

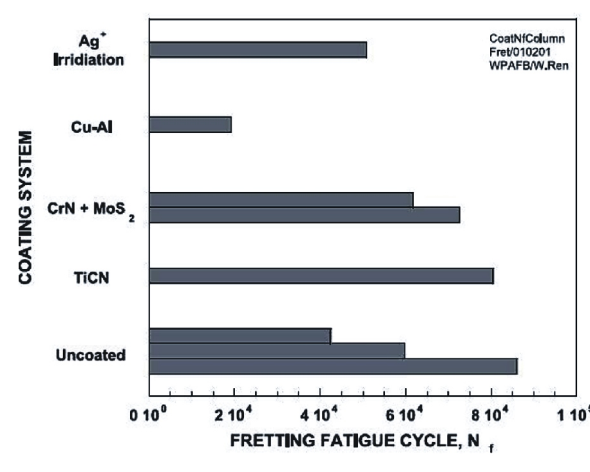

Fig. 3. Comparison of fretting fatigue lives under different coating conditions. [6]

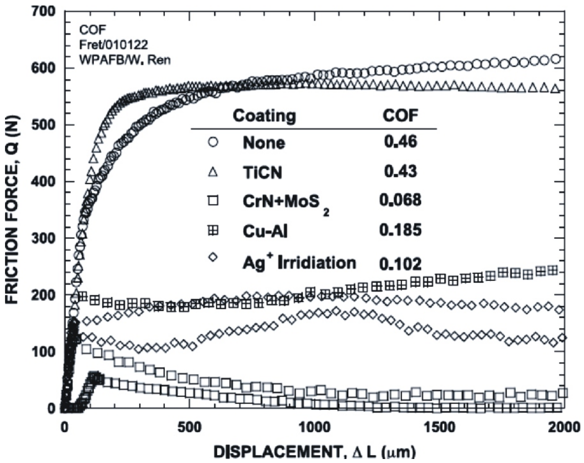

Fig. 4. Comparison of coefficient of friction of different coating systems. [6]

Reference [7] conducted the fretting fatigue tests of Ti-6Al-4V specimens which were initially shot peened by the application of independent pad displacement using dual actuator setup at a certain applied stress under slip controlled mode and found that fretting regime changes from partial to mixed mode slip and then by increasing the relative slip upto 50 µm it changes into gross slip. Due to compressive residual stresses the fretting fatigue life of shot-peened specimen was found to be longer than un-peened at the same slip range.

Investigation on the fretting fatigue response of Ti-6Al-4V specimens and pads using two different experimental setups and five coating systems resulted that the specimens with DLC coatings and LSP and LPB (without surface coatings) show significant improvement in fretting fatigue strength [8].

Reference [9] found that surface treatments like Laser Shock Processing (LSP) and Low Plastic Burnishing (LPB) induce compressive residual stresses that can increase the fretting fatigue strength of the specimen by reducing the coefficient of friction but do not eliminate crack nucleation and propagation.

Reference [10] investigated the effect of Laser Shock peening on fretting fatigue life of Ti-6Al-4V specimens by applying the conditions similar to those as in blade/disc contacts in gas turbine. As compare to untreated specimens the LSP specimen showed 5-, 10-, 15-fold increase in fretting lives although it cannot eliminate the formation of fretting fatigue cracks and the fretting cracks were distributed throughout the surface.

Highly localized contact stresses were found to be responsible for crack nucleation. Sum of initiation life (using Socie paremeter, Chu-Bonnen parameter, Findley parameter and σ_{eq}) and propagation life gave the total predicted life. Shot peening increased the stresses at which run out (10^6 cycles) occur from 170 to 275 MPa. Coated specimens after losing their coating in first 50,000 cycles seen to have same failure life as of the shot peened specimen. Fig. 5. exhibits the methodology adopted in this study [11].

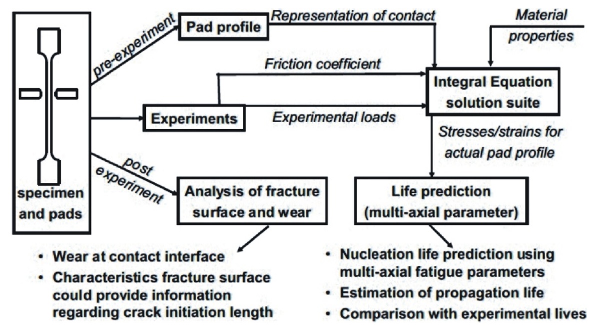

Fig. 5. Methodology adopted to study fretting fatigue phenomenon. [11]

Selected surface treatment techniques: diffusion treatments, hard coatings (TiN and CrN), soft coating (Cu-Ni-In), titanium-matrix TiB_2 in situ formed composite and shot peening were used to evaluate which one is best to enhance the tribological performance of Ti-6Al-4V and 60Ni-40Ti. They found that surface treatments significantly improve the wear performance of the specimens but their relative rankings varied significantly with lubricated and non-lubricated conditions [12]. CrN coated specimen exhibited least amount of wear as shown in Fig. 6.

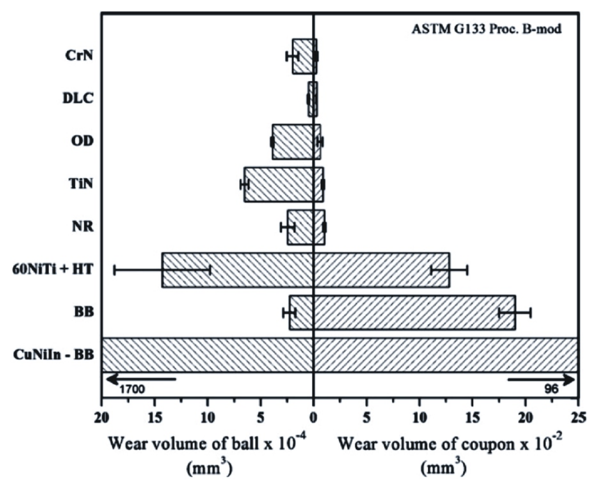

Fig. 6. Wear volume of coupons and balls tested under ASTM G133 Proc. B-mod. [12]

Reference [13] proposed a sequential finite element model (implicit and explicit) to study the effect of shot peening on shear stress, normal stress, bulk stress and slip amplitude which are key factors in fretting fatigue. Further it was found that compressive residual stresses had the major effect on fretting parameters and the mainly affected parameter was bulk stress.

Reference [14] used the technique of Ultrasonic

Non-crystalline Surface Modification (UNSM) and conducted lubricated fretting wear and friction tests using ball-on-flat specimen configuration of commercially available pure titanium and Ti-6Al-4V. Fretting wear debris of UNSM-treated specimens was found to be smaller and shallower than the untreated specimens. Also grain size was refined from 35.5µm to 200nm. Surface hardness also showed increment.

Reference [15] studied the electrochemical behavior of chromium nano-carbide coating applied using HVOF thermal spray technique under atmospheric conditions up to a finished thickness of 100µm on Ti-6Al-4V and Co-Cr-Mo alloys. All coated material showed greater corrosion resistance to mechanical abrasion as compare to native alloys. The presence of H_2O_2 at high temperature and low pH causes reduction in corrosion resistance of all the materials.

X-ray photoelectron spectroscopy and SEM with energy dispersive X-ray microanalysis was employed to study the effect of mechanical treatment on the surface chemical state, composition and morphology of commercially available Ti-6Al-4V. A considerable grain refinement along with the formation of nitrides and oxynitrides (both within and outside the contact area) was observed by ultrasonic impact treatment of Ti-6Al-4V in the presence of liquid nitrogen environment. The highest microhardness was found of the sample undergone ultrasonic impact treatment for 120s. For the first time mechano-chemical synthesis of nitrides in the Ti-6Al-4V alloys was found to occur at a high rate under ultrasonic impact in liquid nitrogen environment at cryogenic temperature [16].

Reference [17] investigated the wear and corrosion response of electroplated Ni/CNT composite coating on Ti-6Al-4V in Hank's solution and experimentally observed that the presence of CNT in the coating increases hardness of the alloy up to 98.5% higher than that of pure Ni coating. Moreover, this coating forms a stable and dense passive coating that improves wear and corrosion resistance in Hank's solution.

2.2 Crack Growth

A crack may be defined as the displacement discontinuity in a solid material due to applied stress. Prediction of crack growth is the primary objective of damage tolerance discipline.

10% of total life and 100% of life tests were conducted involving the application of fretting fatigue cycles followed by characterization of fretting damage using SEM and surface roughness measurement, marking of fretting cracks by using heat tinting and then the fracture of all the specimens under uniaxial loading. Fig. 7. shows residual fatigue strength results for 10% and 100% of total life. Cracks were nucleated near the edges and stress or strain criterion was found to be the predominating criteria causing nucleation of cracks. Cracks nucleated having surface lengths of 100µm or less have no effect on the fatigue strength. No correlation was found between surface roughness and fretting damage [18].

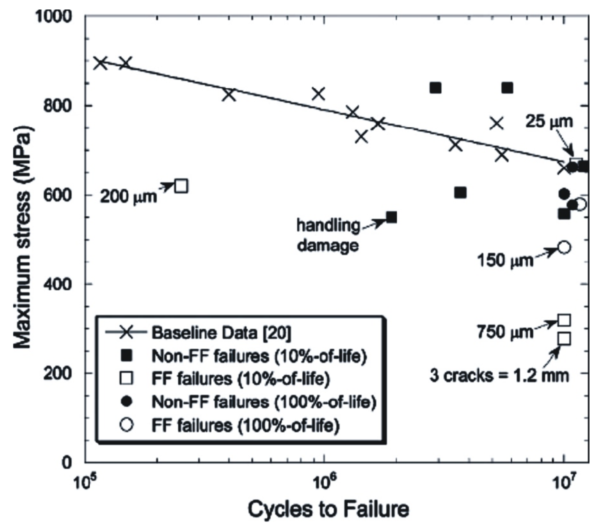

Fig. 7. Residual fatigue strength. [18]

C-shaped Ti-6Al-4V pads were utilized as test specimens which were previously used in fretting fatigue tests and heat tinting to locate the cracks and heat treated to release the stresses. High cycle fatigue step testing was conducted and threshold stresses were calculated while crack propagation threshold ΔK_{th} was calculated form measure crack sizes. When specimen failed at the leading edge the depth of damaging crack was found to be 75µm and 50µm when failed from the trailing edge [19].

Ti-6Al-4V dovetail specimen were tested using tension-compression MTS with an aim to establish a quantitative description of its fretting response under ambient conditions. An energy approach was used to formulated frictional behavior under gross slip conditions and a normalized wear parameter was derived that quantified the wear kinetics of Ti-6Al-4V irrespective of pressure, relative sliding amplitude, duration or contact dimensions [20]. Fig. 8 shows debris flow chart for the wear kinetics of titanium specimen.

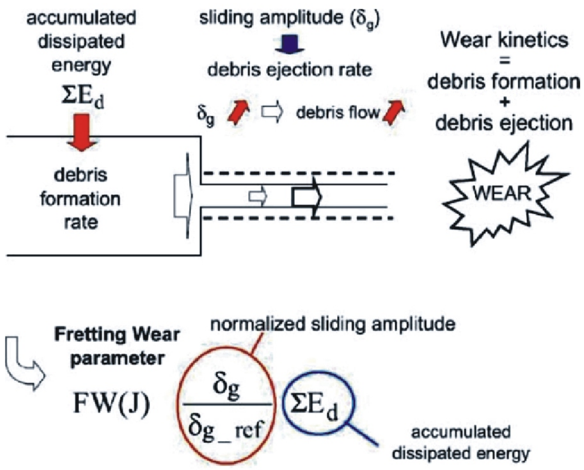

Fig. 8. Debris flow chart illustrating the Ti-6Al-4V wear kinetics at gross slip conditions. [20]

Influence of variation in microstructure of α/β Ti-6Al-4V was investigated which varied from homogenous duplex to fully transformed heterogeneous lamellar structure on fretting crack initiation. With this change in microstructure, the resistance to fretting initiated crack was found to be decreasing. Also it was observed that crack growth rate decrease consistently with the increase in the colony size at a certain given stress intensity factor [21]. Fig. 9 shows the S-N relationships for the three microstructures.

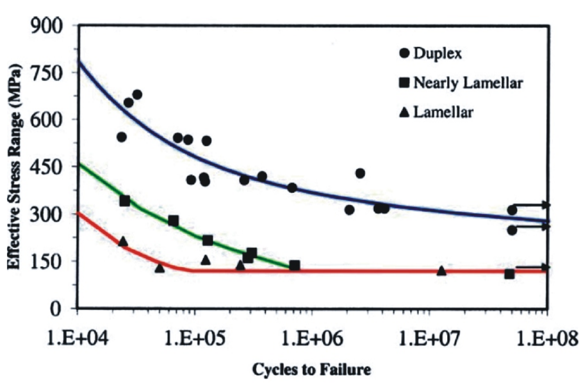

Fig. 9. S-N relationship based upon effective stress for three microstructures. [21]

Reference [22] analyzed the fractured surfaces of Ti-6Al-4V dog-bone and C-shaped specimens obtained after fretting fatigue tests on four point bending machine using optical and SEM. Fretting cracks were found to be small and shallow in depth and are concentrated/present around contacting interface perimeter and propagate into the material on elliptical fronts depending on stress gradient, geometry of contact and material properties. Fig. 10 shows SEM fractograph of C-specimen.

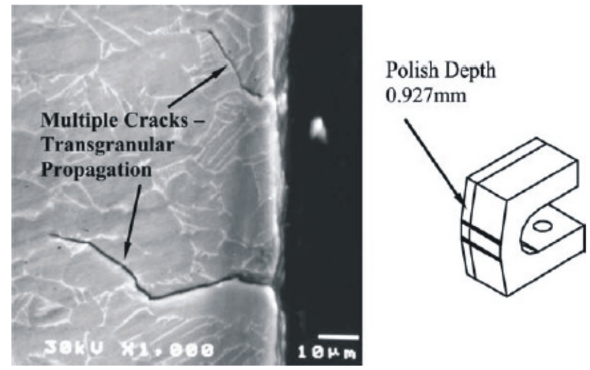

Fig. 10. Fretting crack profile produced on the C-specimen. [22]

Reference [23] investigated the fretting nucleated crack propagation unique double dogbone Ti-6Al-4V specimen under two conditions: high clamping stress and low clamping stress. Fractured surfaces were subjected to careful fractographic investigation and crack lengths were measured using SEM while AFGROW was utilized for crack propagation analysis. Fretting fatigue cycles were found to have no effect on the residual strength of the material until the crack depth exceeds 50µm. A high coefficient of friction was found to be responsible for the experimentally obtained crack propagation lives.

Fretting fatigue crack growth behavior in Ti-6Al-4V specimens with two types of contact geometries: cylindrical pads with 50.8 mm radius and flat pad with rounded edges was investigated using fracture mechanics based analysis technique and finite element sub-modeling using ABAQUS (for the specimen analysis when no crack is formed) and FRANC2D/L (for crack propagation). Effects of contact load, maximum tangential force and coefficient of friction on crack propagation life were studied. Under high cycle fatigue regime, crack nucleation and initiated consumes greater than 90% of total fretting fatigue life. As the initial crack length increases the grain size by two or three times, dependency of normalized crack propagation life on initial crack length vanishes [24].

Reference [25] presented and validated a model that quantifies the effect of fretting wear upon fretting crack initiation. The fretting fatigue tests were conducted at room temperature using cylinder-on-flat configuration showing dependence of crack behavior on slip regime and fretting scars were studied using profilometry and SEM. To model the cyclic plastic behavior of Ti-6Al-4V a linear kinematic hardening plasticity model was introduced. Spatial adjustment for the contact nodes in the simulation was achieved by user subroutine UNMESHMOTION together with an adaptive meshing framework with in ABAQUS.

Reference [26] studied the effect of stress gradient on the crack nucleation of cylinder/plane Ti-6Al-4V specimen under low cycle fatigue conditions. Plain fatigue experiments were conducted using MTS hydraulic machine. Cracking zone in dovetail joint has been illustrated in Fig. 11. Crossland and Papadopoulos fatigue criterions were examined and compared. The results of three non-local approaches allowed the proper prediction of the threshold with in margin of error 3-5%. Square averaging, critical distance and weighted function approaches were also been employed and compared.

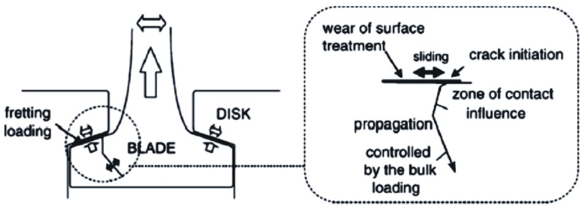

Fig. 11. The fretting fatigue crack found in dovetail joints of turbine engines. [26]

A micro-mechanical modeling methodology for fretting fatigue crack prediction in Ti-6Al-4V was presented based upon unit cell crystal plasticity model, frictional contact model and implementation of a microstructure sensitive fatigue indication parameter for indication of crack nucleation. A cylinder-on-flat configuration was employed. The microstructure-sensitive approach predicted partial slip cracking, corresponding with experimental data and was adopted to facilitate a novel wear prediction methodology [27].

2.3 Heat Treatment

The main purpose of heat treatment is to acquire desired physical, chemical and mechanical properties in a specimen. Heat treatment includes: annealing, case hardening, precipitation strengthening, quenching and tempering.

Reference [28] studied the relaxation behavior of residual stress in dogbone Ti-6Al-4V specimens (un-peened and shot-peened) during fretting fatigue tests at room temperature, 100 and 260^{0}C while stress ranging from 333 to 666MPa. Greater residual stress relaxation was found to occur when high cyclic load, contact load and temperature are increased. Comparison and analysis of stress relaxation behavior and corresponding fretting fatigue lives was carried out at different testing conditions. Fig. 12 shows the effect of temperature and time on stress relaxation.

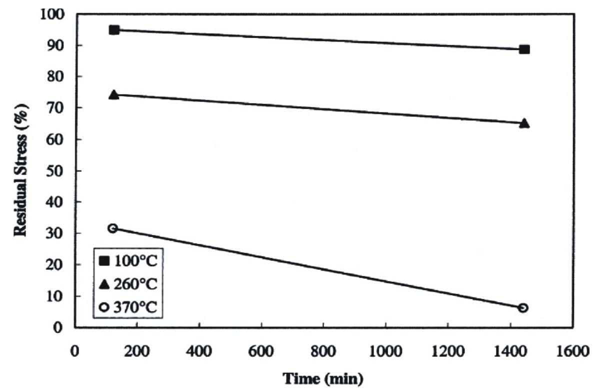

Fig. 12. Graph showing temperature effect and exposure time effect on residual stress relaxation. [28]

Fretting fatigue lives of Ti-6Al-4V flat-on-cylinder configuration specimen and pads were observed by conducting the experiments and through finite element analysis by using ABAQUS both at room temperature and at 260^{0}C. Specimens were subjected to a number of heat treatment processes: solution heat treatment at 935^{0}C and annealing at 700^{0}C. The coefficient of friction and its variation was found similar at both temperatures due to the fact that glaze oxide layer does not form on specimens' surface at 260^{0}C. Moreover, no difference in data values for plain fatigue and fretting fatigue lives were found at room temperature and at 260^{0}C [29].

Effect of cutting speed on fatigue lives of alpha-beta Ti-6Al-4V (ASTM Grade 5 and Grade 23) specimens was studied which were mill annealed and beta annealed. The surface roughness of all the materials was between 0.29μm and 0.44μm. Stress level was 600 MPa. It was found that cutting speed within the range of 50-150 m/min had no measureable influence on fatigue lives of either of the alloys and mill annealed heat treated specimens had greater fatigue lives than beta annealed heat treated specimens [30]. Fatigue life at various cutting speeds and surface conditions is shown in Fig. 13.

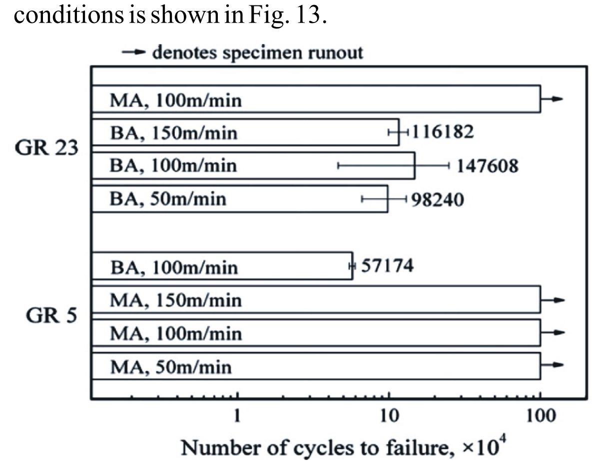

Fig. 13. Mean fatigue life of different materials at various cutting speeds. [30]

Effect of plasma nitriding under a gas mixture of $N_2/H_2 = 4$ at temperature varying from 700 to 850^{0}C for time durations from 2 to 10h was studied on tribological characteristics of Ti-6Al-4V disc shaped specimens. Plasma nitriding system is shown in Fig. 14. An increase in surface hardness, surface roughness, wear resistance, dynamic load-ability and coefficient of friction was observed due to plasma nitriding at increasing temperature and time. SEM, AFM, XRD and micro hardness techniques were employed for surface characteristic evaluation [31].

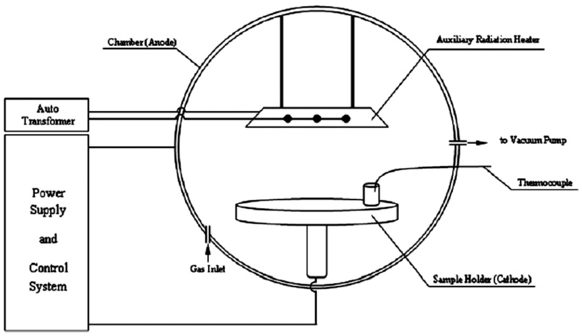

Fig. 14. Schematic diagram of plasma nitriding system used in this study [31]

2.4 Types of Loading

The damage caused by fretting fatigue depends a lot upon the type and load amplitudes.

Fretting fatigue response of Ti-6Al-4V dogbone specimens under varying and constant amplitude loadings at room temperature was investigated using servo-hydraulic uniaxial load frame. At higher frequencies fretting fatigue lives were found to be less than those found at low frequencies. For the predictions of variable amplitude loading tests Miner's linear summation model was applied. Microscopic examination revealed fretting surfaces for variable amplitude similar to those at 200Hz constant amplitude [32]. Fig. 15. shows the test rig.

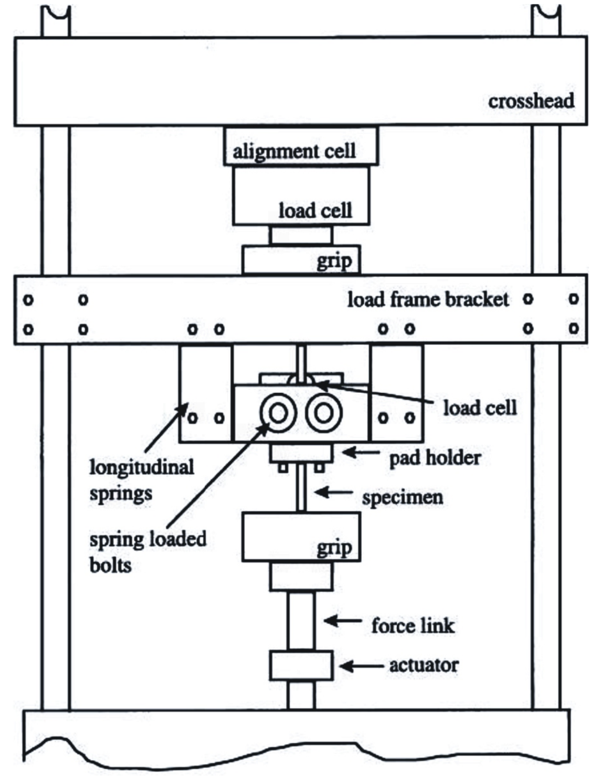

Fig. 15. Schematic diagram of fretting fatigue test frame [32]

Reference [33] investigated the fretting fatigue response of Ti-6Al-4V specimens and pads of flat-on-cylinder configuration using servo-hydraulic fatigue testing machine under variable loading conditions which involved two frequencies: 1Hz and 200Hz. The experimental fretting fatigue data differed from the predicted data obtained from Palmgren-Miner linear damage rule and hence it was found that in this case of variable amplitude loading condition, linear method of damage accumulation is less suitable than nonlinear method to estimate the fretting fatigue strength.

An investigation was carried out to establish a baseline for dry fretting contacts and to characterize the fretting response of Ti-6Al-4V on Ti-6Al-4V in point contact at high pressure. The material response and running condition at room temperature and 260^{0}C was same [34].

Reference [35] conducted a strain controlled multiaxial fatigue tests at room temperature on tubular Ti-6Al-4V specimens. Two types of proportional loadings (push-pull and reversed torsion) and two non-proportional (900 phase difference) loadings were applied. There was considerable decrease in fretting fatigue lives due to non-proportional loading about 1/10th than that for proportional loading for the same amplitude of strain via Mises' equivalent model. Fig. 16 shows Mises' equivalent stress-strain relationship.

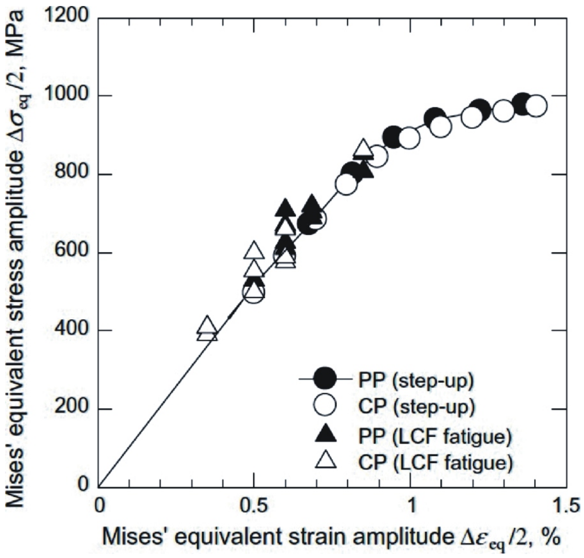

Fig. 16. Cyclic stress-strain relations. [35]

2.5 Contact Pads

Contact pads are subjected to high level of contact stresses that can also initiate cracks in them. Contact pad geometry and material are of prime importance in fretting fatigue tests.

Fretting fatigue tests using Ti-6Al-4V cylindrical and flat pads with rounded edges and at different pad displacements with two normal forces on the pad were conducted. These tests were performed at stress range amplitude 266MPa. Fretting fatigue life was found to be minimum and independent of the contact configuration at relative slip range between 50μm and 60μm. Tangential force and tangential to normal force ratio increased in direct relation with pad displacement independent of its geometrical shape. Contact configuration affected the fretted surface profile [36].

Reference [37] developed a setup to study the fretting fatigue response of Ti-6Al-4V dog-bone specimen capable of applying independent pad displacement (measured using extensometer) under normal force and stress amplitude conditions. Fretting fatigue life was minimum at slip ranges between 50μm and 60μm but increases as the relative slip increases and above 60μm the specimen does not fail due to gross sliding.

Effect of dissimilar mating materials on the fretting fatigue response of Ti-6Al-4V flat specimen was studied which was initially tested on uniaxial hydraulic machine against cylindrical pads made of Ti-6Al-4V, aluminum alloy 2024 and Inconel 718. Finite element analysis was performed using ABAQUS. At the same level of applied stress, there was no significant difference found in the fretting fatigue lives by using different pad materials. Later prediction of number of cycles for crack initiation was done by using modified SWT, SSR, MSSR and Findley parameter while only SSR and MSSR parameters were found to predict the location and orientation of the crack initiation precisely [38].

Reference [39] investigated Ti-6Al-4V specimen in contact with the pads of two different materials (aluminum 2024 and Inconel 718) at different levels of applied stresses and contact forces. Finite element analysis showed that increase in amount of the contact force results in smaller relative slip and greater width of stick zone. In general, the specimens which were fretted at lower contact force showed more damage on the contact surface than those subjected to high contact force.

Reference [40] investigated the mechanical and microstructural response of fretted Ti-6Al-4V specimen and pads. Fretting frequency was 100Hz and these tests were conducted using MTS 810. Three types of fretting pads were used: one with 3mm flat dimension with chamfered edges, second 1 mm chamfered edge and third with 3mm flat and 3mm transition radius as shown in Fig. 17. Pad geometry was found to have no effect on the fretting generated cracks.

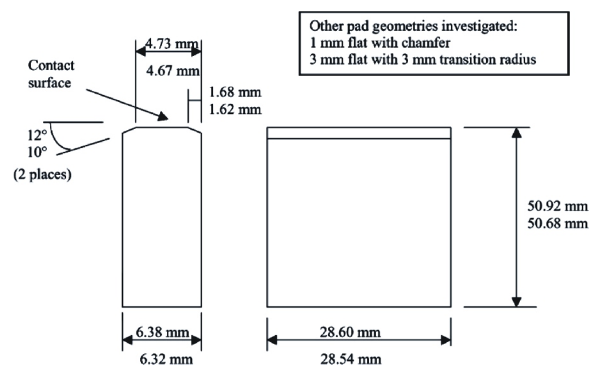

Fig. 17. Fretting pad geometry. [40]

2.6 Life Prediction Models

A series of remote fatigue tests on Ti-6Al-4V C-shaped specimen were conducted that were previously undergone to fretting fatigue loading conditions. CAFDEM was used to analyze the contact stresses developed in the tested specimen. Equivalent stress model provided a reasonable approach for correlation of total specimen life tested at wide range of loadings. MATLAB code was utilized for the calculation of fatigue crack propagation life [41].

A fretting life prediction model was applied for Ti-6Al-4V dog-bone shape specimens. The life prediction model included crack initiation life and crack propagation life along with initial flaw size determination. This model was applied to two types of fretting fatigue experiments and also compared with existing life prediction models. CAPRI was used for the stress determination. This model successfully predicts the experimental data and proves to be a good achievement [42]. Fig. 18. shows stress profile into depth of specimen considering opening and closing of crack.

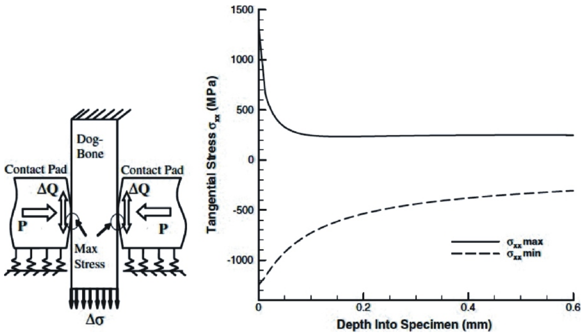

Fig. 18. Figure showing tangential stress profiles into the depth of specimen considering opening and closing of cracks. [42]

A new probabilistic analysis was developed to predict the fretting fatigue lives of Ti-6Al-4V specimens by considering the effects following variables: initial crack size, coefficient of friction, relative slip, contact pad profile and crack growth law. Various quantitative and qualitative techniques were applied to the results including probabilistic sensitivities via linear regression. Monte Carlo sampling was used as input in this study [43].

III. Conclusions

Findings of fretting fatigue behavior of Ti-6Al-4V by considering the effects of various surface treatments, crack growth, heat treatment processes, types of loadings, contact pad configurations and life prediction models can be summarized to get to the following conclusions:

1. Surface treatment processes like shot peening (SP), ion-beam-enhanced deposition (IBED) CrN films, (SP) + IBED CrN films, Laser Shock Processing and Diamond Like Carbon (DLC) coated specimens increased their fretting fatigue strength by inducing compressive residual stress, reducing coefficient of friction, increasing surface roughness and hardness. Furthermore it was found that re-shot peening can eliminate the effects of any damage occurred after initial shot peening due to fretting phenomenon.
2. Cracks were nucleated near the edges and stress or strain criterion was found to be the predominating criteria causing nucleation of cracks. Cracks are small and shallow in depth and concentrate around the contacting interface perimeter and propagate into the material depending upon stress gradient, geometry and material properties. More than 90% of total fatigue life was consumed during nucleation and initiation of cracks under high cycle fatigue.
3. Greater residual stress relaxation was found to occur when high cyclic load, contact load and temperature were increased. Moreover, mill annealed heat treated specimens had greater fatigue lives than beta annealed heat treated specimens. Plasma nitriding causes surface increase in surface hardness, toughness, wear resistance, dynamic load-ability and coefficient of friction at increasing temperature and time.
4. Microscopic examination revealed fretting surfaces for variable amplitude loadings similar to those at 200Hz constant amplitude loadings. In case of variable amplitude loading linear method of damage accumulation was found to be less appropriate than nonlinear method for estimating fretting fatigue life. There was considerable decrease in fretting fatigue lives due to non-proportional loading about 1/10th than that for proportional loading for the same amplitude of strain using Von Mises' equivalent model.
5. At the same level of applied stress, there was no significant difference observed in the fretting fatigue lives by using different pad materials. Also it was found that fretting pad geometry had no effect on the cracks generation.

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