A Fundamental Approach to Fatigue Behavior of Ni-Base Superalloys -A Review

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ABSTRACT

Many researchers have defined fatigue as a process that occurs over centuries. The major categories are load control/elastic range and strain control/elasto-plastic range responses. In both cases they are defined as slip band intrusions and extrusions phenomena in the crystalline metal grains within the competing processes of strain hardening and recovery at high temperature. The imposition of temperature, corrosion and mechanical phenomena complicates the formulations in certain cases. The facts illustrated in this review contain different aspects of fatigue with particular reference to Ni-base superalloys. However the experimental instances are grouped for every possibility of fatigue at high temperature. These include high cycle fatigue, low cycle fatigue, creep fatigue, thermal fatigue, thermomechanical fatigue and corrosion fatigue. Corrosion fatigue on the other hand helps in responses to fatigue failure, where changes of surface area of metals by corrosion phenomenon are responsible for such increments of stress/strain. The influence of thermal barrier coating (TBC) on fatigue of nickel base superalloys has been examined.

Key words: -Empirical definitions, Fatigue, Creep, Life prediction, Thermal barrier coatings, High temperature, Nickel base superalloys, Gas turbine

INTRODUCTION

The study of fatigue behavior in Ni-base superalloys is interesting from a fundamental point of view. Fatigue leads to a rich variety of phenomena. Fatigue in Ni-base superalloys is considered one of the most important design quantities. Reliable prediction of fatigue failure in Ni-base superalloys can be obtained only by a thorough understanding of the complex physical mechanism associated with it. The study of failure in Ni-base superalloys has also enormous practical and economical consequences. The phenomenon of fatigue in Ni-base superalloys is of great theoretical interest and significant practical importance. Several excellent reports on fatigue behavior have appeared in the literature in recent years which have dealt with the maximum scope of fatigue in Ni-base superalloys from an understanding of the continuum description of the defect mechanism of flow. An important development has been the application of dislocation theory to fatigue fracture. A fatigue failure is insidious in nature. Fatigue results in a brittle appearing fracture with no gross deformation at the fractured surface. A characteristic fatigue fracture surface contains a smooth region with concentric clamshell markings and a region of granular fracture. An important structural feature which appears to be unique to fatigue deformation is formation of slip band extrusions and intrusions as shown in Figure 1. It is one of the most spectacular aspects of fatigue which appear at the surface from the well defined slip bands in the form of ridges and grooves. There seems to be considerable ambiguity and confusion about the mechanism of fatigue failure in Ni-base superalloys. No adequate all-encompassing theory of fatigue has yet been developed. An interesting aspect of fatigue failure is that cracks initiate at the free surface. The extreme sensitivity of fatigue to surface conditions is well established. It has been recognized from the early days that surface conditions can appreciably affect fatigue performance. This point of view is supported by a number of classical experimental observations.

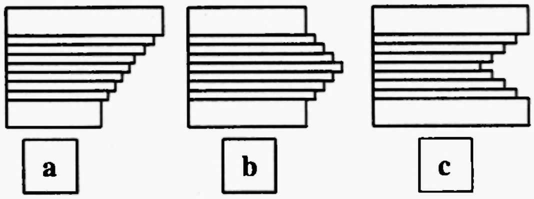


Fig. 1: (a) Static (b) Extrusion (c) Intrusion slip bands /1,2/

The paper presents a broad picture of the fundamentals of the fatigue behavior in Ni-base superalloys. The mechanism of fatigue failure in these high temperature alloys has been given considerable prominence. A fundamental approach to fatigue behavior in Ni-base superalloys has been followed in order to develop a few central ideas about how the deformation process under fluctuating stresses co-operate to give rise to nucleation and growth of fatigue crack. The analytical discussion will tend to focus on relatively new concepts which have emerged in recent years as a result of excellent experimental verifications.

Repetitive or fluctuating stress causes failure of metal at much lower stresses than that required to cause fracture on a single application of load. Equipment such as automobile, aircraft, compressors, and turbines are subjected to repeated loading and vibration, where fatigue accounts for at least 90% of all service failures. The factors of importance are tensile stress of high value, large fluctuation of applied stress and number of cycles of applied stress. In addition fatigue conditions are altered by stress concentration, corrosion, temperature, overload, metallurgical structure, residual stress, and combined stress. Thermal fatigue is the failure of metal after repeated application of thermal stresses of a lower magnitude, where linear expansion/contraction of metal is the variable of interest.

Thermomechanical fatigue is the failure of metal under the mutual effects of fatigue and creep properties. The failure transition is indicated by a transgranular fractograph (a high creep strength) to intergranular fractograph (a low creep strength) at high magnification. In the latter case factors like increment of mean stress and intergranular corrosion increase the creep tendency. Moreover, variables of interest are total time and total cycles to failure at high temperature. The creep phenomenon is sensitive to grain size. Therefore at high temperature a coarse-grained metal microstructure performs better than a fine-grained metal. However a low cycle fatigue at high temperature produces transcrystalline fracture at high frequency and intergranular fracture at low frequency. The variable of interest appears to be interaction of environment. Corrosion fatigue failure is the additive effects of fatigue strength, creep strength and corrosion resistance. It is expected that corrosion reduces fatigue life by 50%. Thin section high temperature components are simulated by small crack growth experiments of Paris' law. Corrosion eliminates this regime and small cracks grow into large cracks. Therefore an aggressive environment on thermal barrier coated components at high temperature reduces [[??factor of shafty]] based on porosity of ceramics and diffusion tendency of gases intervening, when corrosion resistance of bond coating is the life limitation for components /1,2/.

The simulated design for fatigue may include fluctuating stress, high temperature and high cycle fatigue test. Fatigue in this mode always plays below yield strength of any room temperature static tension test. The fluctuating stress forms micro-hysteresis curves within the changed axes of co-ordinate corresponding to the load limits. Since the experiments are load controlled, there is no plastic deformation zone. Therefore energy associated with the micro-hysteresis develops minor changes with respect to the other types of fatigue tests. The isothermal fluctuating stress brittle fracture forms upon hardening of metal by elemental diffusion at high temperature /3/. The micro-hysteresis within load limit helps in diffusion being associated with trans-crystalline slip band formation. 3

FATIGUE IN EMPIRICISM

The history of fatigue failure in metals has been written by several workers /2/. The contemporary definitions exist in the literature.

Table 1 represents the basic differences of static and fatigue failure at room temperature /2/.

Changes in mechanical and physical properties accompanying fatigue

Earlier methods used to measure changes in internal friction or damping capacity in a specimen during a fatigue test. Damping capacity is measured by either measuring stress-strain hysteresis loop during a stress cycle or measurement of temperature developed in metal by heat dissipation during fatigue test. Damping behavior during fatigue test has been divided into three stages /3/. In annealed metals damping is high in the initial stage and decreases rapidly during the primary stage. The primary stage is accompanied by increase in hardness. The secondary stage occupies the greater part of fatigue test and during this stage there is little

Table 1 /2/

Metallographic observations as obtained from room temperature static and fatigue test

Static stress	Fatigue stress
Sharp lines are fairly and evenly distributed over each grain. At high magnification each band consists of parallel lines of various lengths.	Slip bands appear close to or within existing slip bands so that bands gradually broaden but there may be extensive regions between them which appear from slip
Produce unlike slip bands	Produce bands confined to the middle of grains and do not extend to grain boundary
Deformation occurs by coarse slip (Wood)	Deformation occurs by fine slip
Consists of series of steps on surface	Consists of series of steps on surface, multi-planer slip forms shallow and undulating grooves and ridges, and closely spaced planes slip from sharply defined crevices and walls

variation in the damping capacity and no change in hardness. In the tertiary stage, which is usually short, the damping rises gradually at first then increases rapidity until the specimen breaks. The last stage is associated with plastic flow and crack formation. However damping in the secondary stage increases gradually and initially hardened metal is accompanied by softening. Damping and persistent slip bands are not related /4/. The former is a bulk property and restored by annealing without affecting life. Damping is a measure of state of deformation of specimen as a whole. It is suggested static deformation occurs by coarse slip and fatigue deformation occurs by fine slip /5/. Fine slip can be easily accommodated within crystal distortion. It has been observed that if applied stress is above fatigue limit, there is a progressive change during fatigue test /6/. The change is interpreted as a gradual breakdown of original grains into slightly misoriented sub grains or crystallites. Change in physical property of a fatigued specimen of nickel has been investigated when its temperature in increased /7/. In statically stressed specimen the process occurs primarily by recrystallisation while in fatigue specimen recovery occurs with little or no crystallization. Cyclic stressing results in over aging leading to coarsening of the precipitate /8/. The behaviors are attributed to an increase in the role of atomic diffusion induced by cyclic stress. It is believed that the effect does not result simply from local increase in temperature produced by deformation, but by the measurement of vacant sites produced by cyclic stress.

Fluctuating tensile tests

To obtain a quantitative measure of resistance to fatigue it is necessary to carry out tests under controlled conditions. During a fatigue test the stress cycle is usually maintained constant so that the applied stress condition can be written as $S_m \pm S_a$, where S_m is static or mean stress, and S_a is alternating stress equal to half the stress range. Fluctuating tensile stress fluctuates from tension to tension. The stress conditions may, alternatively be defined in terms of maximum and minimum stress in the cycle, i.e. S_{max}, and S_{min}. The algebraic ratio $\frac{S_{min}}{S_{max}}$ is called the stress ratio, as shown in Figure 2.

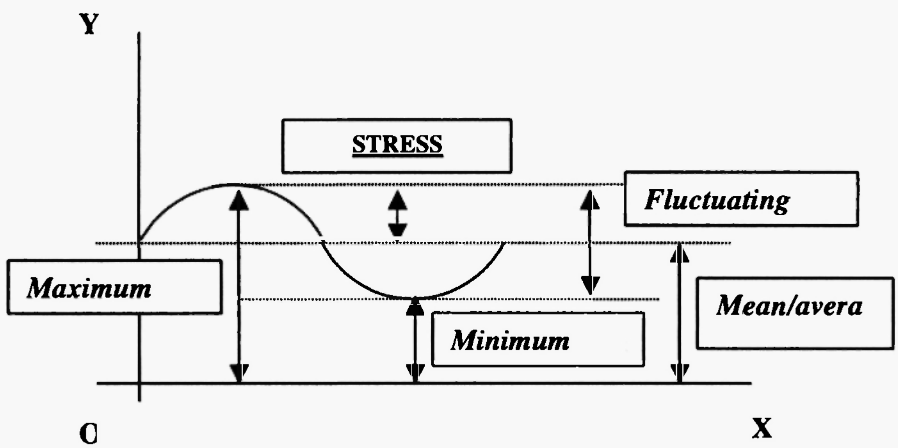


Fig. 2: Schematic of fluctuating stress cycle in fatigue experiments /1,2/

Fatigue strength and fatigue limit

Fatigue strength is defined as maximum fluctuating stress, which a material will withstand without failure for a given number of cycles. Flatten out S-N curves of confidence to extrapolate are usually determined over a range from about 10^5 to 10^8 cycles. The term fatigue limit should be used only for those metals whose S-N curves become horizontal. The occurrence of a fatigue limit can be explained on the basis of a gradual change in the metal structure induced by cyclic stress.

The relation between stress and strain during fatigue

Although fatigue features appear in a brittle manner, fatigue test often shows that some plastic deformation occurs. The relation between stress and strain during fluctuation of stress forms a closed loop. The occurrence of stress strain loops results from strain lagging behind the stress and they are therefore known as hysteresis loops. A loop is bounded by ratio of plastic to elastic strain per cycle with respect to number of cycles. The amount of plastic strain occurring depends markedly on stress. The area of hysteresis loop represents work done on the material during stress cycle. A small portion of this work may be stored in the material as a result of permanent distortion of structures, but almost all of it is dissipated as heat. At high stress ranges in direct stress fatigue machines the dissipation of heat may result in an appreciable rise in temperature of specimen.

Empirical predictions of fatigue strength under fluctuating stresses

The fatigue strength of a material with a static stress superimposed on the alternating stress S_a is plotted against static or mean strength S_m to get R-M diagram, where R is range of stress, equal to twice the alternating stress. The alternating fatigues limit or alternating stress for a given endurance is plotted on the co-ordinate and static tensile strength on the abscissa. The curve joining two points represents the contour of the combinations of static and alternating stress giving same endurance. To determine this curve experimentally a number of S-N curves are required each for a constant value of S_m, S_a, or R (equal to $\frac{S_{min}}{S_{max}}$). The two straight lines and the curve represent the three most widely used empirical relations. The straight lines joining the alternating fatigue strength to the tensile strength is the modified Goodman Law. Goodman's original law included the assumption that the alternating fatigue limit was equal to one third of the tensile strength and this has since been modified to the relation shown, using the alternating fatigue strength determined experimentally. The original law is not now used and the modified law is often referred to simply as the Goodman law. Gerber found that the early experimental results of Wholer fitted closely to a parabolic relation and this is now known as Gerber's parabola. The third relation is known as Soderberg's law that is given by a straight line from the alternating fatigue strength to the static yield strength. For many purposes it is essential that the yield stress should not be exceeded and this relation is intended to fulfill the conditions that neither fatigue failure nor yielding occur.

The effects of mean tensile stress on the fatigue strength of ductile metals

The ratio of alternating stress to the alternating fatigue strength is plotted against the ratio of mean stress to tensile strength to compare different alloys. The result lies between the Goodman line and Gerber parabola in most cases because maximum stress of the cycle is below the yield stress. If the yield stress is exceeded there may be considerable permanent deformation but the results where this occurred are all above the Goodman line.

Effect of frequency of the stress cycle

Usually fatigue machines operate at a frequency between 500-10000 cycles/minute and in this range fatigue strength of most metals are based on a given number of cycles to failure. Fatigue strength slightly decreases with decrease in frequency. Normally all fatigue experiments the waveform of the stress cycle is approximately simple harmonic. However wave forms far from simple harmonic have been reported /9/.

Influence of temperature on fatigue strength:

The results of fatigue tests show a stress-endurance relation at all temperatures although at high temperatures there is seldom a fatigue limit and downward slope of the curve is usually steeper than at room temperature. At high temperature, a limiting factor in design is usually static strength but resistance to fatigue is an important consideration in engine design, particularly when static and alternating stresses are combined.

Fatigue at high temperature

At high temperature application of a static load to a metal produces a continuous deformation or creep, which may eventually lead to fracture. The creep rupture strength decreases rapidly with increase in temperature to values which may be considerably lower than fatigue strength. Consequently heat resistant alloys have been developed primarily to give high creep strength. It is found that those alloys which possess good creep resistance are also resistant to fatigue. Although ratio of fatigue strength to creep rupture strength is markedly dependent on temperature, quite a close relation between the two is obtained for some materials. For Nimonic series the degree of agreement is sufficiently close to permit the prediction of fatigue strength from the more extensive creep rupture results.

Influence of metallographic structure

Strength at high temperature is often obtained by precipitation hardening. Both the solution treatment and aging treatment have an important influence on the high temperature mechanical properties. Solution treatment is important because it influences the grain size. At moderate temperature a fine grain size gives a higher creep resistance than a coarse grain size but this is reversed at high temperature. The fatigue strength is influenced in a similar manner by grain size. Consequently there is a range of temperature that is important practically when a coarse grain produces higher creep strength but lower fatigue strength. In these circumstances it might be advantageous to vary the heat-treatment to suit the stress conditions. The influences of aging treatment on high temperature fatigue strengths have received little attention. There is evidence that fluctuating stresses accelerate aging on the materials at high temperatures. If so it is possible that better fatigue strengths would be achieved by under-aging treatment.

Influence of corrosion

It is usually found that heat-resisting alloys also show high resistance to corrosion fatigue. Most investigations of corrosion fatigue at high temperature have been concerned with the effect of corrosive constituents in engine fuels. For example, it has been shown that the fatigue strength of Nimonic 80 at 1073K is unaffected by an atmosphere of sulphur dioxide but its fatigue strength at 1023K is reduced by about 10% at 1000 hours by a coating of fuel ash containing vanadium salts.

Fatigue under fluctuating stresses at high temperature

In order to compare the behavior of different materials at various temperatures, it is more convenient to plot the ratio of alternating stress to fatigue strength against the ratio of mean stress to the creep rupture strength. It appears that the addition of an alternating stress up to 40% of the mean stress makes surprisingly little difference to the rupture strength and in some cases may increase it significantly. Such increases have been observed on a number of heat resistant alloys but the reason for it is uncertain. It has been suggested that the fluctuating stress accelerates constitutional changes in the alloys, which result in an increase in hardness, or that transcrystalline slip is produced by fluctuating stress and relieves grain boundary stress concentration.

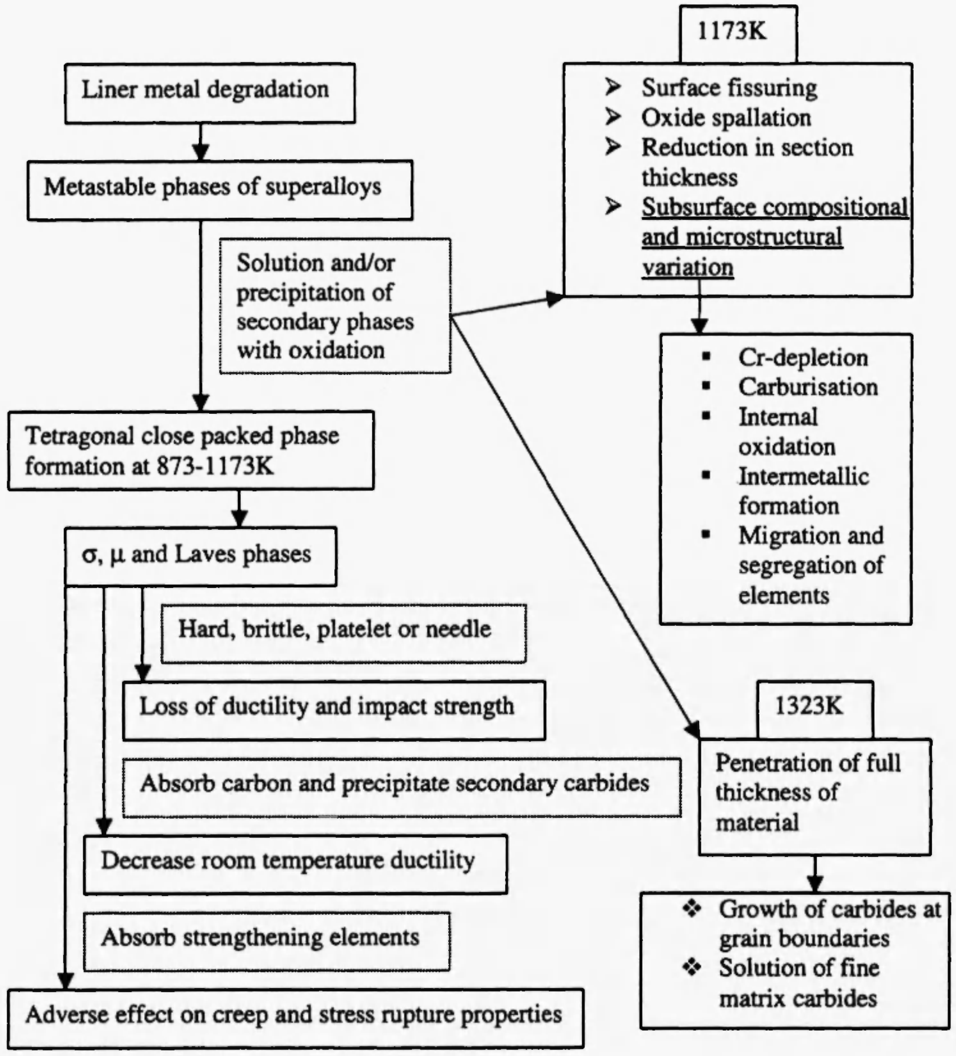
Modified Goodman law and Gerber parabola, drawn from the fluctuating fatigue strength to the creep rupture strength, generally give an over-conservative estimate of the strength under combined static and fluctuating stresses. It certainly gives closer agreement with the experimental results although individual values show wide variation. An alternative empirical relation is to use the modified Goodman line by drawing a line drawn between the fluctuating fatigue strength and the tensile strength but with certain restrictions. Such a criterion cannot be used to predict fluctuating fatigue strengths accurately but it fits data at high temperature as closely as the circular arc and is a better guide to fluctuating fatigue strengths at moderate temperatures. The criterion fits the experimental data reasonably closely which is an indication that in general there is a little interaction between creep and fatigue processes. The appearance of fractures which results from fluctuating stresses at high temperature may be similar to creep fractures or to fatigue fractures or to a mixture of the two, depending on relative magnitude of static and alternating stresses. The amount of deformation in the region of fracture is found to decrease as the ratio of alternating stress to mean stress increases. It is not always sufficient to limit fluctuating stresses only to prevent fracture. For some applications it may be necessary to limit the creep deformation to a specified amount. The influence of fluctuating stress on creep deformation may be represented graphically in a similar way to those used for fracture. Attempts have been made to predict the creep occurring under fluctuating stresses for any instantaneous value of varying stress. It is found that superimposing an alternating stress on a static stress may significantly increase the creep rate at moderate temperatures but at higher temperatures the effect is similar and the creep rate may even be decreased if the alternating stress is small.

Influence of frequency of the stress cycle

The normal operating frequency range of fatigue test machines has little effect on fatigue strength of most metals although reduction in frequency reduces slightly the number of cycles to failure at a given stress range. The effect usually becomes greater with increase in the temperature, so that failure tends to depend on the total time of application of the stress range instead of on the number of cycles. This behavior can be markedly influenced by metallurgical changes in the material. Under fluctuating stresses the cyclic frequency affects both the life and the amount of creep. The results of fluctuating stress tests carried out on several heat resistant gas turbine alloys at frequencies between 1 and 15000 cycles/minute show that the influence of frequency can be complex /10/. For a given static stress, the addition of an alternating stress increases the creep rate and reduces the life both at low and high frequencies but has the reverse effect at intermediate frequencies.

FATIGUE IN NICKEL BASE SUPERALLOYS

Normally the following types of fatigue mechanisms are observed in the gas turbine. General trends of linear substrate degradation in a gas turbine component are shown in Flow Chart 1. Mechanical behavior of different nickel base superalloys has been described in Figures {3(a) to 3(c)} /11/.



Flow Chart 1: Flow chart for general trend of liner substrate degradation

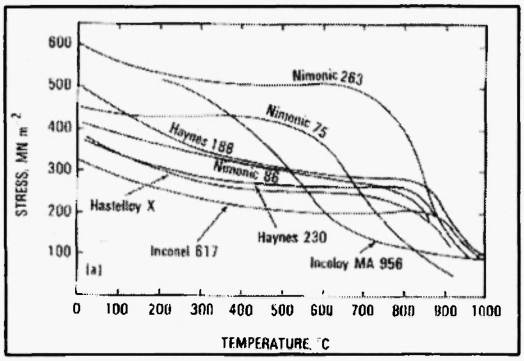


Fig. 3: (a) Typical 0.2% proof strengths of some sheet alloys /11/.

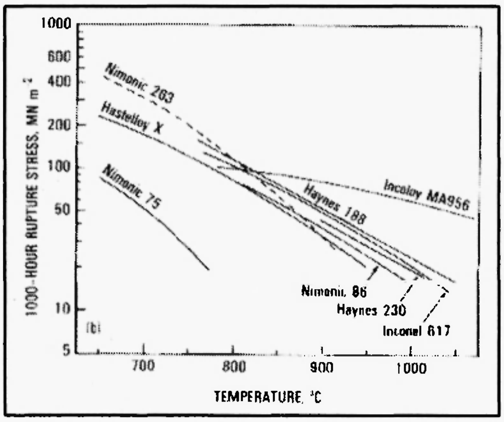


Fig. 3: (b) Typical rupture properties of some sheet alloys /11/.

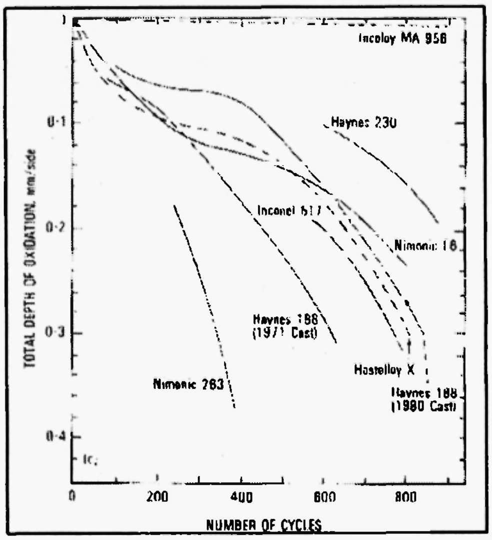


Fig. 3: (c) Oxidation resistance tested in exhaust gas stream (gas velocity: 170m/s, thermal cycle: heated to 1373K in 1 min, held for 30 min, cooled to 623K in 1 min) /11/.

High cycle fatigue

Aircraft gas turbine engines demand durability, high reliability, lightweight and high performance. Therefore, the aircraft engine design community has adopted lifetime failure free design criteria based on the Goodman Diagram and Miners rule for ensuring safety of critical structural components. The design process usually consists of a structural dynamics analysis to determine natural frequencies and mode shapes at certain operating speed ranges and a stress analysis to calculate the dynamic stress distribution for identifying the maximum vibratory stress location or area under a series of given excitation. Once the maximum stresses for each vibration mode are determined, high cycle fatigue assessment can be achieved by measuring the margin between the maximum vibratory stress and the material fatigue capability. The design criteria, design guides, or design codes are established using the results of a simple deterministic analysis procedure without taking into account the information such as degradation of material properties, scatter in testing data. It helps in successful design and eliminates the possibility of uncertainties inherent in the operating conditions in the real world. A number of structural failures have occurred in aircraft engines during development, testing, and operational service. Hence the current aircraft engine critical structural components must satisfy the lifetime failure free design /12/.

Turbomachinery blade failures of aircraft engine result from high vibratory stress during forced response as shown in Figure 4 /13/. Forced response usually occurs under a nonuniform flow field-operating environment. Hence for an adequate blade design, all the resonant conditions must be avoided or minimized. Realistically this is not possible as the sufficient real world loading information is not available at the time of the analysis and design. In addition, the gas turbine engine operates in an environment of a non-uniform flow field which creates widely distributed high vibratory stresses leading to high cycle fatigue (HCF) degradation of metallic structures and in its early stages the accumulating degradation is often very difficult to detect. Furthermore, the vibration cycling due to variability in geometry, aerodynamics, and materials cannot be provided with certainty and must be considered as a random process. Since the effects of randomness in a real world operating environment cannot be quantified accurately by a traditional deterministic design approach, it is beyond the capacity of such approaches to provide the important information regarding risk of

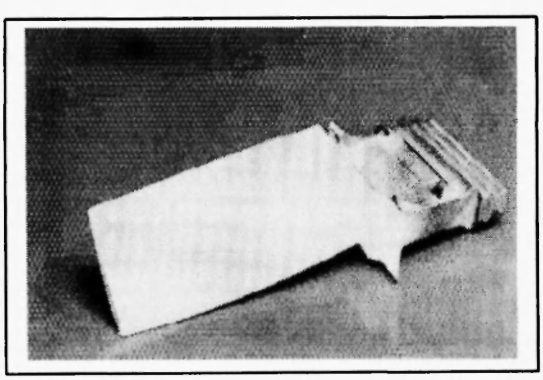


Fig. 4: A turbine blade with ceramic coatings (TBC) /13/

failure, or the sensitivities of the design variables to risk. An innovative probability based reliability HCF design and life prediction methodology for gas turbine engine blades has been developed to calculate important design and maintenance information of sensitivity, (High cycle) fatigue reliability and associated risk based on variability in geometry and aerodynamic loading. The general aspects of such concepts include the description of deformation process, the analysis of failure associated with creep rupture, high cycle fatigue, crack initiation and propagation, the establishment of appropriate design criteria and control and identification of structural responses /14/. HCF remains a pervasive problem as it is related to the high empirical approach based on the Goodman diagram which is currently employed to estimate HCF capability. A fracture mechanics threshold based HCF approach would be, therefore, highly desirable. Mechanisms of crack arrest associated with fatigue crack propagation (FCP) thresholds are very complex and there is a large discrepancy between results predicted from theoretical threshold models and experimentally determined values. These models deal exclusively with either intrinsic or extrinsic factors affecting the threshold without taking into account their synergistic interactions. Elevated temperature long crack FCP tests have been performed at high frequencies in a nickel base turbine disk alloy under a variety of experimental conditions such as temperature, frequency, microstructure, and load ratio. These variables have been systematically varied in order to understand the relative importance of individual factors and the level of interaction between them /15/. Fatigue crack propagation (FCP) tests have been conducted on powder metallurgy nickel-base superalloys KM4 at temperatures of 293K, 823K, and 923K under different heat treatments (one yielding a relatively coarse grain size and another yielding a fine grain size) at 100Hz and 1000Hz and at load ratios between 0.3 and 0.7. Paris regime results at high frequencies for KM4 are identical to those observed at lower frequencies. Variables such as coarse grains, low load ratios, low temperatures and higher frequencies generally have resulted in lower crack propagation rates. However in contrast to Paris regime behavior, thresholds are a complicated function of microstructure, load ratio, temperature and frequency, and the only variable that have resulted in a consistent trend in threshold is the load ratio. It is reported that threshold increases from 100 to 1000Hz for the fine-grained materials at 823K but decreases at 923K. One possible reason for this complexity is a change to inter-granular fracture in the fine-grained microstructure at 923K. Higher load ratios and lower frequencies promote inter-granular fracture. Scanning electron microscope (SEM) stereo-fractography is utilized to determine quantitative measures of fracture surface roughness. The roughness of the fracture surface is found to increase as the load ratio is increased for both microstructures. For the coarse grained microstructure, there is a direct correlation between fracture toughness and FCP threshold over the entire range of temperature, frequencies, and load ratios. However, measurements of closure loads indicate that roughness induced closure is not the sole reason for the varying FCP thresholds /15/.

Fracture characteristics and fracture mechanisms in a nickel base single crystal superalloy have been studied at high cycle fatigue under load control at 1073K and 85Hz. SEM fractographs show cleavage and tearing dimple modes of fracture which indicate that the fracture modes are associated with planer slip, dislocation cell formation, and formation of low angle grain boundaries. TEM images reveal that g¢-morphology changed from cubical to spherical during high cycle fatigue /16, 17/.

Long term high cycle fatigue behavior of nickel base superalloy IN792 has been investigated to examine the influence of the ratio of static mean stress to HCF stress amplitude as well as the influence of notches. The HCF data can be correlated with creep rupture data by a combination of the method of Keil and Maier and of the Moore-Kommers-Jasper diagram. It enables us in certain cases to replace costly long-term HCF tests by short-term tests at high temperature. The superposition of HCF and LCF loading leads to lifetime reductions by simple drainage accumulation rules /18/.

The results of high cycle fatigue tests at 923K on several casts Ni_3Al alloys are reported and compared with cast IN-731C. These alloys include IC-221M and several variations to the IC-221M composition. The effect of casting temperature is investigated. The results show that IC-221M cast at the highest temperature has the best fatigue strength, exceeding that for IN-713C. In these alloys, crack initiation occurs at shrinkage microporosity and the effect of casting temperature on porosity is related to the observed differences in fatigue lives /19/.

Low cycle fatigue

There is growing recognition of engineering failures that occur at relatively high stress and low number of cycles to failure. This type of fatigue failure must be considered in the design of nuclear pressure vessels, steam turbine, and most other types of power machinery as shown in Figure 5 /20/. Low cycle fatigue conditions are created where the repeated stresses are of thermal origin in nature. Thermal stresses arise from the thermal expansion of the material. The fatigue results from cyclic strain rather from cyclic stress. Strain controlled low cycle fatigue tests on a single crystal nickel base superalloy, CMSX-2, under a strain ratio of zero at 873K in air, shows higher fatigue strength compared to some other kinds of polycrystalline nickel base superalloy or a directionally solidified superalloy CM247LC-DS. The fatigue small crack growth rate increases proportionally with increasing crack length on the macroscopic level. However, they are significantly affected by the microstructure. The microscopic observations of the crack path, fracture surface

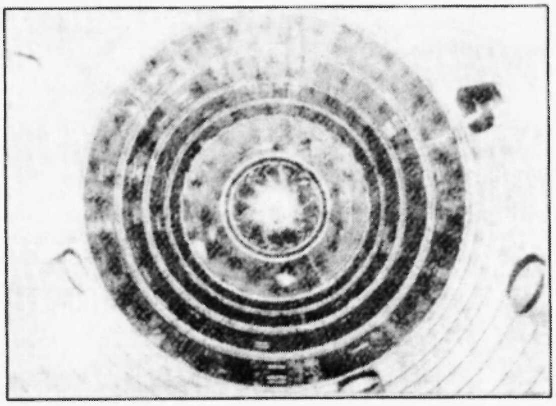


Fig. 5: View into combustor primary zone /20/.

and deformation around the crack tip, reveal that the small cracks propagate in the γ′ phase matrix on (100) cubic planes. As the crack becomes longer the crack propagation planes are switched onto {111} slip planes where the crack rapidly grows by the slip plane de-cohesion mechanism, cutting the γ′. phases. The above transitions of crack propagation plane occur when the stress intensity factor range reaches a critical value /21/. Strain rate effects on the low cycle fatigue (LCF) behavior of a Nimonic PE-16 superalloy in the temperature range of 523-923K at strain amplitude of 0.6% on samples possessing two different prior microstructures have been studied. Microstructures in the solution annealed condition are free of γ′. and carbides whereas microstructure in double age condition displays γ′ and $M_{23}C_6$ carbides. The cyclic stress response behavior of the alloy depends on the prior microstructure, test temperature and strain rate. A softening region arises as a result of shearing of ordered g¢. Negative strain rate-stress response, serration on the stress-strain hysteresis loops and increased work hardening rate are attributed to the dynamic strain aging. The calculated activation energy matches well with that for self-diffusion of alloying elements in the matrix. An increase in fatigue life with an increase in strain rate from 3×10^{-5} to 3×10^{-3}/sec is reported which decreases with further increase in strain rate. DSA influences the deformation and fracture behavior of alloy at 723K and 823K and low strain rates. Dynamic strain aging increases the strain localization in planer slip bands and impingement of these bands causes internal grain boundary cracks and leads to reduced fatigue life. Fatigue crack initiation and propagation are accelerated by high temperature oxidation and the reduced fatigue life is attributed to oxidation fatigue interaction. Maximum fatigue life at the intermediate strain rates originates from lower strain localization. Strain localization as a function of strain rate and temperature is quantified by optical and SEM and is correlated with fatigue life /22/.

Microstructural studies in low cycle fatigue of directionally solidified MAR-M200 + Hf superalloy at 1248K have shown internal as well as external oxidation and precipitate coarsening at the ahead of a crack tip. Near the crack tip internal oxidation of the material due to interstitial diffusion of oxygen is observed. Oxygen combines with reactive Al and Ti elements of γ′ precipitate and with the Cr atoms of the γ′-matrix by non-metallic bonding and embrittles the material and enhances the crack propagation. An external layer of loosely packed oxides develops on the crack surfaces upon further oxidation which is supported by partial diffusion of Al, Ti, Hf, and Nb from the oxidized uniphase layer beneath it. These elements are available as a result of modifications of the γ′-precipitates in a uniphase layer by internal oxidation. Most of the γ′-precipitates remain undissolved but tend to coarsen leading to a uniform layer. As a means of local internal stress relaxation coarsening takes place in the uniphase layer and in bulk material adjoining it /23/. Effects of hafnium on microstructures and high temperature low cycle fatigue (HTLCF) characteristics of DS Rene 80 have been studied at 1033, 1144, and 1255K. Hf increases the resistance to crack propagation by changing the morphology of carbides from script type to blocky type and suppresses the crack initiation by increasing the resistance to oxidation. Cyclic softening has been reported during HTLCF tests. At 1033K, the cyclic softening arises due to disordering of γ′-precipitates as well as due to dislocation shearing at 1255K /24/. HT-LCF failure has been studied in unidirectional solidified MAR-M200 + Hf nickel based superalloy in pure N_2 and CO_2 environments at 1248K. A uniphase layer is formed ahead of the propagating crack tip in both CO2 and N2 environments. This layer is produced via internal oxidation or nitridation caused by interstitial penetration of oxygen and nitrogen respectively. It is evident that the nature of formation and the properties of the uniphase layer exert a decisive effect on the HTLCF crack growth characteristics /25/. Low cycle fatigue behavior at 1000K, a temperature above the monotonic brittle to ductile transition temperature (BDTT) on intermetallic NiAl samples prepared by two fabrication techniques: hot isostatic pressing (HIP) of prealloyed powders and extrusion of vacuum induction melted [Cast-plus extruded (C + E)] castings has been examined. At 1000K in an air environment, both the hot isostatically pressed and C + E samples cyclically softened throughout most of their fatigue lives. At this temperature, samples are insensitive to processing defects. The processing method has a small effect on fatigue life. The lives of the HIPped samples are about a factor of three shorter than the fatigue lives of the C+E-NiAl. The C+E material also undergoes dynamic grain growth during testing while the HIPped NiAl maintains a constant grain size. At plastic strain ranges less than 0.3%, the fatigue lives of the HIPped NiAl are controlled by intergranular cavitation and creep processes such that fatigue lives are shorter than anticipated. HIPped samples tested in vacuum have a factor of three longer lives than tested in air. NiAl has a superior fatigue life as compared to superalloys on a plastic strain basis but is inferior on the stress basis /26/.

GH4049 is a γ' phase strengthened wrought nickel base superalloy with good oxidation resistance and strength at elevated temperature upto 1223K. This alloy is currently developed for turbine blades in aircraft engines. These components are operated at high temperatures and are frequently subjected to varying loads. Hence the damage from high temperature low cycle fatigue is one of the factors affecting the service life of the turbine blades. High temperature low cycle fatigue has been an area of scientific interest in recent years. The low cycle fatigue behavior of three wrought nickel base superalloys has been studied and it was observed that an increase in temperature from 298K to 811K led to a substantial reduction in fatigue life. It is reported that Inconel 718 and IN-617 display similar behavior. The fatigue crack initiation and propagation behavior of these alloys have been studied and it was unambiguously demonstrated that modes of crack initiation and propagation are strongly influenced by the change in the temperature /27/.

Creep fatigue

Creep, fatigue and oxidation may contribute to failure concurrently under fatigue loading at elevated temperatures. The role of each damage component may change significantly ranging from creep-fatigue in creep-ductile for power plant equipment, oxidation-fatigue to creep-brittle high strength alloys for aerospace applications and creep-fatigue oxidation in materials under complex loading conditions such as thermomechanical fatigue. However information pertaining to fracture mechanisms and their relevance to the interaction of creep-fatigue-oxidation remains scarce. At present there is no unified approach with which the problem of fatigue crack growth at elevated temperatures can be solved in a generally acceptable manner /28/.

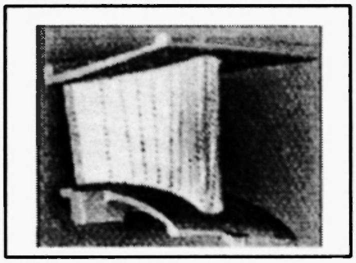
Nickel base superalloys have superior tensile strength and low creep ductility. Oxidation is primarily responsible for high temperature low cycle fatigue (HTLCF) damage in such materials. The subject of creep fatigue has been studied extensively. Most of the published work is concerned with established wrought alloys such as Inconel 718 or Waspalloy. The performance of the new generation of superalloys developed using powder metallurgy technique has to be critically examined and evaluated. The new alloys optimized for high strength at the expense of damage tolerance have to be examined under typical operational conditions to establish the relevant damage mechanisms, which may include the combination of creep, fatigue, and oxidation. The influence of temperature, strain dwells, and crystal orientations on high temperature fatigue-creep behavior of single crystal SRR-99 nickel base superalloy has been studied. The longest fatigue for a given temperature and loading condition life is observed with [001] orientations, while the [111] orientation results in the shortest fatigue life. The shortest fatigue life is observed with a compressive dwell at 1023K. At 1323K with a tensile dwell the shortest fatigue life is reported compared with continuous cycling tests. Tensile dwells show remarkably longer lives at 1023K, significantly shorter lives at 1323K, and almost identical lives at 1223K, where as compressive dwells always exhibit shorter lives than continuous cycling tests at all temperatures. The influence of strain dwells on the life of SRR 99 originates from the simultaneous effects of mean stress, additional inelastic strain, and time dependent damage. A mean stress modify strain range partitioning method has been used to predict the fatigue creep life /29/.

The growth rate of fatigue cracks on two single crystal nickel base superalloys, CMSX-6 and SRR-99, along the <001> planes is rationalized in terms of two interacting crack propagating mechanisms. One is attributed to crack tip plastic blunting and the other attributed to the brittle failure of the oxide scales. The role of the oxide scale is two-fold. It wages the crack and modifies the blunting term through a crack closure effect, but a positive effective stress intensity range is required to fracture the oxide scale. Fatigue tests carried out at different temperatures (773-1323K), frequencies (0.001-20 Hz), cycle waveforms and load ratios (0-0.9), with starter crack length of ~100mm match with the model predictions. Even though both materials are nickel base superalloys, CMSX-6 has an improved oxidation resistance over SRR 99. However, the life expectancy depends on the applied test temperature and loading cycle /30/. The absences of grain boundaries in single crystal superalloys (SRR 99) are examined to study mechanical behavior in different orientations. It is observed that both the cyclic stress strain response and fatigue life exhibit orientation dependence. The elastic modulus of the [111] orientation is larger compared with e.g. [001]. Consequently [111] specimen exhibits a higher stress range as well as a high elastic strain range leading to shorter fatigue lives. Orientation dependence of mechanical behavior has been described in terms of an orientation function /31/.

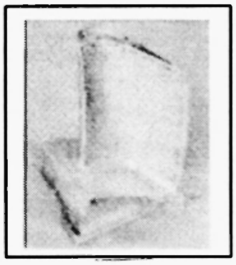
Creep-fatigue tests on a single crystal nickel base superalloy CMSX2 in vacuum, air and melted salt have been done to study the effect of environment. The creep fatigue of CMSX2 decreases, as corrosion environment becomes more severe. The creep-fatigue lives under PP and CC strain waveform conditions seem to be more sensitive to environment than those under PC and CP conditions /32/.

Thermo-mechanical fatigue

The behavior of metals and alloys in the plastic range is enormously, essentially, infinitely complex. No mathematical expressions, no matter how elaborate, can portray the response in completely full and accurate detail. However, some formulations can provide reasonable descriptions of material behavior under specific loading conditions. Uniaxial and multiaxial fatigue behaviors continue to be a topic of concentrated research and theories are developed and modified to reproduce appropriate responses under a broader spectrum of mechanical and thermal histories. However, the sophisticated formulations at the expense of model simplicity might limit practical usage if the implementation of the algorithmic into finite element code becomes time consuming. Owing to the complexities inherent in these theories, the selection of the optimum model for the specific application is one of the more difficult tasks that design engineers have to fulfill. A comparative study of several candidate models based on the number of parameters, the degree of difficulty in determining these parameters, the predictive capabilities, the time of computing, and the implementation into a finite element code has to be done thoroughly. IN738LC is a nickel base superalloy used for turbine blades, and vanes as shown in Figure 6(a) and 6(b). Constitutive equations have been developed for this particular alloy /33/. These united viscoplastic models are distinct in their approaches. The Chaboche model assumes the existence of a yield criterion, which separates purely elastic from inelastic deformation. But in the Slavik Schitoglu model no conventional yield criterion is used. Consequently, this approach allows for the possible existence of elastic and inelastic deformations at all stages of loading. These two models have proved their high potential to describe the inelastic uniaxial behavior at high temperature of several nickel base superalloys /34/.



6(a)



6(b)

Fig. 6: (a) and (b) Figure of a high-pressure turbine (HPT) vane and blade of a jet engine /33/

A simple form of thermal and technical testing called thermal mechanical fatigue testing, was developed in the 1970s to estimate in laboratory the loading conditions experienced by turbine blades and vanes. Thermomechanical fatigue testing offers several advantages. It can be conducted with a wide range of strain-temperature histories. It can be applied for material selection, and it can be used to evaluate the capability of life prediction models. Life prediction models for non-isothermal conditions can generally be classified into conventional engineering models and physically based models. Conventional engineering models are based on the extension of models proposed for isothermal fatigue conditions. Because of the shortcomings and limitations of these models, physically based life prediction models are considered to be promising tools for accurate predictions under non-isothermal loading conditions. In GTs, coatings are currently applied to blades and vanes not only to protect the underlying base metal against erosion, oxidation, and corrosion, but also to act as thermal insulation. Coatings alter the fatigue and creep resistance of substrate materials /35/. The new process to predict thermo-mechanical fatigue life of high temperature aerospace engine alloy referred to TMF/TS-SRP is based on the total strain version of strain range partitioning, the bi-thermal testing technique for characterizing TMF behavior, and advanced viscoplastic constitutive models. Predicted lives are in agreement with experimental lives to within a factor of approximately two /36/. Advanced thermal life prediction methods employing high temperature, low cycle, thermal and mechanical fatigue for high strength oxidation resistant superalloys used in aerospace propulsion systems are based on strain controlled thermo-mechanical and load controlled, strain limited, bi-thermal fatigue tests /37/.

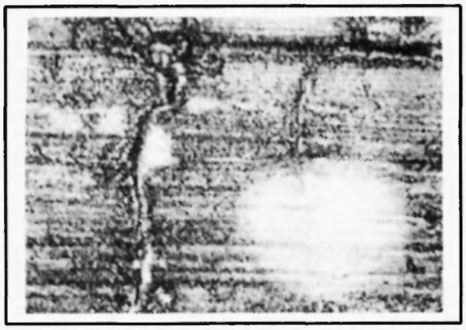
The cyclic life of IN738LC, when investigated under thermo-mechanical fatigue loading conditions, using a temperature variation range of 1023-1223K with a suitable temperature variation rate and constant mechanical strain ranges between 0.8-2% and at a constant mechanical strain rate of 10.5/sec, shows that the life under thermo-mechanical fatigue is strongly dependent on the nature of the test, i.e. stress controlled or strain controlled /38/. A model has been developed for predictions of thermo-mechanical fatigue crack initiation /39/. It estimates mode I growth of gas turbine hot section gas path superalloys. The model based on a strain density fracture mechanism approach has been modified to account for thermal exposure and single crystal anisotropy. Thermomechanical fatigue crack initiation and small crack growth have been modeled by employing an initial material defect size. Model capability is further quantified by applying to two hot section gas path superalloys: uncoated MAR-M509 and MCrAlY overlay coated PWA-1480. Thermo-mechanical fatigue model stresses have been determined from nonlinear finite element analysis of thermo-mechanical fatigue specimen strain temperature history. Non-linear stress-strain behavior has been predicted using unified viscoplastic constitutive models. Models used for thermomechanical fatigue life predictions are in good agreement with observed uniaxial thermomechanical fatigue specimen lives. Thermomechanical fatigue-cracking effects captured by the model include coating thickness, single crystal anisotropy, crystal wave shape, dwell, and thermal exposure.

The thermomechanical fatigue behavior of AMI nickel base superalloy single crystal is strongly dependent on crystallographic orientation. The cyclic stress strain response is influenced by variation in Young's modulus, flow stress, and cyclic hardening with temperature for every crystallographic orientation. The main crack initiation mechanisms depend on the mechanical strain range. Oxidation induced cracking is the dominant mechanism in the lifetime of interest for turbine blade /40/.

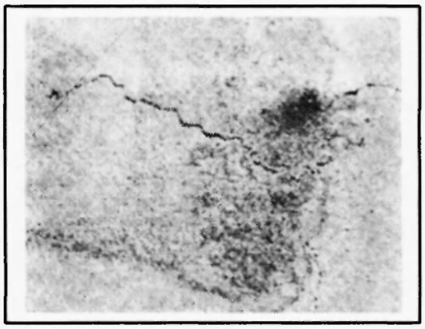
During startup, steady state operation and shutdown gas turbine disks and blades made of superalloys are subjected to high-strain, low cycle fatigue due to the strain-temperature cycling which often leads to the failure of these critical components. The thermal-mechanical fatigue (TMF) test is an important method to simulate the cyclic stress-strain behavior and damage process of these components in service. The thermal mechanical fatigue life of a real component is comparatively shorter than that of isothermal fatigue (IF) at the maximum temperature and corresponding strain amplitude. The thermal-mechanical fatigue behavior of cast K 417 nickel based superalloys when investigated under in-phase and out of phase loading in the temperature range from 673-1123K reveals that the tendency to cyclic hardening under thermal-mechanical and isothermal fatigue is higher than that under static tensile testing at 1123K. Isothermal fatigue causes higher cyclic flow stress than TMF. At corresponding strain amplitude, the thermal-mechanical fatigue life is lower than that of isothermal fatigue and the TMF life of out-of phase cycling is higher than that of in phase cycling. Scanning electron microscopic observations of fracture surfaces and longitudinal sections have revealed intergranular fractures under in phase TMF that lead to the decrease in fatigue life /41/.

Thermal fatigue

Fatigue failure often occurs by fluctuating thermal stresses without mechanical stresses. Thermal stresses originate from the change in dimensions as a result of a temperature change. If failure occurs by one application of thermal stress, the condition is called thermal shock. However if failure occurs after repeated applications of thermal stress of a lower magnitude, it is called thermal fatigue. Thermal fatigue is frequently encountered in high temperature equipment as shown in Figure 7(a) and 7(b). Thermal shock and thermal



7(A)



7 (B)

Fig. 7: (a) Thermal fatigue cracks on a gas turbine vane surface /13/
(b) Thermal fatigue cracks on a hastelloy-X sample surface /13/

fatigue test methods are employed for screening candidate materials for thermal shock applications. The method involves electron beam heating of the surface of specimens using a thermal flux equal to that experienced during actual service operations. Computer-controlled electron beam radiation can be used for determining thermal shock resistance of turbine blade material as well as rocket engine /42/. Thermal fatigue degradation of cast IN-100 nickel base alloy has been studied by an induction heating procedure coupled with an advanced alternating current potential drop system (ACPD). The respective stress-strain histories have been determined from thermo-elastic-plastic finite element analysis. The surface degradation depends on (i) scalloping and (ii) through thickness cracking of a uniform oxide layer. The degree of scalloping depends on the magnitude of compressive strain at the surface. Severe scalloping is reported after 3000 thermal cycles between peak strains of –0.48% at 1323K and +0.08% at 673K whereas more than 3000 cycles between peak strain of –0.24% at 1323K and 0.23% at 673K do not produce scalloping. The number of cycles to crack initiation is found to correlate with peak compression strain. Mechanism of scallop initiation and growth involves cyclic oxidation cracking and cyclic ratcheting /43/.

Methods for thermal fatigue testing of specimens with coatings in vacuum have been developed. Microcracks at different location have been observed in outer layers of CoCrAlY coating and inner layer of CoN-CrAlY coatings. Separation of CoNiCrAlY coating through intermediate a-Cr layer has been observed. The introduction of plastic intermediates layers between the base material (EP220, EP539) and CoCrAlY coating increases the life of alloy coating compound /44/.

Based on the interaction between thermomechanical fatigue and matrix oxidation in a cyclic thermo-mechanical loaded IN 738 LC superalloy at 673-1173K in air an attempt has been made to explore the mechanism of thermo-mechanical fatigue of turbine blades. SEM images indicate general as well as referential matrix oxidation of interdendritic and intergranular areas. It is suggested that the mechanical strain range influences the general matrix oxidation. It is found that the change in sheet thickness does not significantly alter thermal fatigue life of polycrystalline nickel based superalloys 263 sheets. Scanning electron micrographs revealed that out-of-phase non-isothermal fatigue (resulting from thermal stresses) assisted by grain boundary oxidation is the main mechanism of failure in these tests /45/. Failure of EB-PVD, thermal barrier coating (TBC) as shown in Figure 8 deposited on a single crystal superalloy with a platinum aluminide bond coat has been studied as a function of thermal cycling temperature and cycling time in order to determine the specific mechanism leading to TBC spallation /46/. The stress in the TGO is measured using photo-luminescence spectroscopy (PL-PS) during cyclic oxidation tests at 1373, 1404 and 1424K. The measured TGO stress remains relatively constant at failure of the TBC specimens for the various temperatures examined. The residual stresses in the TGO evolve with cycles. The evolution is qualitatively similar at the different cyclic temperature. The rate of evolution is relatively insensitive to time and temperature and seems to depend primarily on cycles. Cyclic plasticity and ratcheting are most likely responsible changes. The failure occurs more frequently at the TGO to metal interface with increasing temperature. All failures are edge-

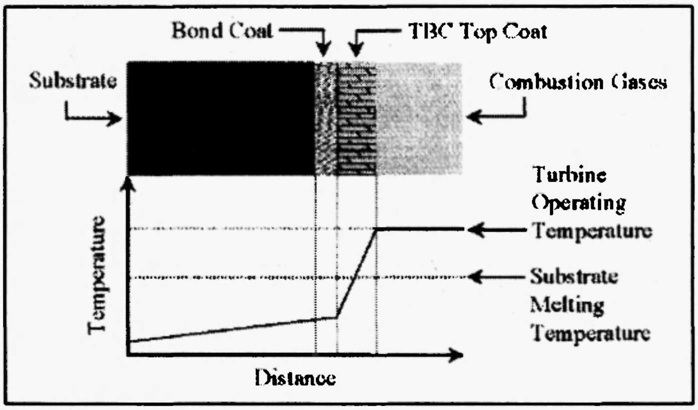


Fig. 8: A schematic cross section of thermal barrier coating (TBC) systems, and Temperature profile in a gas turbine /13/

connected in nature /47/. On the other hand sodium within sheet metal construction for valves relieves thermal stresses of superalloys (NO-6601, 60% Ni) that is operating at 1223K /48/.

Corrosion fatigue

A nickel base superalloy has been subjected to different waveforms of loadings, fatigue, creep, and three kinds of combined creep-fatigue to study the effect of hot corrosion on the strength properties and fracture behavior. Tests have been performed at 1073K on Inconel 751 specimens coated with a synthetic salt mixture composed of 90% Na_2SO_4-10% NaCl. The hot corrosion induces serious degradation of the rupture life, depending on the loading conditions. In particular, the combined creep-fatigue tests result in a minimized rupture life in the corrosive environment, while monotonic creep cause the most prolonged life. A fatigue component is found to be responsible for the corrosion induced premature fracture, together with a creep component. The hot corrosion environment also leads to intergranular fracture in a brittle manner regardless of the loading conditions which is directly caused by the stressenhanced intergranular penetration of sulphides, oxides and or chlorides /49/. The corrosion rate of the alloy IN-657 in the presence of a molten mixture of 60% V2O540% Na2SO4 has been determined for the temperature range 950-1050K, in both oxidizing and inert atmospheres /50/.

The hot corrosion resistance of yttria stabilised zirconia (YSZ) thermal barrier coatings (TBCs) system can be improved by depositing an overlay of alumina on the surface of TBC using the EB-PVD and the high velocity oxy-fuel (HVOF) techniques. It has been established by hot corrosion test on the TBCs with and without the alumina-overlay in the molten salt mixture (Na_2SO_4 + 3%V_32O_5) at 1223K for 10 hrs. The microstructure of TBC and overlay before and after exposure of hot corrosion when examined by means of scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) shows that the YSZ reacts with V_32O_5 to form YVO_3. As a result a substantial amount of M-phase of ZrO_2 is formed within YSZ without the alumina overlay. In contrast for the TBC/alumina composite coating, the dense and compact alumina overlay isolates the YSZ from the attack of molten salt and arrests the penetration of salt into the pores and cracks in the TBC. The densification of the YSZ (formation of M-phase within YSZ) is remarkably refrained due to the presence of alumina-overlay, especially for the composite coating with the alumina overlay deposited by HVOF. The HVOF alumina-overlay is denser and more compact than the EB-PVD one, consequently fewer cracks are found within the HVOF alumina-overlay and at the YSZ/alumina interface after long-term exposure to molten salt /51/.

Erosion is an additive effect to corrosion. Figure 9 shows the erosion rate at different conditions /52/.

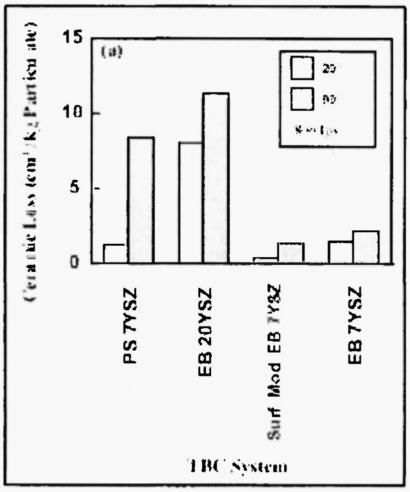


Fig. 9: Ceramic erosion test results for the candidate materials /52/.

CONCLUSION:

Fatigue failure occurs without prior indication and is difficult to predict. The slip band phenomenon initiates the fatigue crack/failure. Metallurgical fatigue failure is a complicated inter-variable which depends upon the type of fatigue, metallurgical microstructure, temperature of exposure, frequency of application, corrosion etc. over the large variation of stress, period, and cycles of exposure.

Fatigue strength is improved by decreasing temperature and high temperature corrosion rate using thermal barrier coatings. Thermal insulation by ceramic coatings on quaternary bond coating improves fatigue strength and reduces corrosion rate. Selection of superalloy composition and fabrication occupies important position for an aggregated service life. A high strength metal at high temperature may not perform better under dynamic loading in hot aggressive environment of gas turbine. A thermal fatigue resistant metal may or may not provide strength under thermomechanical and creep fatigue process. A metal may have corrosive strength but may not have strength under fatigue. Application of insulation coating on corrosion resistant bond coat over thin section components made of existing super alloys draws interest for increasing life at a marginal increase of efficiency by operating at higher temperature and maximum utilization of fuel.

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