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Methodology for Application of Damage Mechanics Approach to Model High Temperature Fatigue Damage Evolution in a Turbine Disc Superalloy

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ABSTRACT

Aeroengine gas turbine components operate under complex loading environments. Turbine disc is one such component which experiences stresses at high temperature and accumulates life critical cyclic damage in the material during usage. This accumulation of cyclic damage results into significant deterioration in material strength which in turn may initiate the failure in these rotating components. This necessitates the need to develop an advanced lifing approach for fatigue life assessment of turbine disc. As there are no available standards for damage mechanics application, an attempt has been made in the present study to develop a methodology for application of damage mechanics approach to model high temperature fatigue damage evolution in a turbine disc Superalloy. High temperature (650 °C) stress-controlled fatigue tests on turbine disc alloy have been performed to evaluate parameters for damage mechanics based models. Using this approach, damage evolution has been simulated at specimen level. A good correlation has been observed in the damage mechanics based model's predicted damage and experimentally determined values.

Keywords: Methodology; Damage mechanics; Fatigue; Turbine disc superalloy

1. INTRODUCTION

1.1 Life Prediction of Aero-Engine Alloys

In the recent times, variety of life assessment techniques has been evolved. This has largely been driven by the need for maximum possible utilisation of the intended life of aeroengine[1]. Damage Mechanics, Damage Tolerance and Safe-Life based lifing procedures (Fig. 1) are some of the best known life assessment methodologies for aeroengine components.

While safe life-based approach has been used in legacy designs, it has limitation in its conservative estimation which results into higher safety factor and overdesigned components. On the other hand, damage tolerance based lifing approach is based on the assumption that unknown manufacturing defects are likely to grow in-service. Therefore, the total technical life is estimated as a fraction (typically 1/2) of the cycles required to grow the crack to a critical crack size. The component is discarded from service even if such defect remains undetected. This results into wastage of costly inventory. Hence, a need is felt to develop a more advanced lifing approach which can mitigate these limitations and enhance component life prediction.

The advances in modeling and simulation techniques as well as material and defect characterization techniques have collectively resulted in a strong conviction that the presence of defects as well as its type and distribution inside the material dictates the mechanical response of components[2]. It was observed that significant deterioration occurs in material strength before a crack is detected. This lead to the development of damage mechanics based lifing approach (Fig. 1) for critical gas turbine components.

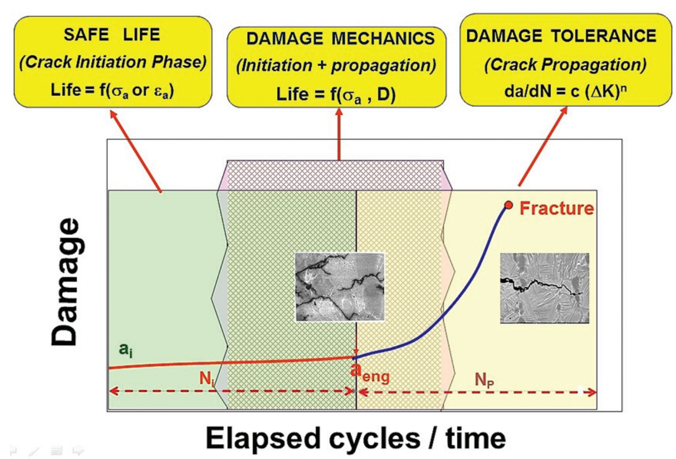

Figure 1. Life prediction methodologies.

1.2 Damage Definition and its Evaluation

Damage Mechanics (DM) is an analysis driven methodology. In this methodology, coupled deformation-damage models, through special constitutive equations are used to quantify evolving damage. All DM models feature a special internal variable that quantifies the local micro-crack density. Further a kinetic equation is defined for the evolution of damage with applied load/stress/strain or cycle or time. By

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definition, damage is the progressive physical process by which materials fail[3] and DM explains this deterioration of materials under load/stress/strain, through mechanical variables. Several models[4-8] have been proposed in literature to describe the onset of damage and its evolution with different loading types.

The process of damage evolution (quantified as D) in a material of a specimen is generally considered as the generation and growth of micro-defects in the material. The effective load carrying cross-sectional area of the specimen gets reduced due to these microscopic deterioration[9]:

$$D = 1 - \left(\frac{\bar{A}}{A}\right) \quad (2.1)$$

Where, $\bar{A}$ and A are the effective cross-sectional area and the overall cross-sectional area, respectively. The procedure for microscopic damage measurement is very tedious. Hence, it has now become a general practice to deduce damage from its influence on measurable physical/mechanical responses. Measurement of stiffness/modulus, cyclic plasticity, ultrasonic velocity, micro-hardness and electrical resistance[3] are some of the established methods for damage quantification.

The above defined damage is further integrated into mechanical response through the effective stress concept[10-11]. The effective stress $\tilde{\sigma}$ is defined as the force P, which acts on the effective cross-sectional area i.e. $\bar{A}$:

$$\tilde{\sigma} = \frac{P}{\bar{A}} = \frac{\sigma}{1-D} \quad 2.2$$

where, σ is the applied stress. Damage mechanics further defines a concept of strain equivalence. The strain equivalence states that the strain associated with a damaged state under applied stress is equivalent to the strain associated with an undamaged state under effective stress. Thus by applying this concept, the Hooke's law of a damaged material can be written in the following form:

$$\varepsilon = \frac{\tilde{\sigma}}{E_0} = \frac{\sigma}{E_0\,(1-D)} \quad 2.3$$

where ε is the elastic strain and E_0 is Young's modulus of undamaged material.

Let $E_D = E_0(1-D)$ 2.4

where, E_D is Young's modulus of damaged material. Now the damage parameter, D, can be written as:

$$D = 1 - \frac{E_D}{E_0} \quad 2.5$$

The damage parameter associated with change in elastic modulus is applied for capturing irreversible changes (micro-plasticity, microcracks or crack propagation) in the properties of materials during cyclic loading conditions[12].

1.3 Damage Mechanics Methodology

Generally, Damage Mechanics (DM) based methodologies have been categorized into two approaches[13]: Micromechanics and Phenomenological. The focus of the micromechanics approach is to determine the combined effect of damage manifestations, such as voids and micro-cracking at the mesoscale and then establish a functional relation between the random heterogeneous microstructures and the material behavior at the macro-level[4-5,14]. On the other hand, phenomenological approach[6-7,15] uses macroscopic internal variables to represent the effects of damage at the continuum level. The Representative Volume Element (RVE) concept is very important in describing the process of damage evolution in both approaches. DM generally refers to the phenomenological approach to study damage[13]. The advent of powerful computer-aided numerical methods of structural analysis has resulted in extensive exploitation of the FEM for damage analyses. The localized nature of damage evolution is readily amenable for efficient computation by FEM. The damage models may be incorporated into the main FEM code[16-17] or made to function concurrently with a standard commercial FEM solver such as ABAQUS[18-19] through a user subroutine.

As per damage mechanics approach, progressive damage accumulated during loading is evaluated in the material till this damage reaches a critical value. To conduct fatigue simulations, two types of models are required. First is deformation or constitutive model and second is damage model. These deformation and damage models are finally coupled to simulate fatigue loading in a laboratory scale specimen. Basic steps involved for implementation of damage mechanics methodology are summarised as:

- Specified mechanical tests with online damage assessment
- Damage evolution curve from online damage data
- Damage parameter evaluation from the damage evolution curve
- Deformation parameter identification from experimental data
- Implementation of damage and deformation parameters into finite element models
- Experimental validation of simulation of damage evolution.

1.4 Coupled Model for Fatigue Damage Simulation

As per the theory of damage mechanics, there exists a state coupling between elastic strain and damage. This is due to the fact that elasticity is directly influenced by damage. On the other hand, damage affects plasticity due to decrease in the elemental area of resistance. However, it is assumed that damage does not influence the slip mechanism directly. Hence, a kinetic coupling exists between damage and plasticity[3]. The fatigue damage model applied in the present study works on the principle of effective stress and strain equivalence concepts[18, 20,21] and hence can also be coupled with deformation models. In this fatigue damage model, damage (d) is integrated as a function of the equivalent inelastic strain (p):

$$\dot{d} = \dot{p}\left(\frac{Y}{S_o}\right)^{s_o} \quad (2.6)$$

where, is the damage rate, $\dot{p}$ is inelastic strain rate, S_0 and s_0 are material constants and Y is strain energy density release rate.

In the framework of damage mechanics, damage coupled elasto-plastic constitutive model is used for study of plasticity by incorporating the damage (loss of load carrying capacity) into the constitutive equations[16]. The Chaboche plasticity model[22] is one such model. This simple model has been shown to be capable of excellently capturing cyclic deformation (elastic, elastic-plastic or visco-plastic) behaviour of materials[22-24]. In

Table 1. Chemical composition of the Ni-base superalloy (wt.%)

Chemical composition in %											
C	Cr	Cu	Ti	W	V	Mo	Al	Nb	Co	Fe	Ni
0.05	14.0	0.02	2.5	0.02	0.01	5.0	3.0	3.0	9.0	0.4	Bal.

Table 2. Tensile properties of the alloy at 650 °C

0.2% YS	UTS	% Elongation	% Reduction of area
820	1200	25.0	25.0

the present work, same model has been used using the Zebulon software 8.4.2[25]. The software has been designed for modelling of coupled damage models.

This Chaboche model comprises of two major components, i.e., isotropic and kinematic hardening:

Isotropic hardening $$\sigma = Ro + Q(1 - exp(-bp)) \quad 2.7$$

The onset of plasticity is defined by Ro (the cyclic yield stress). The positive value of Q describes isotropic hardening, while negative Q outlines softening in the material during loading. b is the convergence rate to Q and p is accumulated plastic strain.

Kinematic hardening $$X = \left(\frac{C}{D}\right)(1 - exp(-Dp)) \quad (2.8)$$

where the asymptotic value of back stress is expressed as C/D. The convergence rate for C/D is defined as X.

2. MATERIAL: TURBINE DISC SUPERALLOY AND ITS BASIC PROPERTIES

As a first step towards application of damage mechanics methodology, evolution of high temperature fatigue damage in a turbine disc Superalloy has been analysed in the present investigation. The present study were carried out on an aeroengine turbine disc alloy, which is a wrought Ni-base Superalloy. The chemical composition of the turbine disc alloy in wt. % is given in Table 1. This alloy in fully heat treated condition consists of γ' (gamma prime) precipitates distributed uniformly throughout the γ –matrix (Fig. 2a). The micrographs in Fig. 2b show the presence of uniformly distributed primary (coarse) and secondary (finer) γ' (gamma prime) precipitates throughout the matrix (γ). The primary γ′ precipitates are near cuboidal in shape, while the secondary γ′ precipitates are irregular in shape. For this alloy, the tensile properties at 650 °C are mentioned in Table 2.

3. HIGH TEMPERATURE FATIGUE TESTS: DEFORMATION AND DAMAGE MODEL PARAMETER IDENTIFICATION

To evalaute the damage and deformation model for fatigue from experiments a scheme has been evolved (Table 3). The fatigue samples were extracted from turbine disc in the manner shown in Fig. 3(a).

The fatigue deformation parameters (isotropic hardening, kinematic hardening, cyclic yield point) have been identified/calibrated from strain controlled LCF fatigue tests at 650 ^{o}C under fully reversed cyclic loading condition for a total strain amplitude of 1 % with 0.5 Hz frequency. For fatigue damage parameters, in situ damage assessment (cyclic modulus) has been done on samples tested under stress controlled fatigue tests at 650 ^{o}C. Both stress and strain controlled fatigue tests were conducted as per ASTM standard E-606 on cylindrical specimens (15 mm gauge length and 6.35 mm gauge diameter), as shown in Fig. 3(b). Stress controlled pure fatigue tests have been performed incrementally at an applied peak stress (Stress ratio=0.1) of 600, 700, 750, 800, 850, 950 and 1000 MPa as

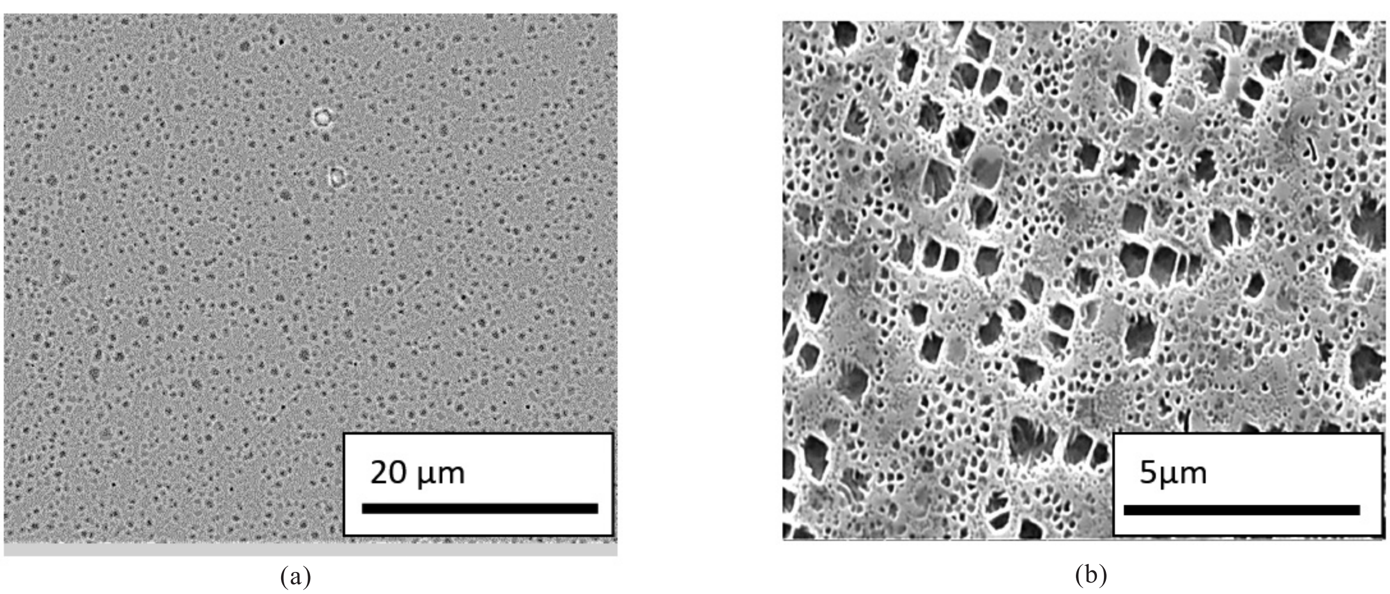
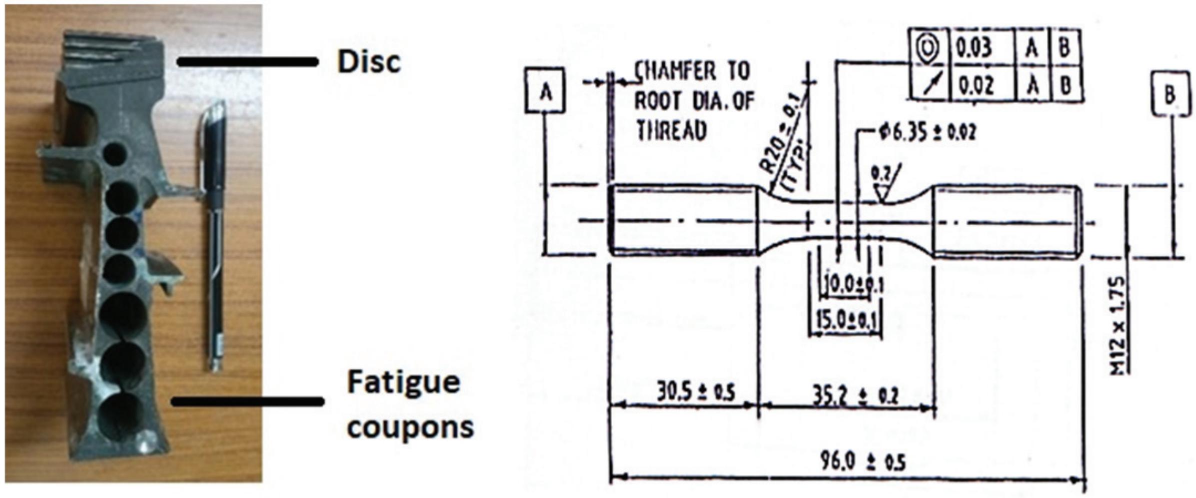


Figure 2. (a) SEM micrograph shows the distribution of γ′ precipitates in γ matrix, (b) SEM micrograph shows the uniform distribution of primary (coarse) and secondary (finer) γ' (gamma prime) precipitates throughout the matrix (γ).



(a) (b)

Figure 3. (a) Sample extraction from disc (b) LCF test sample (All dimensions are in mm).

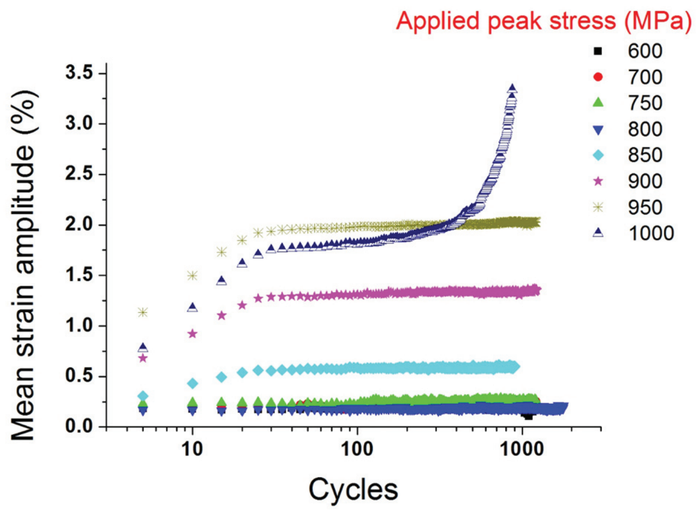


Figure 3. (c) Mean strain amplitude curves for samples tested under different applied peak stresses during incremental stress controlled fatigue tests at 650 °C.

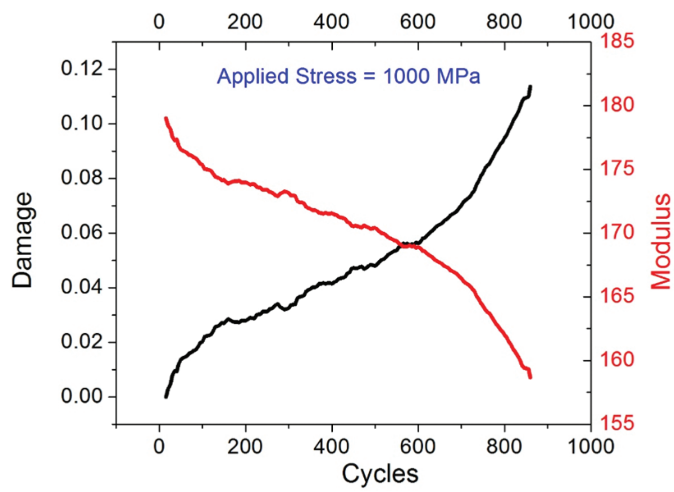


Figure 3. (e) Damage evolution curve for samples tested under 1000 MPa peak stresses during incremental stress controlled fatigue tests at 650 °C.

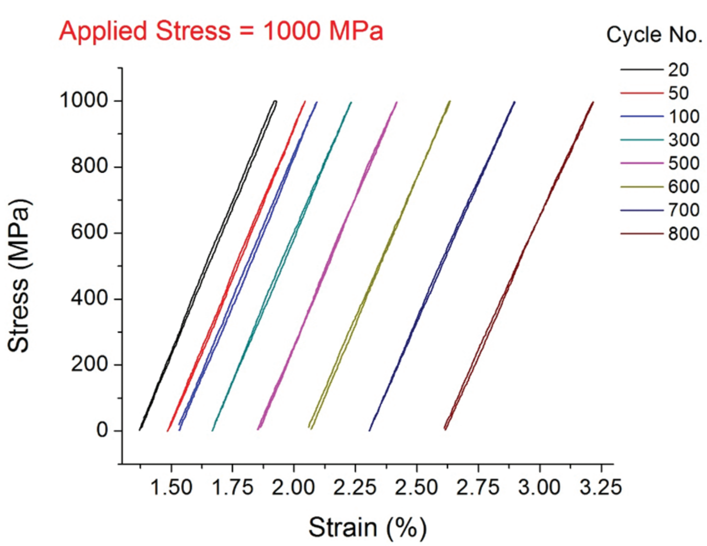


Figure 3. (d) Stress-Strain curve for sample tested at peak stress of 1000 MPa.

shown in Fig. 3(c). It has been observed that the present alloy exhibits cyclic ratcheting effect during stress-controlled fatigue loading (Fig. 3(d). Due to cyclic ratcheting, a movement of cyclic stress–strain loop occurs[26-27]. To maintain the imposed constant stresses, this horizontal movement, i.e., an increase in strain with each cycle arises. At all stress levels except at 1000 MPa, sample has exhibited cyclic strain hardening behaviour (Fig. 3(c) in the initial cycles, followed by a reduced rate hardening. While at peak stress of 1000 MPa, initial hardeing and plateau has been observed, a new phase of increased hardeing was also observed. This increased strain indiactes increased rate of deformation and damage in the material[28]. For damage evolution curves, damage values have been evaluated from cyclic modulus as per equation 2.5. A damage evolution curve vis-à-vis cyclic modulus for each cycle is plotted in Fig. 3(e) for the duration of test at 1000 MPa peak stress. The damage has been found to increases with the increase in fatigue cycles. As explained in section 1.4, strains are damage drivers and a kinetic coupling exists between these two parameters**.** So

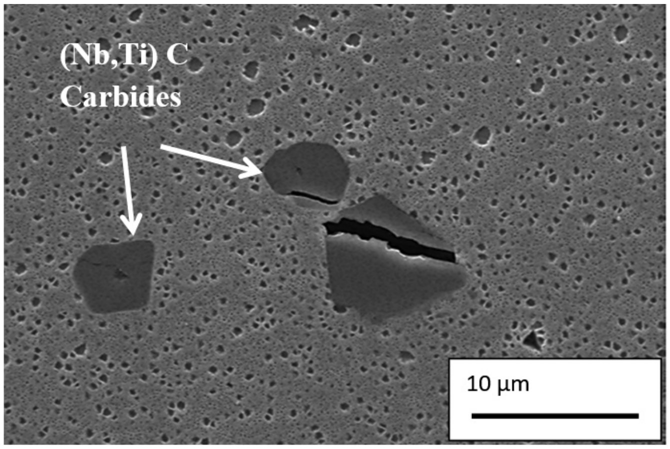


Figure 3. (f) Fatigue damage feature in the present alloy.

as the strain increases in the sample, the damage also increases consequently. The advantage of damage mechanics over other methodologies is the cumulative damage assessments. The damage at the end of one set of stresses becomes the initial damage for next set of applied stress tests. This is important in cases where sequence of stress plays an important role in determining the overall life and safe operation of an aeroengine component.

The fatigue damage in the present alloy has been mostly found in the form of voids and microcracks on NbC particles as shown in Fig. 3(f). These MC type carbides are randomly distributed in pockets predominantly within the grains. The MC carbides are coarse and their morphology is irregular and blocky. They present the perfect site for damage evolution in this type of Superalloy[29].

4. FINITE ELEMENT MODELING: SIMULATION OF FATIGUE DAMAGE EVOLUTION

The next critical step in application of damage mechanics methodology is to perform finite element simulation using coupled models. In the present study, damage simulations have been performed at specimen level using experimentally evaluated parameters (Table 3). In the present study, FEA software packages Zebulon 8.0 and ABAQUS 6.11 have been used to perform numerical simulation of fatigue damage. For creation of 2D models and subsequent meshing using ~2600 nodes and ~2400 c2d4r elements of ~1 mm size, ABAQUS software has been employed (Fig. 4(a). Thereafter, the meshed solid model (Symmetrical half vertical section) is transferred to DM-based FEA software Zebulon. In Zebulon, constitutive

Table 3. Damage and deformation parameter identification

Property	Model parameter	Values
Young's modulus	E	180 GPa
Cyclic yield point	R_o	800 MPa
Isotropic hardening	Q, b	148.0 MPa, 8.9 MPa
Kinematic hardening	C,D	41.4 MPa, -0.4 MPa
Fatigue damage	S_o, s_o	5.0, 1.0

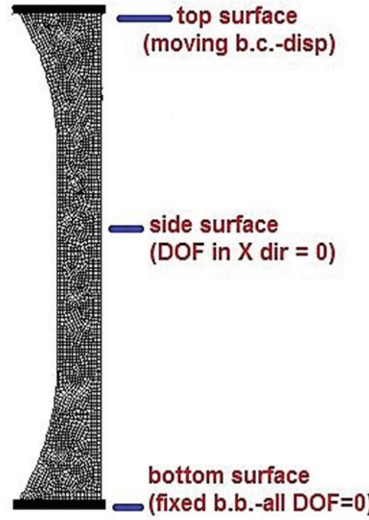


Figure 4. (a) FEM model of the specimen: mesh and boundary conditions.

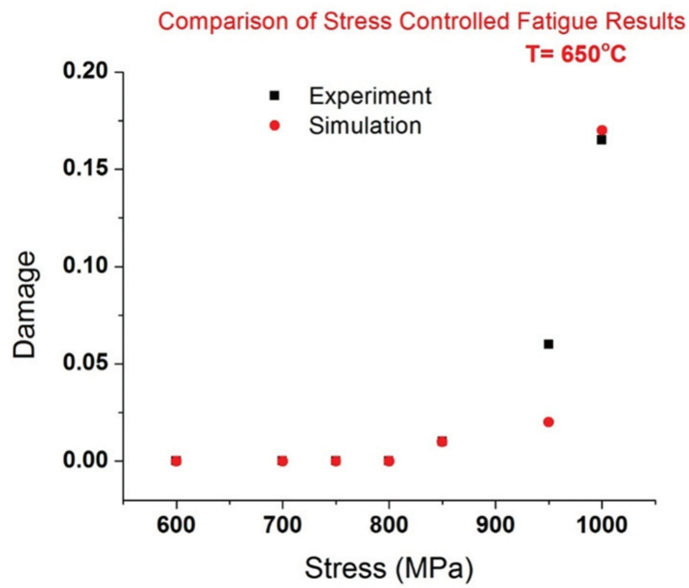


Figure 4. (b) Comparison of damage for experiment and simulation.

behavior of material in terms of damage and deformation parameters is defined for further analysis and it is the only available software where such coupling is allowed.

For identification of fatigue damage and deformation parameters (Eqn. 2.6 - Eqn. 2.8) from experiments, MATLAB software has been comprehensively used in the present study (Table 3).

Using the damage and deformation parametersthus identified (Table 3) fatigue simulations are performed at specimen level. Simulation outputs in terms of stress and damage have been obtained from Zebulon software. To validate the coupled model's predictive capabilities, experimental data is compared with simulation outputs. Damage accumulated at each applied stress level is compared against the experimental values (Fig. 4(b).

Significant damage has been observed only after 850 MPa i.e. after yield stress of the alloy at 650 °C. A very good correlation between simulated and experimental damage values has been observed for all stresses except 950 MPa. The variation in predictions might have arisen due to inability of the model to capture very large damage in the form of microcracks[30]**.** In spite of this difficulty, the present study was able to demonstrate the overall methodology for application of damage mechanics approach to model high temperature fatigue damage evolution in a turbine disc superalloy. This study also substantiates the fact that the damage mechanics based model is valid for other alloys in its present form[30]. This model is applicable to different stress levels and strain control fatigue damage[17].

The damage mechanics based life prediction methodology is also being extended to perform and predict evolution of fatigue damage in other aeroengine disc alloy[31-32].

5. CONCLUSIONS

- In the present study, a methodology for application of Damage mechanics approach has been presented to model high temperature fatigue damage evolution in a turbine disc Superalloy. The damage and deformation model parameters have been identified by conducting high temperature (650 ^{o}C) stress controlled fatigue tests on turbine disc alloy
- Coupling deformation and damage, a fatigue model has been evolved for a turbine disc superalloy of a fighter aircraft. Fatigue damage evolution was simulated at specimen level using the experimentally evaluated model parameters
- Using the developed fatigue model, stress controlled fatigue condition has been simulated and the total accumulated fatigue damage has been obtained. A good correlation between model predicted and experimental damage values has been observed in the present study.

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In the current study, he guided in reviewing the manuscript and providing valuable inputs.