Effect of mean stress, stress concentration and inclusion on fatigue of different materials

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ABSTRACT

Fatigue properties of materials are considered as an important parameter while selection of materials. Predominant material properties play an important role in estimating the remaining service life of critical components. The most common phenomenon of damaging metallic materials is fatigue. The fatigue is weakening of material caused by repeating & heavy loads. This is gradual and local damage to the structure that occurs when the material is periodically loaded. Fatigue may result in cracks which may cause fracture of material after sufficient number of fluctuations. Therefore, prevention of material from fatigue cracking is necessary. The fatigue crack develop due to parameters such as mean stress, stress concentration and inclusion were discussed. This paper reviews various experiment carried by different researchers on effect of mean stress, stress concentration and inclusion on fatigue of different materials were analyzed, studied and presented in this paper. The purpose is to identify effects of parameter such as mean stress, stress concentration and inclusion on fatigue to increase material resistance in various conditions.

KEYWORDS

Fatigue,
Mean Stress &
Prediction of Life,
Stress Concentration &
Inclusion.

1. Introduction

The use of modern materials is currently used in the manufacture of many components, such as gears, crankshaft and machinery equipment and so on. This component has several repetitive loads during operations, and most of them did not withstand fatigue. Therefore, the material prediction of life is very important. Fatigue is the failure of material, when materials are subjected to repeat cyclic loading. The failure may occur when applied stresses are much less than the maximum stresses. Fatigue may result in cracks. These cracks are microscopic in the beginning, at each load cycle cracks grows in size and finally leads to fracture. For over 150 years, the stress approach has been developed as a technical effort to prevent fatigue. In recent years, several new approaches have emerged based on strain and fracture mechanism [1].

The fatigue compound mechanism is damaged in the same direction depending on the loading mode. An important result of the fatigue life cycle is the definition of the limits of fatigue. The highest resistance to fatigue is achieved when the composite is only a unidirectional fibre and represents by directional fibre loading [2]. It was experimentally found that the fatigue crack growth rates at notches were higher than the one predicted by elastic solutions for short cracks indicating that the single parameter i.e. stress intensity is not capable of prediction of growth rates for very short cracks [3]. An analysis was made of the growth of fatigue crack along the metal ceramic interface and it was found that the crack growth was carried out at cyclic loading in single crystal [4].

Most of materials exhibit the same behaviour, as the fatigue strength decreases with an increasing average stress [5]. Thus, mean stress affect the fatigue life of component. The microscopic cracks initiate at a point of stress concentration. Increasing the top stresses around holes,

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grooves, Cracks, sharp corner and other changes in area are called stress concentration. Failure of material can occur via propagation of cracks when the concentrated stress is greater than the intermolecular strength of material. The geometric features of secondary stresses area successfully minimize the effects of stress concentration. The material defects occurs during manufacture was main reason of inclusion. Different types of inclusion and it's effect on fatigue was reviewed [6,7]. Usually, the fractures due to fatigue or the cracks are initiated from the surface of metals or are due to the inclusions present in the surface layers. In case of very high cycle fatigue fractures the reason behind the development of cracks is the presence of inclusions below surface layers.

The aim of this paper is to summarize the effect of fatigue causes due to parameters such as mean stress, stress concentration and inclusions. The purpose of this paper is to focus on the idea of developing the technologies for increasing fatigue strength, in addition to the strength of the material. The goal is to enhance material properties to increase material resistance in various fatigue conditions.

2. Effect of Mean Stress

Mean stress affect the fatigue life of component. In order to take into account the influences of mean stress on the service life, a new model of the average fatigue stress is proposed, based on strain energy [8]. Authors compare the proposed model with the marrow and Smith-Watson Topper (SWT) mean stress correction model. Five experimental fatigue data were used for cast iron 120-90-02, ASTM A723 steel, 1045HRC 55 steel, 7075-T561 and 2024-T4 aluminium alloy with moderate tensile and compressive stress. The proposed damage model is given by equation (1)

$$W_{gen}^{dev} = (S_{max,i}e_{a,i}^{e} + S_{a,i}e_{a,i}^{p})_{max} = f(N_f) \qquad (1)$$

A large positive mean stress ($\delta_{max}>0$), negative mean stress ($\delta_{max}<0$) and zero mean ($\delta_{max}=\delta a$) conditions were applied in above equation. It was observed that proposed mean stress correction model and SWT model gave similar results and provides good correlation for positive and negative mean stress. But, in a case of higher compressive mean stress, the proposed model shows a relatively good correlation, whereas SWT model does not correlate the fatigue data. The marrow model provides low correlation and conservative results for compressive stress and non-conservative results for tensile stress. The fatigue life of metal can be predicted, when the mean stress parameter is modified into dissipated strain energy by introduction of two mean stress correction factor [9]. A modified TSED model is proposed that takes account the effect of mean stress on fatigue life prediction. The accuracy of proposed forecast model is compared with model of damage parameter generated by walker, SWT, Morrow. The proposed model looks better than other models discussed in this paper under uniaxial/compressive mean stress condition. For 316 stainless steel, the effect of mean stress on service life and the fatigue limit was investigated [10]. It was concluded that the correction of mean stress is not required in the areas where the cyclic load is controlled and ratcheting strain is limited. The case study done by Swapnil V. Kumbhar and Mr. R. M. Tayade [11] concludes that mean stress affects the fatigue life of component. By using effect of mean stress proposed by different theory like morrow rule, SWT relation & Gerber Goodman Soderberg relations, the author estimate effect of mean stress on fatigue life of component. By Numerical justification author proved that as mean stress increased, life of component gets reduced. Stress & strain for different condition is calculated from equation (2).

$$\frac{\Delta\varepsilon}{2} = \frac{(\sigma_f' - \sigma_{mean})}{E}\ (2N_f)^b \qquad (2)$$

σ_f'=fatigue strength coefficient =1100Mpa, b=fatigue strength exponent=-0.005, N_f=Number of reversal cycle.

The effect of mean stress based on exponential stress approach was discussed [12]. The proposed relationship between fatigue strength and mean stress is linear. It was used directly where, the mean stress decreases the fatigue strength or durability or when fatigue behaviour can improved by compressive mean stress. The strength and ability to predict the life of this approach improved the stress based model and has proven to be effective towards SWT based approach.

Constant line diagram (CLD) is plotted by taking the combination of stress amplitude and mean stress at different life cycle value [1]. Weiying Meng and Co-authors [13] perform predictive study of exhausted life of notch fibers that have

Table 1
Laminate component material property.

Material	Elastic Modulus (GPa)	Poisson's Ratio
Metal layer	72.4	0.3
Fiber layer	54.6	0.252

strengthened Al-Li alloy laminate 2060 with constant life diagram under spectral loading. The first author reviews about CLD model in order to predict life of composite material which highlight the effect of accuracy. The fibrous 2060 Al-Li laminating alloy 2/1 structure and 3/2 structure were selected to perform load testing in this paper. The laminate component used in this test is tabulated in Table 1.

The results showed that Goodman and Piecewise linear model have same advantages over other complex models for predicting the life span of laminated position with different designs from load of mini-twists. The forecast for S-N curves, based on Piecewise model, is most appreciated and accurate of all models. Designed for composite materials CLD models can be effectively used to predict the life span of notched metal fibers under mini-twist load.

3. Effect of Stress Concentration

Increasing the top stresses around holes, grooves, Cracks, sharp corner and other changes in area are called stress concentration. It makes difficult to calculate stresses due to stress concentration. This can be achieved by replacing the sharp corner in high stress region with around groove, preferably with the maximum possible radius of groove. These steps are less expensive to build components, but they are much more expensive than damage to the site due to poor design [14]. As per study performed by A.M. Wahl & R. Beeuwkes [15], on stress concentration, the specimen used in these test was grooved specimen. A test sample was performed from a sample of Bakelite hardening. On each specimen fine scratches were made parallel to axis specimen, close to hole and notches. The purpose of providing these scratches was to determine true edges of holes & notches on the photograph. The distance from edge of hole or notches on the photography was measured by using microscope or a comparator. Then by knowing distance & actual magnification the true edges can be determine accurately on photograph. During these test, monochromatic light was employed, a mercury lamp with appropriate filter being used. In the case of larger hole with a diameter equal to the width of the bar, the stress concentration factor is equal to 2, when the lateral displacement of the smallest part of the bar is small relative to the thickness of section. The following empirical formula (3) and (4) for the stress concentration coefficient k gives the similar result as test result.

For a bar with a hole, under tension

$$K=3-3.13d/w+3.76(d/w)^2 \qquad (3)$$

For a bar with a notches, under tension

$$K=2.75-2.75d/w+0.32(d/w)2+0.68(d/w)^3 \qquad (4)$$

A design method developed in this study was to analyse the effect that occurs due to change in design load.

P. K. Mallick [16] studied the effect of stress concentration and its mitigation on the tensile strength of sheet molding compound (SMC-R50) composites with consideration being given to both centric & eccentric holes locations. Hole creates stress concentration in an area adjacent to the hole boundary and reduce the tensile load carrying capacity of the member. The material investigated in this study was on R50 sheet molding compound (SMC) composite containing 50% by weight of 25mm long chopped E-glass strands in a vinyl ester resin. Rectangular specimens, 100mm long by 25mm wide, were tested in static tension universal testing machine.

The result obtained from these experiments shows that tensile strength of the R50 material is improved by applying a transverse normal pressure around the holes boundary. The author from these tests addresses a simple method of mitigating the holes concentration in a member by applying a transverse normal pressure around the hole boundary. Three types of structurally modified epoxy adhesives were used to study the fatigue behaviour of notched sample by considering the effect of stress concentration [17]. Quasi-static and fatigue testing was carried out on an instron E300 and electrodynamic tester with a load capacity of +3KN. S-N curve for notched and un-noched sample are govern at a constant amplitudes and R=0.1 in the range from $N_f=10^3$ (LCF) to $N_f=10^6$ (HCF). It was observed that the presence of notches, especially in the case of HCF, reduces fatigue strength. Adhesive showed unusual value of notch sensitivity (q) with q for adhesive is much less than value of metal. It was observed that fatigue strength of notched sample is 62-78% and un-notched sample is 67-78% of tensile strength at $N_f=10^3$. Moreover fractography results shows that availability of voids near notches.

D. Arola and C. L. Williams [18] estimate the fatigue concentration ratio for machined surfaces. The specimen used to evaluate fatigue strength is AISI 4130 CR steel. Omax model 2652 abrasive water jet (AWJ) is used to process the fatigue specimen from AISI 4130 sheets. To analyze the texture obtained by processing AWJ, author used the contact prototype Hommel T8000 with diameter of 10µm diamond probe. Samples experienced axial fatigue at a constant amplitude and tensile stress using MTS 810 stretching/twisting frame. The entire fatigue test was performed under load control in a form of sinusoidal load, a frequency of 12 Hz and a stress ratio (R) of 0.1. After each sample failure, record number of sample failure and inspect the deformation surface to determine the cause of failure. The fatigue concentration (kf) of a machined surface determine from experiment was found to range from 1.01 to 1.08. The AWJ 4130 CR fatigue test result shows that the size of surface roughness affects the material strength. The rough surface of the crack and the visible wrinkles of the LCF specimen indicate that the destruction was mainly due to integration of internal defects. Timothy A. Furnish et. al. [19], studies fatigue stress concentration and notch sensitivity of NC materials. Two sets of nickel/iron (NiFe) NC film are coated with chemicals. A galvanic pulse method is used, which provides 1 second and 3 second cycles per second. In both the cases, NiFe was deposited on a thick Cu layer with a thickness of 100mm, which was electronically deposited on a titanium adhesive layer with a thickness of 20nm on a pad of Si. Fatigue test were performed on notched and un-notched samples at room temperature using specially designed thin film testing machine. In this study the fatigue test is configured to control the force, giving constant amplitude and a constant average sinusoidal load at a frequency from 4 to 7 Hz.

Result shows that all notched samples significantly reduced the fatigue life due to relatively high fatigue stress concentration and notch sensitivity of NC particles. Additional tests were performed in order to determine the limit at which the material becomes truly insensitive to the stress concentration from the notches. This shows that notched fatigue micro structure constantly demonstrates abnormal grain growth in all the samples at onset of rapture. In order to check weather, fatigue test result depend on stress concentration factor (SCF), an experiment was performed with a use of 1.4301 stainless steel sample [20]. The fatigue test was carried out on smooth and notched samples with three different fillet angles of shape factor 1.4, 2, and 2.6. The result clearly indicates that fatigue failure depends on geometry of sample. Notched sample have lower fatigue strength than smooth sample. The fatigue test results decreases with an increase in stress concentration. Moreover, high notch sensitivity are consider suitable for sample preparation technique. The carburising effect on the fatigue strength and notch sensitivity in AISI 316 austenic stainless steel was discussed [21]. Fig 1 shows S-N curve for notched carburize specimen in relation with maximum stress.

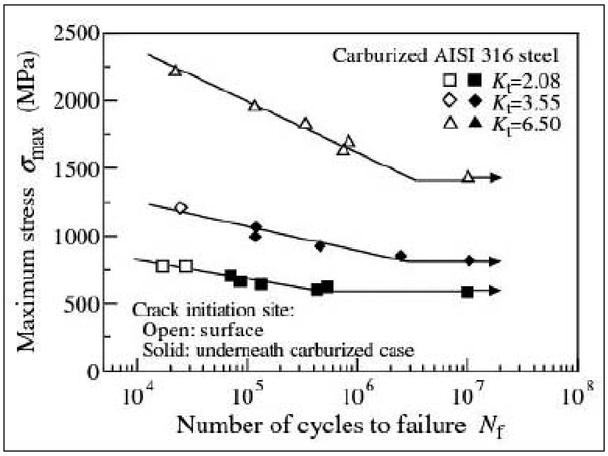
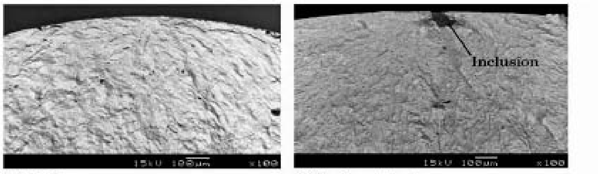


Fig. 1. S-N curve for notched carburize specimen in relation with maximum stress [21].

As it was observed that fatigue strength of untreated and carburize sample decreases with increase in value of k_t. untreated and carburize sample shows lower notch sensitivity. A study on notch SCF butt welded joints of steel under uniaxial pressure was investigated using finite element analysis with 2D linear strain [22]. Welded profile are modeled as grooves. The effect of parameter such as sheet thickness, weld, flank angle, radius of weld, length of weld and linear mismatch was evaluated. Finally, four new parametric equations are obtained that can calculate the SCF of welded joint having a radius of a variable peak without linear mismatch or $q=r_{ref}$=1mm. In this study, the influence of stress concentration was measured by testing the strength of butt joint with fatigue in welding or without welding [23]. Fatigue strength during welding was measured by a high frequency fatigue machine. It was observed that fatigue cracking in a weld starts due to stress concentration in the root of the weld. The concentration coefficient of stress concentration with a weld reinforcement is 1.5. Thus high stress concentration reduces the fatigue strength.

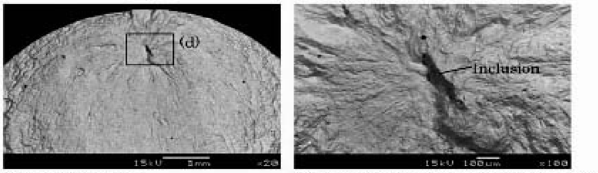
4. Effect of Inclusion

As per study conducted on effect of inclusion on very high fatigue properties (VHCF), a focus was made on Transition area (Ta) from 105 to 2×107 cycle [24]. The two different specimens of two different diameters i.e. D_4= 4mm & $D_{7.5}$= 7.5mm were used. A high strength martensic specimen was used during the test in Ta. Experiment was carried out on servo-hydraulic testing ring which operate at testing frequencies of 30Hz. Ring maintains the temperature of two specimen at 200^0C and 3500^0C. The entire specimen was analyzed by Scanning electron microscopy (SEM) to identify the fracture origin. From the experiment the average defect size of D4 & D7.5 were observed as 28-98µm and 10.98µm. The result obtained shows slight deviation from the experiment performed by other authors. Royota Yakura and Co-authors [25] conducted study to grasp the fatigue properties, including the properties in a VHCF region of a low alloy steel used for the solid type crank shaft of a 4-cycle diesel engine. The study was conducted on the relationship of fatigue life with respect to the size of inclusion. Test material was made from steel ingots weighting 12 to 65 tons. The test steels included 40 CrMo8, developed by Kobe steel, as well as 34CrNiMo6, 36CrNiMo8 and 42CrMo4 of S & O. Rotating bending fatigue test at frequency of 60 Hz were performed on the super carbon steel. The specimen collected from the crank shaft was subjected to axial load fatigue test. In order to compare the fatigue characteristic up to very high cycle region of super clean steel and conventional grade steel, cantilever bending test were performed. The test was conducted at a frequency of 52.5 Hz at 10^9 cycles. Fracture surface of failed specimen was observed by SEM. Result found that the axial fatigue test in high cycle fatigue have two fracture, in one fatigue crack initiated from surface inclusion and in other they are initiated from internal inclusion. And three types of fatigue crack initiation sites were observed which are shown in figure 2 are Metal surfaces (a), surface inclusions (b) and internal inclusions (c and d) while in case of VHCF shows no fracture initiation from internal inclusion.



(a) Surface (Cantilever rotating bending fatigue test, σ_a=450MPa, N_f=1.15×10^6cycle)

(b) Surface inclusion (Axial load fatigue test, σ_a=395MPa, N_f=4.23×10^6cycle)



(c) Internal inclusion (Axial load fatigue test, σ_a=410MPa, N_f=9.56×10^6cycle)

(d) Enlarged view of Internal inclusion on (c)

Fig. 2. Examples of fatigue crack initiation sites [25].

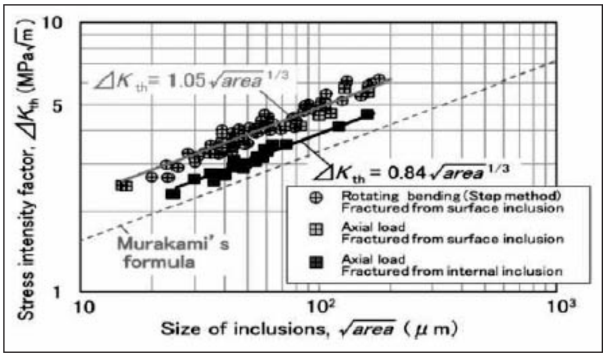


Fig. 3. Relationship between ΔK_{th} and area for 40CrMo8 [25].

The equation (5) shows that decreasing inclusion size improves not only the fatigue strength working against surface fracture but also that attributable to internal fracture.

$$\Delta K = a(N_f / \sqrt{area})^{\beta} \qquad (5)$$

A relation between Δk_{th} and area for 40CrMo8 is shown in Fig. 3.

The study focuses on the properties of non-metallic inclusion and their effect on fatigue strength of standard case-hardened carbon steel 20MnCr5 in gear [26]. This steel is also called clean steel due to good inclusion distribution. To evaluate the mechanical properties, the result from the rotary bending test was compared and increase in fatigue strength of 37.5% was observed. The ultrasonic test show differences in the defect sizes for materials with different manufacturing process and reduction degree. Moreover while using ultrasonic test to determine the distribution of defect it was recommended

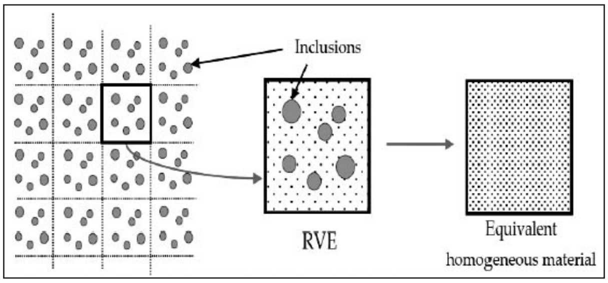


Fig. 4. Schematic of representative volume element (RVE) method [31].

to use lower FBH. The effect of inclusion on the VHCF cyclic torsion was investigated at various load ratios [27]. Ultrasonic test was carried out using high-intensity spring steel made on the basis of SWOSC-V composition, which intentionally includes an increased content and inclusion size. Even if the maximum shear stress is lower than torsional yield strength, a high mean stress sensitivity m_τ=0.41 was detected. This was the result of inclusion, which affects only the cyclic shear strength of positive load factor.

Spriesters bach, P. Grad and E. kerscher [28] study the effect of various types of inclusion on the formation of cracks in VHCF. The material used in this study is bainitic carbon chromium high strength steel containing 100Cr6. The fatigue specimens possess an hour glass- shape with a least diameter of 4mm in the focal point and stress concentration factor of 1.027. The fatigue pressure test (R=1) was performed using a piezoelectric ultrasonic fatigue test with a frequency of about 20 kHz. Specimen tested at a load cycle of 10^9. The stress amplitude maintained during the test was increased by 50 or 100 Mpa. The non-metallic inclusion inside the material takes place when the cycle is higher than 10^5 and stresses below 1100 Mpa. In this study the inclusion types found are titanium oxide (TiN), calcium oxide (Cao), aluminum calcium oxide (AlCao), Magnesium oxides (Mgo) and sometimes inclusions with a mixture of different types. Fatigue due to material inclusion can be divided into two groups: acute cracks which are caused by uniform inclusions, such as cracks in metal treatment cavities, Formed by cracks starting with TiN, and heterogeneous inclusion such as AlCaO. This method shows that the stress-intensity factor in the cyclic fatigue mode is very high depending on the type of inclusion. Thus, in addition to the threshold cracks for a cracks or long cracks in fish eye k_t, you can find additional threshold for formation, called fine granular area which is characterize VHCF. The threshold depends on the function of inclusion interaction between the inclusion and surrounding matrix. Thus, each type of inclusion has a threshold value that causes cracks during FGA formation in VHCF regime. In addition, the threshold containing TiN, which collapses at the first load and lead to almost perfect cracks, appear to be an absolute failure threshold. The effect of inclusion size and stress ratio on the fatigue properties of stainless steel with a fish eye failure model was discussed [29]. According to experimental results, the fatigue life is reduced almost half, when inclusion size doubles. The fatigue strength, inclusion size, fatigue life and stress ratio are apparently associated with equation (6).

$$\sigma_a = C N_f^l a_0^m (1 - R/2)^\alpha \qquad (6)$$

The model was then used to assess fatigue strength using the estimated maximum inclusion size obtained from Gambel distribution. Quantitative inclusions are found in A356 aluminium alloy and are associated with fatigue properties under uniaxial high cycle conditions [30]. SEM analysis was performed on the fatigue sample containing 3 dendritic cells of different sizes (DDS). This study also focuses on other metrics such as NND (Nearest neighbor distance) of inclusion, free surface to inclusion distance, and type of inclusion. This study is necessary to identify the effect of numerous micro structural inclusion that interfere with fatigue life. The result clearly shows that the maximum pore size (MPS) gas pore and NND and DCS can affect the fatigue life.

Qingming Deng and Co-authors [31] studied the effect of randomly distributed micro inclusions on the fretting fatigue behaviour of heterogeneous material. The analysis is carried out using Finite Element Method (FEM) for different sizes, shapes and properties of inclusions. The crack initiation process is directly affected by the contact stresses. The contact stresses are influenced by various factors such as loading magnitude, contact geometry and surface imperfections. Inclusions are present in the form of particles, films or group of films. From the results obtained by experiment on high strength steels that the inclusions inside the matrix are responsible for the fatigue failures. In this analysis the authors mainly considered two kinds of common inclusions in aluminium alloy 2024-T3. To study the effect of local randomly distributed inclusions on the stress distribution in a specimen, a numerical analysis is presented in which, the effect of micro inclusions on macroscopic material properties are considered by means of representative volume element (RVE) as shown in fig 4. The investigation is done based on effect of different variables like material properties, volume ratio and shape of the inclusion. The investigation is done based on effect of different variables like material properties, volume ratio and shape of the inclusion. It is inferred that the effect of inclusion size is more dominant than the influence of inclusion type on the surface stress distribution. Thus, it is shown in the analysis that there is a considerable influence of micro inclusions on macroscopic material properties which cannot be ignored.

As compared to the material properties of inclusion and volume ratio, the shape and size of the inclusion do not have much effect on the macroscopic material properties. In addition to this, various parameters of inclusion have little effect on the ultimate tensile stress which showed no change as of homogeneous material.

5. Conclusions

1. Mean stress affect the fatigue life of component. By using modified models on Morrow relation or SWT relation, we can estimate the effect of mean stress on fatigue life of component.
2. It is clear that increased mean stress reduced the fatigue life of component. But if mean stress is compressive then it will increase the fatigue life of component.
3. Selection of a suitable CLD model is very important for accurately prediction of total fatigue life for notched fiber-reinforced metal laminates under Mini-Twist spectrum loading.
4. Stress concentration effect depends on geometry of sample. One simple way to prevent stress concentration is to replace the sharp corner in high stress region with a round groove, preferably with the maximum possible radius of groove. These steps are less expensive to build components, but they are much more expensive than damage to the site due to poor design
5. It was found that under low cyclic fatigue and increased surface roughness leads to increase in fatigue life caused due to surface stress concentration.
6. It is concluded that decreasing inclusion size improves not only the fatigue strength working against surface fracture but also that attributable to internal fracture.

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