iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 5 Issue: XII Month of publication: December 2017

DOI:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
Volume 5 Issue XII December 2017- Available at www.ijraset.com

Estimating Mechanical Fatigue Life—A Review

Dr L C Singal[1], Rajwinder Singh Gill[2], Parmvir Singh Kang[3]
[1, 2, 3] *Department of Mechanical Engineering, Landran, Mohali*

Abstract: Fatigue is due to cyclic loading and unloading of one kind or the other. Fatigue takes place at a much smaller stress than the actual strength due to reversal of stress. Fatigue life is infinite for materials at a stress lower than the endurance limit stress. Every material does not have a definite endurance limit. Such materials have short fatigue life. Fatigue life estimation methods are stress life approach, strain life approach and crack initiation-crack growth periods. Fatigue life in stress life approach depends on material behavior, surface condition, method of manufacture and the environmental conditions. Many empirical correlations are available on stress life approach. Most of the experimental data fall between the Goodman and Gerber curves. A Goodman correlation is often used due to mathematical simplicity and slightly conservative values. The Soderberg line is seldom used in design since it is very conservative (high factor of safety) and thus becomes very expensive. Strain life use Coffin-Manson equation for constant amplitude loading while the rain flow model has been used under variable amplitude loadings. Total fatigue life consists of three periods namely the crack initiation period, crack growth period and fracture period. But the main fatigue life comes from the crack initiation period only especially for brittle materials. Crack growth period is quite small as compared to crack ignition period even in case of ductile materials. Final fracture is sudden, instantaneous and without any warning. Many more correlations for estimating fatigue life are available in literature.
Keywords: Fatigue, Fatigue life, Stress life approach, strain life approach and fracture mechanics approach

I. INTRODUCTION

Fatigue endurance limit (σe) represents a stress level below which the material does not fail even after infinite number of cycles [1-5]. Fatigue is reduction in strength due to a progressive and localized structural damage that occurs when a material is subjected to repeated cyclic loading and unloading. The nominal maximum stress which causes fatigue is much less than the ultimate tensile strength for brittle materials and the yield stress for ductile materials. Under cyclic load, failure is due to fatigue. Fatigue is a progressive plastic failure starting from a crack at the point of stress concentration which may be due to the presence of notch, cavity, keyway, indentation and a stepped shaft [1-10]. The crack then travels along weaker points and ultimately it results in a facture. Thus the failure occurs in three phases: crack initiation, crack propagation, and sudden instantaneous failure [1-15]. Normally designs are available for static loads which are highly uncommon in real practice. Actual loads are fluctuating loads of various types. In 1860, fatigue life was predicted by A. Wohler (1860) based on bend tests (completely reversing loads). But many other types of fluctuating loads could not be accounted for in predicting the fatigue life. Consequently, empirical correlations were developed to predict fatigue life. These are based on Stress life approach (used for elastic deformation), Strain life approach (used for plastic deformation) and Crack Growth Approach

II. FATIGUE LIFE ESTIMATIOM METHODS

A. Stress Life Approach

Under a static load, mean stress is zero and stress ratio R= --1. In such cases it is easy to work out the fatigue life from S-N diagram which are available for number of materials based on experimental data. There are high cycle fatigue life and low cycle fatigue life. Materials such as carbon steel have flattened portion in S-N diagram indicating the endurance strength which leads to infinite fatigue life. Materials which do not have a flattened portion of the S-N diagram (copper & aluminum) fall into the low cycle fatigue life of 10^4 to 10^8 cycles. There is a large number of practical applications of repeated cyclic loading where mean stress is non-zero with stress range $R \neq -1$. The failure under a repeated cyclic varying load causes failure at a much lower stress in the elastic range. Very less experimental data is available for such loadings. Thus there is a need to develop some correlations to account for non-zero mean stress to predict fatigue life. Fatigue failures occur due to cracks which result from plastic deformation in localized areas due to the presence of discontinuities/ dislocations. Plastic deformation occurs due to usually stress concentration sites on the surface or somewhere inside the surface of a component.

Stress life approach gives infinite life (high cycle fatigue life) of materials where stresses remain elastic even around the stress concentrations as is found applicable for steel and titanium components shown in figure 1. In the same figure, finite fatigue life (low cycle fatigue) is observed for copper, aluminum and nonferrous components which do not have a defined fatigue limit. Figures 2 shows fatigue life for some materials while figure 3 shows the effect of surface finish on fatigue life.

It is obvious from Fig.3 that the endurance limit strength (σ_e) for a polished surface is 50% of the applied tensile stress. Further σ_e of polished surface> ground surface>Machined or cold drawn>Hot rolled>forged surface. Fatigue Stress Life Method Both is applicable for Constant and Variable Amplitude Loadings

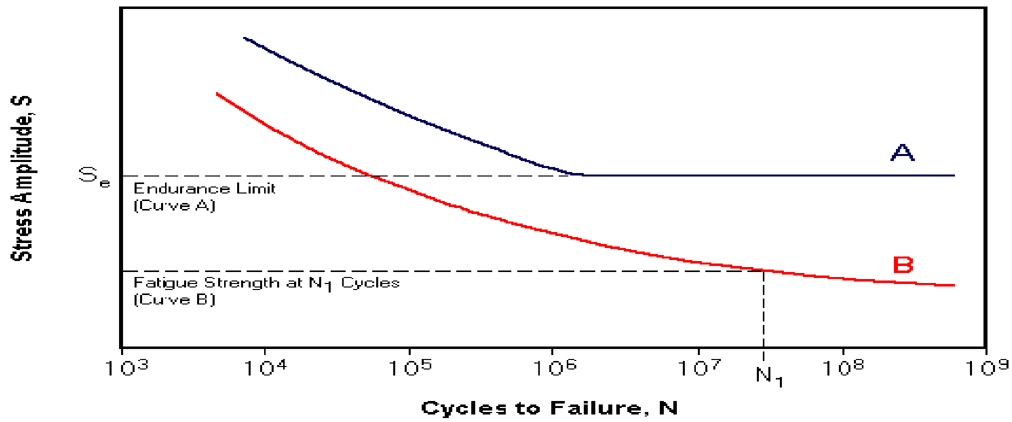


Fig .1 : Stress amplitude Vs number of reversals to fatigue failure

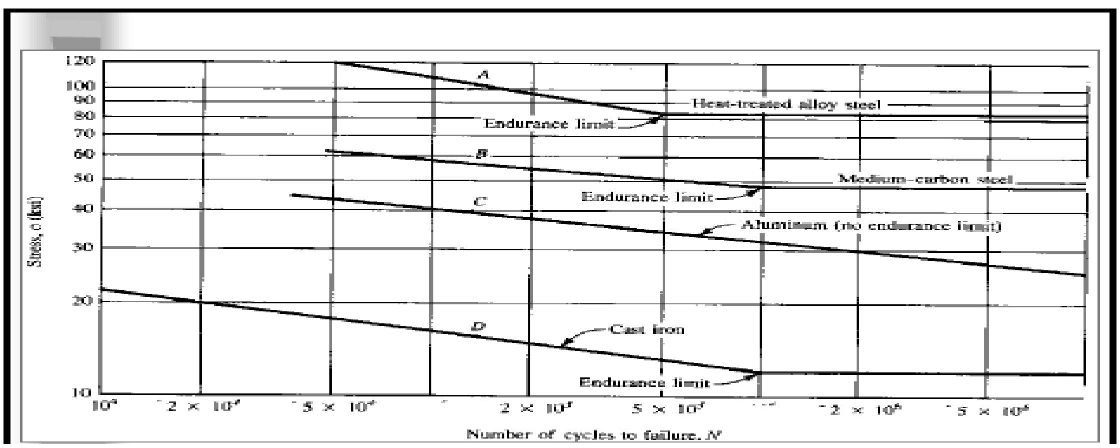


Fig.2 : Stress amplitude Vs number of reversals to fatigue failure

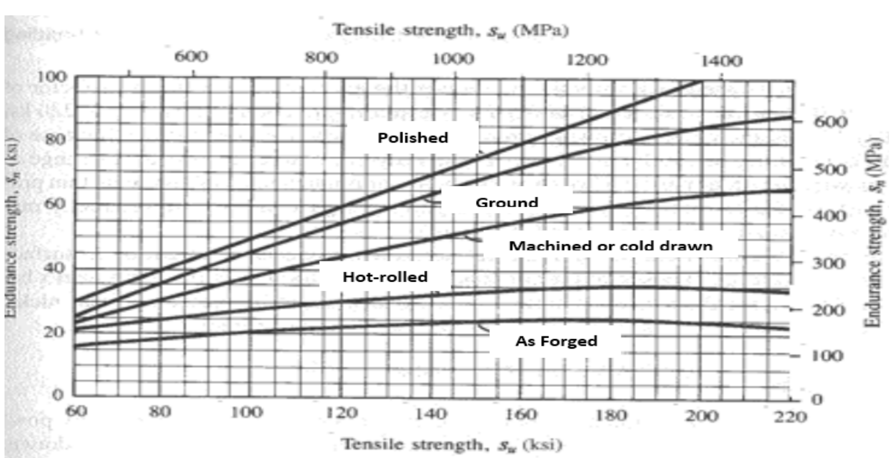


Fig 3: Effect of surface finish on endurance limit.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
Volume 5 Issue XII December 2017- Available at www.ijraset.com

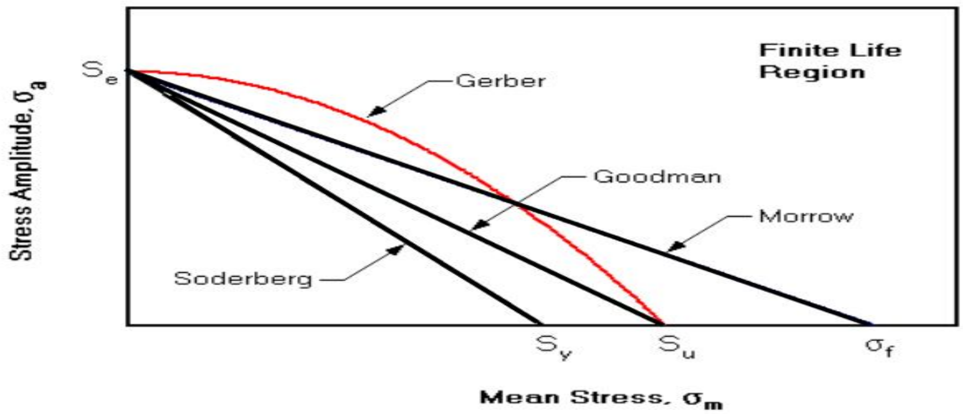


Fig.4: Comparison of fatigue life empirical correlations

1) *For constant amplitude loading:* When a component is subjected to only one type of load with a constant amplitude and constant mean stress. From a SN curve, designers can find quickly the number of cycles leading to component failure and hence the fatigue life. Stress life approach with zero mean and constant amplitude stress uses Basquin fatigue life equation

$\Delta\sigma/2 = \sigma_a = \sigma_f' (2N_f)^b$

Where

σ_f' is the fatigue strength coefficient (for most metals ≈ σ_f , the true fracture strength)

b is the fatigue strength exponent or Basquin's exponent (≈ -0.05 to -0.12),

$2N_f$ is the number of reversals to failure (fatigue life)

2) *Stress Life Approach for variable amplitude loadings :* It uses the empirical correlations given below:

a) Gerber (Germany, 1874)

$\sigma_a/\sigma_{e'} + (\sigma_m/c_{ult})^2 = 1$

b) Goodman (England, 1899)

$\sigma_a/\sigma_{e'} + \sigma_m/\sigma_{ult} = 1$

c) Soderberg (USA, 1930)

$\sigma_a/\sigma_{e'} + \sigma_m/\sigma_y = 1$

d) Morrow (USA, 1960s)

$\sigma_a/\sigma_{e'} + \sigma_m/\sigma_f = 1$

Where σ_a = amplitude stress

$\sigma_{e'}$ = endurance limit

σ_m = mean stress

σ_f =Actual fracture stress

σ_{ult}= Ultimate tensile stress

B. Comparison of Fatigue Life Empirical Correlations

In figure 4, most of the experimental data fall between the Goodman and Gerber curves. A Goodman correlation is often used due to mathematical simplicity and slightly conservative values. The Soderberg line is seldom used in design since it is very conservative (high factor of safety) and thus becomes very expensive. For strong steels (brittle), where the ultimate strength approaches the true fracture stress, the Morrow and Goodman curves are essentially equivalent. Fatigue strength reduces with the increase of mean stress and stress range and vice versa.

C. Strain Life Approach

1) *For constant amplitude:* Constant Amplitude Strain-Life method had major developments around 1960's. This approach is applicable for finite life (low cycle fatigue) of materials where plasticity around stress concentrations occurs and has been found

applicable for copper, aluminum and nonferrous materials as shown in figure1. Strain life approach is applied by using Coffin-Manson equation.

$\Delta\varepsilon_p/2 = \varepsilon'_f\,(2N)^c$

Where
$\Delta\varepsilon_p\,/2$ is the plastic strain amplitude;

ε_f' is fatigue ductility coefficient (the failure strain for a single reversal)

$2N$ is the number of reversals to failure (N cycles);
c is an empirical constant ranging from -0.5 to -0.7 for metals in time independent fatigue.

2) For variable amplitudes
The rain flow-counting algorithm is used to convert n spectrum of varying stress amplitudes into a set of simple stress reversals. For achieving this, it uses Miner's Rule. Miner's Rule is probably the simplest cumulative damage model. There will be number of damage fractions at different stress levels. Under variable amplitude loading, it is divided into a number of different constant amplitudes Vs number of cycles. For each constant amplitude, damage fraction will be C as given below:
$C = \sum n_i/N_i = (\, n_1\, s_1 + n_2\, s_2 + n_3\, s_3 \ldots\ldots)/W_{failure}$

Where n_i is the number of cycles at stress s_i
C is the fraction of life consumed (damage fraction) at a certain stress level
In general, when the sum of damage fractions reaches 1, failure occurs
Individual damage is often expressed as product of stress and the number of cycles operated under this stress i.e.
$W_i=n_i\, s_i$, $W_1=n_1\, s_1$, $W_2=n_2\, s_2$
Assuming that the critical damage is the same across all the stress levels which is $W_{failure}$.
$W_{failure} = N_iS_i$
a) Example 1: Let us assume $W_{failure}$ =100 for a component.
Then the component will fail after 20 cycles at a stress level of 5, or fail after 10 cycles at a stress level of 10, and so on or combination of 10 cycles at a stress of 5 and 5 cycles at a stress level of 10. Failure will occur when
$C =(\, n_1\, s_1 + n_2\, s_2 + n_3\, s_3 \ldots\ldots)/W_{failure} = 1$

b) Example 2: A part under a fatigue environment spends 10% of its life at an alternating stress level, σ_1, 20% is spent at a stress level, σ_2 , and 70% at a stress level σ_3 . Find the number of cycles, n, and the part will undergo before failure? From S-N diagram for this material, find the number of cycles to failure at σ_i is N_i (i=1,2,3), then from the Palmgren-Miner rule failure will occur after n cycles
0.1n/N1 +0.2n/N2 + 0.7n/N3 =1
On rearranging, we get
n=1/(0.1/N1+ 0.2/N2 +0.7/N3)

3) Crack growth method for fatigue life estimation: Factors which affect fatigue life are the material surface quality, residual stress, and environmental influence. In a specimen subjected to a cyclic load, fatigue failure is due to a crack. A fatigue crack initiation is microscopic (invisible), crack growth is macroscopic (visible), and finally specimen fails suddenly and instantaneously. Here fatigue life consists of three periods as shown in figure 5.
a) Crack initiation period which is the longest period
b) Crack growth period is relatively small for commonly used components but is significant for real big structures such ships and aircrafts
c) Final fracture period is almost negligible as the fracture is sudden without any warning

There are different fatigue prediction methods for the first two periods of the fatigue crack. Crack initiation period is found from the stress concentration factor K_t whereas crack growth period is found with the stress intensity factor K.

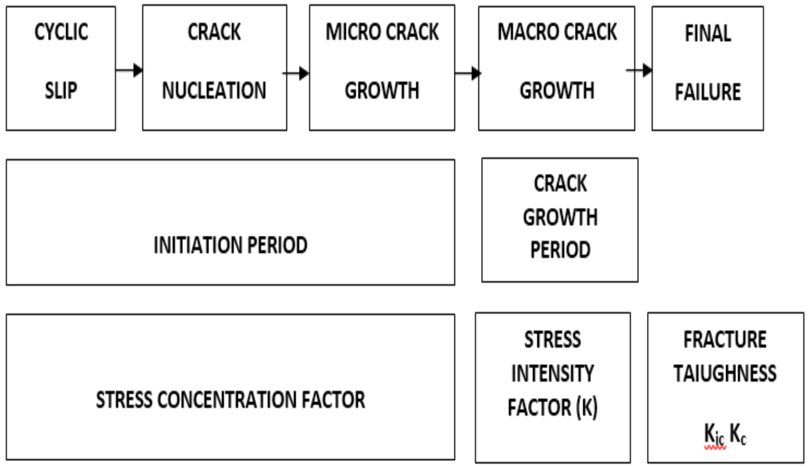


Fig. 5: Different periods of fatigue life and relevant factors

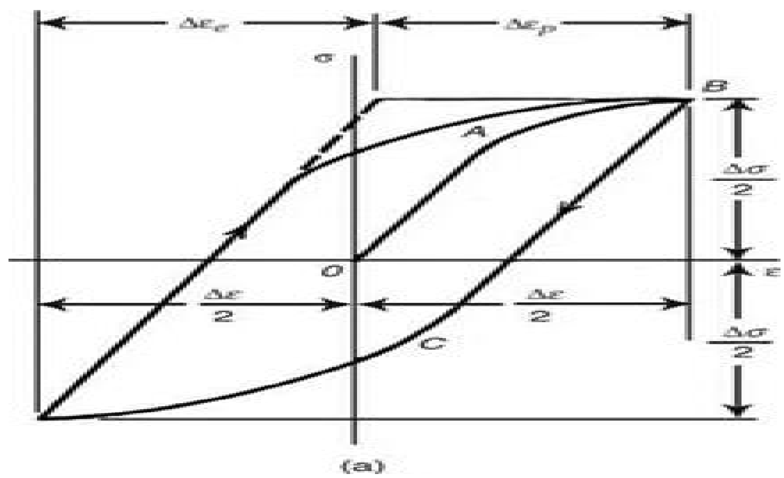


Figure 6: Cyclic Stress Strain Hysteresis loop for constant strain hardening

i. Stress strain curve for initial loading is OAB
ii. Yielding begins on unloading at point C in compression due to Bauschinger effect and continues up to point D
iii. Reloading is along the curve DEFB
iv. Hysteresis loop is formed with x coordinate as $\Delta\varepsilon$(total strain range) and y coordinate as $\Delta\sigma$(Total stress range)
v. $\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p$ = total sum of elastic and plastic strain
vi. $\Delta\sigma$ = Total stress range n the cyclic loading and unloading

4) Estimation of crack initiation period

There is no standard procedure for finding the stress-strain properties during a cyclic loading. CDM based fatigue damage model is used for crack initiation. Fatigue failure of components takes place in three steps namely the initiation and then propagation of a crack and then sudden and instantaneous failure. Thus the total fatigue life will be the sum of crack initiation and crack propagation periods. Fatigue failure life is represented by the total number of loading cycles to failure, N_f, which is represented as given below.

$N_f = N_i + Np$

where Ni is the number of cycles required to initiate a fatigue crack

Np is the number of cycles required to propagate a crack to final fracture after initiation

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
Volume 5 Issue XII December 2017- Available at www.ijraset.com

Fatigue life prediction is complex because it is influenced by number of factors. There is no method which can predict the fatigue life by separating crack initiation and propagation time periods. There are empirical correlations to predict only the crack initiation period. Crack initiation is the cumulative damage caused in each successive cyclic loading. These do not account for the damage caused in each cycle of cyclic load. The damage increases more rapidly as number of cyclic loading and reloading is increased. Crack initiation period completes as soon as the critical damage value is reached. Unloading portion of a hysteresis loop and compressive stresses do not contribute to damage. Thus only reloading increases damage [2]. Ramberg-Osgood developed a model based on the hysteresis loop. Baidurya and Bruce [9] improved this model further. These models require parameters of hysteresis curve and the cyclic properties (critical damage D_c obtained by *continuum damage mechanics* (CDM) based on uni-axial loading of the material. Crack initiation period occupies major part of a fatigue life. Thus the life of the specimen is assumed to be equal to the fatigue crack initiation period only.

$N_f \approx Ni$

Therefore, only one strain or one stress parameter is required for fatigue damage calculation as well as fatigue life estimation. Therefore, the elastic plastic stress-strain behavior of materials is of utmost importance in fatigue life calculations.

The original Ramberg–Osgood nonlinear stress strain correlation for materials which harden with plastic deformation is

$\varepsilon_t = \varepsilon_e + \varepsilon_p = \sigma/E + (\sigma'/K)^{1/n}$

ε_t is total strain

ε_e is elastic strain=σ/E

ε_p is plastic strain= $(\sigma'/K)^{1/n}$

Where,

K = Stress dimensioned material parameter called the strength coefficient = $\sigma_f / (\varepsilon_f)^n$

σ_f is the true fracture stress

ε_f is the plastic strain at fracture

n = dimensionless material parameter called the strain hardening exponent and its range value is ($0.01 < n \leq 0.4$)

σ is elastic stress

σ' is plastic stress i.e. > yield stress

Rambrg-Osgood stress strain relation actually used to find fatigue life is $\varepsilon_t = \varepsilon_e + \varepsilon_p = \sigma/E + \varepsilon_f (\sigma'/\sigma_f)^{1/n}$

Thus Ramberg-Osgood equation contains four material constants: E, σ_f, ε_f, and n. These are available in literature for a few materials as reproduced in table 1.

Many more empirical correlations are available in literature to find the fatigue life.

TABLE 1 Typical Monotonic and Cyclic properties [14]

Material	Monotonic properties							Cyclic properties		
Steel	E, MPa	$\sigma_{y,}$ MPa	$\sigma_{ult,}$ MPa	K MPa	n	$\sigma_{f,}$ MPa	ε_f	σ' MPa	K' MPa	n'
SAE 1020 (hot rolled)	206	262	441	738	0.19	710	0.96	241	772	0.16
SAE 1040 (forged)	210	345	621	738	0.22	1050	0.93	386	786	0.18
Aluminum										
2024-T351	73	379	469	455	0.032	558	0.28	427	655	0.065

III.CONCLUSIONS

A. The fatigue mechanism in metallic materials is associated with cyclic slip followed by crack initiation and crack growth. This mechanism is different for different types of materials.

B. The fatigue life consists of crack initiation period and the crack growth period. The main portion of the fatigue life is crack initiation period especially in brittle materials. Crack growth period may be short duration in case of ductile materials.

C. Crack initiation period is a surface phenomenon in fatigue and hence largely depends on surface conditions, such as surface roughness, type of machining, fretting, corrosion, pits, etc. crack growth period is independent of surface condition of the material

D. Fatigue life is small at high stresses and vice versa.

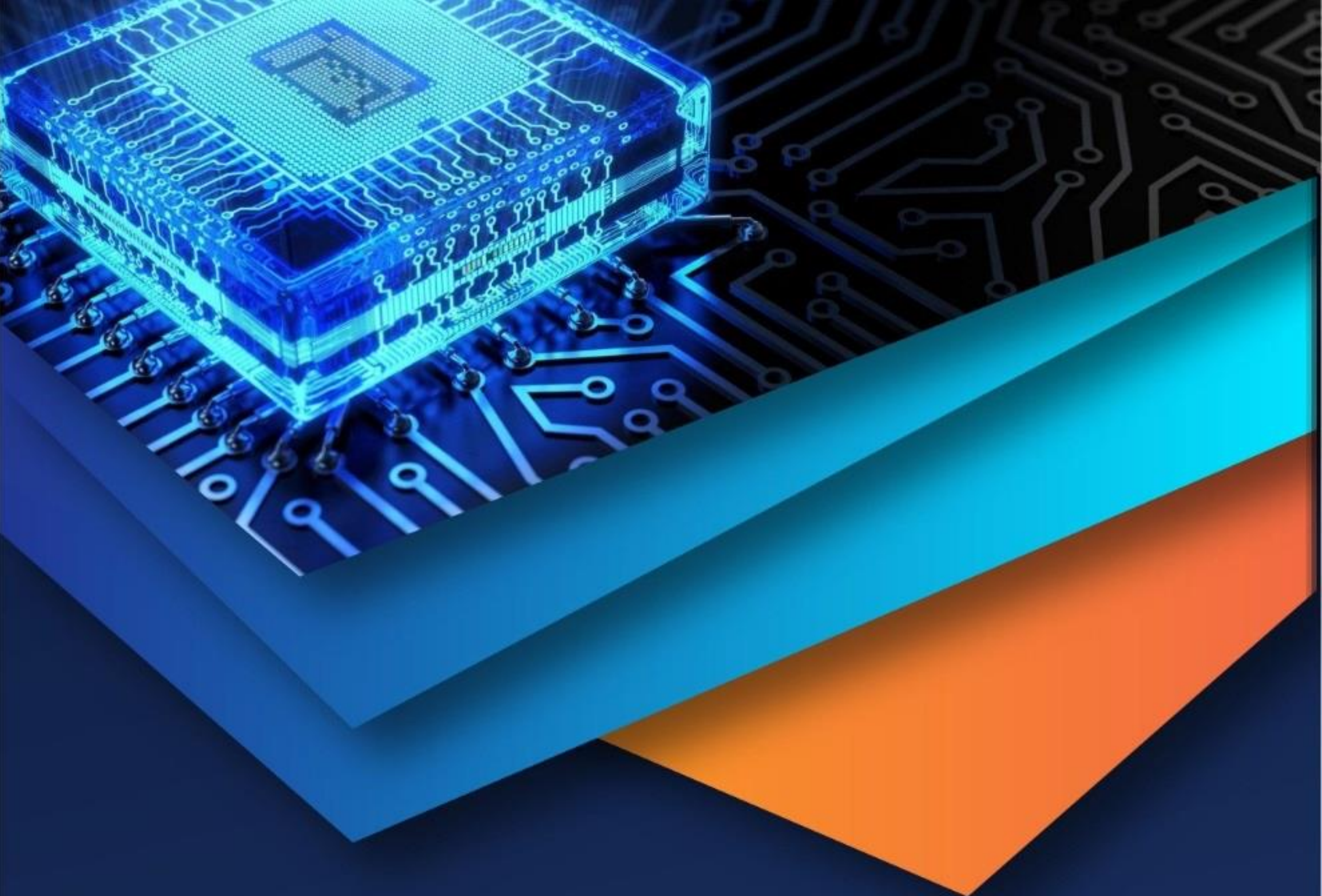
E. Fatigue life is greatly affected by the environmental conditions.

F. Different types of materials behave differently during fatigue. Thus a large amount of experimental data is required for more correct prediction of fatigue life.

G. There are number of empirical correlations to predict fatigue life. However, any single correlation cannot predict the fatigue life for all types of materials.

REFERENCES

[1]. H.O Fuchs and R. I. Stephens," Metal Fatigue in Engineering",1980.
[2]. C.C. Osgood, "Fatigue Design", 2nd Ed. 1982.
[3]. J.A. Ballantine, J.J. Conner and J.L. Handrock, "Fundamentals of Metal Fatigue Analysis",1990.
[4]. Frendahl, M., Rychlik, I, "Rainflow analysis, Markov method", International Journal of Fatigue, 15(4), 265–272, 1993.
[5]. Murakami, Y., Morita, T. and Mineki, K., J. Soc. Mater. Sci., Japan, 46, 1217,1997.
[6]. Murakami, Y., Takada, M. and Toriyama, T., "Super-long life tension-compression fatigue properties of quenched and tempered 0.46% carbon steel", Int. J. Fatigue, Vol. 20, pp. 661–667, 1998.
[7]. Miyata, H. and Endo, M., "Preliminary Proc. of the Kyushu District Meeting", Japan Soc. Mech. Engrs, 998-3, pp. 25-26, 1999.
[8]. Zhou, S. and Turnbull, A., "Influence of pitting on the fatigue life of a turbine blade steel", Fatigue Fracture Engineering Materials Structures,Vol. 22, pp. 1083–1093, 1999.
[9]. Baidurya Bhattacharya, and Bruce Ellingwood, "A new CDM based approach to structural deterioration," Int. J. of Solids and Struct., vol.36, pp. 1757-1779, 1999.
[10]. R. I. Stephens, A. Fatemi, R. Stephens, and H. O. Fuchs, "Metal Fatigue in Engineering", John Wiley & Sons, New York, NY, USA, 2000.
[11]. M. Jono, "Fatigue damage and crack growth under variable amplitude loading with reference to the counting methods of stress-strain ranges," International Journal of Fatigue, vol. 27, no. 8, pp. 1006–1015, 2005.
[12]. M. Makkonen, "Predicting the total fatigue life in metals," International Journal of Fatigue, Vol. 31,no. 7, pp. 1163–1175, 2009.
[13]. T. Ghidini and C. Dalle Donne, "Fatigue life predictions using fracture mechanics methods," Engineering Fracture Mechanics, Vol.76, no.1, pp. 134–148, 2009.
[14]. Hachim, H. Farid, M. El Ghorba, K. El Had, A. Akef, and M. Chergui, "Prediction and evolution of the fatigue crack initiation in S355 Steel by the probabilistic method," International Journal of Engineering Science, vol. 1, pp. 16–21, 2012.
[15]. C. L. Anand and D. M. Parks , Massachusetts Institute Of Technology Department Of Mechanical Engineering Cambridge, Massachusetts 02139 2.002 Mechanics And Materials II Spring 2004 Supplementary Note



10.22214/IJRASET

INDEX COPERNICUS

45.98

ISRA JIF

IMPACT FACTOR: 7.129

TOGETHER WE REACH THE GOAL

IMPACT FACTOR: 7.429

ISI

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY