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ANALYSIS OF FATIGUE CRACK GROWTH RATE AND SERVICE LIFE OF SPUR GEAR

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***Abstract*— A test apparatus is to determine the crack growth rate due to bending fatigue of a spur gear .Under the range of operating conditions, experiments were performed by using standard compact test specimens which were made up of mild steel .The fatigue process leading to tooth breakage due to crack propagation.The crack propagation rate is determine by plotting the graph of the crack growth rate (da/dn) with stress intensity factor (∆K) and crack length (a) versus cycles (N_p). The functional relationship between the stress intensity factor and crack length *K* =*f*(*a*), which is needed for determination of the required number of loading cycles Np for a crack propagation from the initial to the critical length. Service life of spur gear can be found out using Paris Law which is based on crack propagation rate and difference of Stress Intensity factor**

***Index Terms*— Crack growth rate, stress intensity factor, bending fatigue, FEA, crack length, cycle Np**

I. INTRODUCTION

A gear is a machine element design to transmit force and motion from one mechanical unit to another. The design and function of gears are usually closely associated, since gears are designed for a specific function. Various types of gears have been developed to perform different functions, the most common of these being spur gears. Gears are commonly used mechanical components in power transmission and are frequently responsible for gearbox failures Like all mechanical components, gears can and do fail in service for a variety of reasons. Two kinds of tooth damage can occur under repeated loadings that cause fatigue; namely, the pitting and spalling of gear teeth flanks and tooth fracture in the tooth root. The most undesirable damage that can occur in gear units is the crack in the tooth foot as it often makes the operation of the gear unit impossible. Gear contact fatigue is a major failure mode.

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The more operating Torque is increased, the more gear bending fatigue strength is required. The fatigue life of gears has been studied over many years which show the gear contact fatigue performance is very important. Gear tooth bending fatigue is a key characteristic of the gear and affected by design geometry, material, manufacturing methods and other variables. The primary objective of fatigue testing is to optimize gear design by studying the effects of these variables on the fatigue characteristics of the gear. The aim of the maintenance is to keep a gear-unit or technical system in the most suitable working condition and to discover, diagnose, foresee, prevent, and/or to eliminate damage.

Therefore, a test investigation of the bending fatigue strength of spur gears which were made from 18 Ni(250Grade) was completed in this paper. Tests were conducted by using the test rig. Statistical analytical methods were applied in order to improve the accuracy of data processing and analysis for predicting endurance limits. The (da/dN v/s ∆K) graph been obtained by the Paris theory. In most cases, except for an increase in noise level and vibration, total gear failure is often the first and only indication of a problem, out of this failure the most common failure in gear is fatigue failure due to bending fatigue. The compact test specimen is used to evaluate the fatigue failure by determining the FCPR (fatigue crack propagation rate) and examine in a graphical format with stress intensity factor K and number of cycle. N.

Abbreviations and Acronyms

FEA	Finite element analysis
FCPR	Fatigue crack propagation rate
LEFM	Linear elastic fracture mechanics
SIF	Stress intensity factor
DWT	Discrete wave transform
RMS	Root mean square
SHTM	Servo hydraulic testing machine

II. *Literature Review*

Gearbox is one of the most critical mechanical components in machineries, and condition monitoring of gearboxes is an important aspect of engineering maintenance in many industries such as manufacturing, aerospace, automotive and power industries. The fatigue process leading to tooth breakage is divided into crack initiation (N_i) and crack propagation (N_p) periods, where the complete service life is defined as $N = N_i + N_{p.}$ Gear tooth crack propagation was simulated using a FEM method based computer program which uses principles of linear elastic fracture mechanics (LEFM). The Paris equation is then used for the further simulation of the fatigue crack growth [1]. Test apparatus, specimen fixture, spur gear test specimens, the properties of gear material were also introduced as well as the method to determine the stress levels. The test data was analyzed and processed by statistical methods, and the equation parameters of gear bending fatigue and the bending

Fatigue limit were obtained [2]. The group test method was used, which adopted four groups and five samples of each group. After the test, a small spalling pitting phenomenon was observed in the vicinity of the test pinion pitch line which is close to the gear tooth root portion. The analysis results showed that the three-parameter Weibull distribution was best to fit the given stress for the contact fatigue life of carburized gear with better precision and adaptability [3]. Test gears were installed with special crack propagation gages in the tooth fillet region to measure bending fatigue crack growth. Good correlation between predicted and measured crack growth was achieved when the fatigue crack closure concept was introduced into the analysis. As the gear rim thickness decreased, the compressive cyclic stress in the gear tooth fillet region increased. This retarded crack growth and increased the number of crack propagation cycles to failure [4]. Single Gear Tooth Bending Test Facility is a unique test rig capable of conducting high-speed bending-fatigue tests. It enhances further research in the infinite-life regions of the stress-cycle curve, by enabling experiments in the 108 to 109-cycle range in the shortest amount of time possible. Effective load output is dependent upon cycle-rate. Operation between 400 and 800Hz is not recommended for any loading condition. The results demonstrate excessive dynamic anomalies within this range [5]. The tooth foot crack propagation is a function of Stress Intensity Factors (SIF) that plays a very crucial role in the life span of the gear. A two-dimensional quasi-static analysis is carried out using a program that determines the gear geometry, coupled with the Finite Element Code (ANSYS) [6]. The dynamic model of a one-stage gearbox with spur gears and one tooth crack, statistical indicators and the discrete wavelet transform (DWT) technique are investigated to identify effective and sensitive health indicators for reflecting the crack propagation level. The results suggest that the root mean square (RMS) indicator is a better statistical indicator than the Kurtosis indicator to reflect the crack propagation in the early stage; the RMS indicator based on the residual signal segments that are strongly affected by the crack is more sensitive; the proposed DWT approach can improve the sensitivity of the RMS indicator, and the RMS indicator becomes more sensitive with the increase of the DWT level up to a best DWT level, beyond which either the monotonicity is lost or the sensitivity decreases; the proposed approach is effective with the presence of noise; with the increase of the noise level, the DWT level at which the best performance is achieved, and thus the sensitivity decreases[7]. A gear tooth loaded by a point force can be obtained using the Boussinesq solution and a transformation function mapping a bell-shaped curve approximating the real tooth shape in the z-plane into the semi-infinite c-plane [8]. A novel method to prevent the tooth failure in the spur gear by introducing circular root filet instead of standard trochoidal root filet in the gear, In order to

Facilitate the analysis, the gear tooth was considered as a cantilever beam and the tooth force was applied normal to the profile at the highest point of single tooth contact. The study reveals that the proposed design (circular root filet) exhibits higher bending strength rather than the standard trochoidal root filet design [9].Genetic algorithm is introduced for the optimum Design of gear train to solve such problems & propose a genetic algorithm based gear design system. This system applied for simple planetary gear train to show Genetic algorithm is better than the conventional algorithm. Their main demanded characteristics are like root fillet radius, face width and rim thickness [10].

III. METHODOLOGY

There are mainly 2 type of methodology used to find crack propagation rate experimental method and analytical method

1. **First method**: - To design the spur gear or equivalent test specimen to evaluate the crack by standard test specimen. As per ASTM E647 compact test specimen is made up of steel 18 Ni(250Grade) steel for fracture crack growth. The experimental test result evaluates the graph of stress intensity factor ΔK v/s crack length Δa, the graph of stress intensity factor ΔK v/s number of cycle ΔN. da/dN v/s ΔK and Hence by evaluating this graph ,we get the result of crack propagation and crack growth rate. Hence by comparing with analytical method we can get the exact length of crack propagation.

2. **Second method**:- The crack growth rate is analysis by Ansys14.5 followed by spur gear model in solid work. Study the failure of gear theoretical and by taking the standard spur gear in a solid work as per standard spur gear parameter. By providing the crack of 1mm of crack on gear tooth root and by Appling 1.25KN load by considering tooth of gear as a cantilever beam the crack is generated, Hence by providing proper quadrilateral mesh around crack the result is generated, Hence the graph of stress intensity factor (ΔK) v/s crack growth rate (da/dN) and stress intensity factor (ΔK) v/s number of cycles ΔN is evaluated. By comparing the analytical result with experimental result we can estimate crack length service life of a gear.

Spur Gear Model

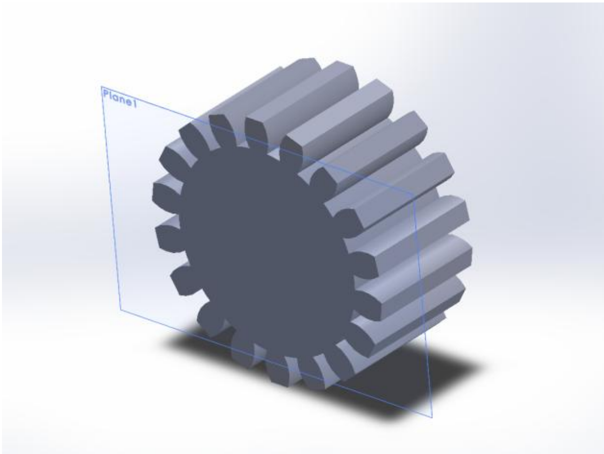
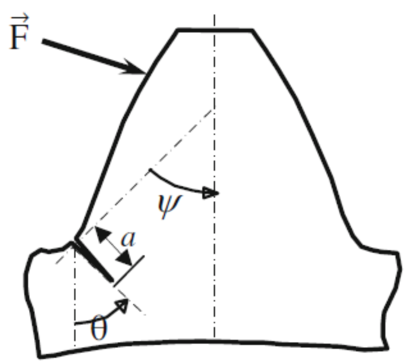
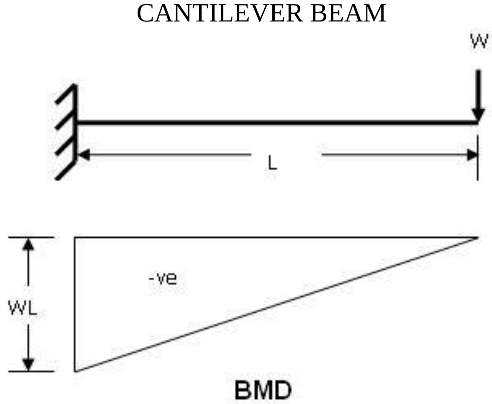


Table.7 Parameters of Spur Gear

Module	6 mm
Pitch Circle diameter	108 mm
No. of Teeth	18
Pressure angle	20Deg.
Face width	60 mm



CANTILEVER BEAM



Instead of performing the Test on actual gear, Test can be done on Compact Tension Specimen

IV. **EXPERIMENTATION- Servo-hydraulic testing machine is used for** fatigue crack growth rate (FCGR) of Compact Tension specimen as per ASTM E647; it is the standard test procedure.

Table 2. Chemical composition of 18 Ni (250 Grade)

C%	0.007%
S%	0.004%
P%	0.004%
Ni%	18.1%
Mo%	5%
Co%	8%
Ti%	0.47%

Table 3. Mechanical properties 18Ni (250Grade)

Tensile strength, ultimate	1100Mpa
Tensile strength, yield	758Mpa
Modulus of elasticity E	210Gpa
Poisons ratio Ʋ	0.30
Fracture toughness, K_{1c}	100Mpa $m^{1/2}$

Table 4. Parameter of compact test specimen

Data of Compact Tension Specimen	
Width ,W	20mm
Thickness ,T	8mm
Stress ratio , R	0.1
Initial crack,	0.5mm
Tensile load	1.25KN

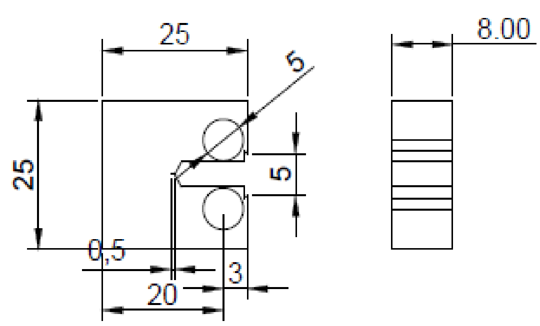


Figure 1 CT specimen

The test specimen consists of rectangular plate of 18Ni (250 Grade). The rectangular plate is a standard compact test specimen for fatigue crack as per ASTM E647. This specimen having notch of 20mm at the center of the plate and two hole of 5mm D diameter for hold the specimen, at the end of the notch a crack is generated of 0.5mm of length for initial crack , hence the specimen is kept on servo hydraulic testing machine(SHTM),To evaluate crack growth rate.

1) Servo hydraulic testing machine`

Servo hydraulic testing machine is an M*TS* system for material testing ; the testing is started at 17̊ c temperature with cyclic load of 1.25 KN. The testing is done by providing pre cracked on specimen and then loaded by cycling loading of 1.25 KN, continue the testing up to failure of specimen. Thus we are getting the graph of da/dN v/s ΔK and number of cycle N to estimate the service life of specimen.

Figure 3

2) Calculation to find Service life of Spur gear Using FCGR data of CT Specimen:-

By experimental method we get the stress intensity factor ΔK , by equation we get Kmin.

$$\Delta K = K_{max} - K_{min}$$

Hence the system is in dynamic load condition so the sinusoidal graph is plot which is having stress intensity factor a controlling factor

By using Paris law,

$$\frac{da}{dN} = C(\Delta K)^m$$

Table 5 parameter used in test specimen

Fracture toughness, K_{1c}	100Mpa $m^{1/2}$
Stress, $\Delta\boldsymbol{\sigma}$	21.357 Mpa
Pre crack, a_i	0.5mm
Critical crack, a_f	5.65mm

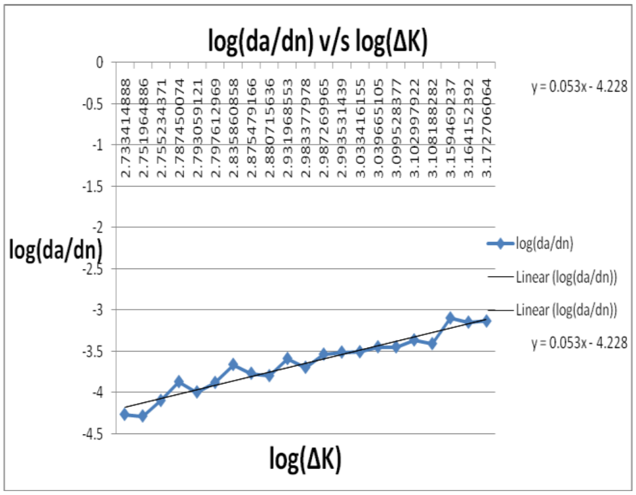
The stress ratio R= 0.1, the stress intensity can be written to evaluate the final crack

$$\Delta K = \Delta\sigma\sqrt{\pi a}$$

Table 6. FCGR data for specimen 18Ni (250 grade)

K_{max} Mpa $mm^{1/2}$	ΔK Mpa $mm^{1/2}$	(da/dn) mm/cycles	Log(da/dn)	Log(ΔK) Mpa $mm^{1/2}$
601.4	541.2	0.0000518	-4.266	2.733
627.7	564.8	0.0000798	-4.285	2.751
632.4	569.1	0.000135	-4.097	2.755
684.1	612.9	0.0001012	-3.86	2.787
690	620.9	0.000132	-3.994	2.793
697.2	685.6	0.0002182	-3.661	2.835
761.4	759.8	0.0001706	-3.79	2.88
834.2	855.0	0.0001594	-3.58	2.93
844.3	962.5	0.0002571	-3.53	2.98
950.2	971.1	0.0002017	-3.53	2.98
1069	985.3	0.0002905	-3.511	2.99
1079	1080.0	0.0003079	-3.50	3.03
1094	1095.0	0.0003111	-3.44	3.03
1200	1257.0	0.0003571	-3.44	3.099
1217	1267.0	0.000356	-3.364	3.102
1397	1283.0	0.0004324	-3.40	3.108
1604	1443.0	0.0003902	-3.09	3.15
1621	855.0	0.000798	-3.14	3.16
1653	962.5	0.00071	-3.13	3.172

Hence the graph of stress intensity factor da/dN v/s ΔK cracks growth length:-



By taking the linear equation from the graph of da/dN v/s ΔK we get,

$$Y=0.053x-4.228$$

Paris law,

$$\frac{da}{dN} = C(\Delta K)^m$$

Hence convert this equation into Paris law

$$\text{Log}(da/dN) - \log(\Delta K)^{0.053} = -4.228$$

$$da/dN = 10^{-4.228} \times (\Delta K)^{0.053}$$

$$da/dN = 10^{-4.228} \times (\Delta \boldsymbol{\sigma} \times (\pi a)^{1/2})\text{^}0.053$$

Hence from this equation we get the value of material constant $c=10^{-4.228}$ $m= 0.053$

$$N_f = \int_{0.5}^{5.65} \frac{da}{10^{-4.228} \times (21.357 \times \sqrt{\pi a})^{0.053}}$$

$$= 7.6 \times 10^4 \text{cycles}$$

The estimated life of the Spur Gear having **is 7.6 x 10^4 cycles**

V. Conclusion

The fatigue crack analysis in spur gear is tested experimentally and analytically to determine fatigue crack growth rate and the direction of crack growth and comparing the result of stress intensity factor to determine crack growth rate. The spur gear is tested experimentally under servo hydraulic testing machine by taking its equivalent compact test specimen. The initial crack on spur gear and test specimen is consider same as 0.5mm and tested under dynamic load to evaluate the service life of specimen and spur gear. By using the relation of da/dN v/s ΔK the service life of the gear can be calculated. By testing method up to 7.6×10^4 cycles the specimen sustain without failure.

VI. References

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