Estimation of Micropitting zone in Case Carburised Helical Gear pair.

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Abstract

Gears are in use since long time and for various applications. They are subjected to variable Torque and various rpm to fulfil the need. Being the critical component in any system it is utmost required that they should work as per need without failure. Various design standards are there to guide the design of gear pair but micropitting is still a concern point and very difficult to predict its nature for different application. This research work is carried for mixer gearbox which runs continuously for 12 hours per day at nearly same mean torque.

A specific need is considered, and the gear pairs are designed in such a way that it should meet the recommended design standard. ISO:6336-1996 is considered here for designing the gear pair. A detailed analysis id performed to predict the micropitting zone . This research work performs all the critical analysis which is required for the micropitting test and various output of this analysis is considered for getting the significant findings. Contact line has been given utmost attention at various point to highlight the concerned findings.

To ensure the accuracy of the KISSsoft software is used to calculate the gear pair, and the lubricant film thickness and Nastran is sued for all other structural analysis.

Keywords: Micropitting, Contact line, KISSsoft

Nomenclature

Symbol	Description	Units
b	Face width	mm
g_α	Length of path of contact	µm
C_f	Start of profile evaluation	µm
N_f	Start of active Profile	µm
F_a	Tip form Circle	µm
F_t	Tangential load	N

F_α	Total Profile deviation	µm
F_β	Total Helix deviation	µm
K_a	Application Factor	-
K_v	Velocity dynamic Factor	-
$K_{H\alpha}$	Load Distribution Factor	-
$K_{H\beta}$	Load Distribution Factor	-
L_α	Profile evaluation length	µm
L_β	Helix evaluation length	µm
Z_E	Elasticity factor	(N/mm^2)^0.5
h_y	Lube Film thickness	mm
α_t	Transverse Pressure angle	degree
β_b	Base helix angle	degree
$\rho_{t,Y}$	Radius of curvature	mm

Introduction

Gear Failure may be defined broadly in two types -Lubricant related failure and non-lubricant related failure. The context of this research is related to Lubricant related failure and is Micro-pitting. Micropitting does not start immediately and when started rarely ends up in catastrophic failure. This type of failure may be defined as the very early of sign of wear failure which initiates in the form of grey staining. It may further grow as being progressive or ends up in early stage after fine grinding of the gear surface in mesh. This increases the surface finish of the gear pair but it results in profile deterioration. Deterioration on tooth profile results in the increase of dynamic load which acts between the gear pairs causing more vibration and initial issue to the bearings to which the gear shafts are supported. The nature of micro pitting and its location is not very sure defined and very difficult to establish many times.

1.1 Gear tooth Parameters

To manufacture the gears as per need it is recommended to have a controlling guideline provided to the manufacturer. ISO:1328 is one of the globally recognised standards which is used by most of the gear designers and gear manufacturers. Since micro pitting is surface related failure, it is important to have the metrological parameters as per standard guidelines to reduce the variation. For this research part tooth helix deviation, and profile deviation is important parameter of many others which need to be controlled and monitored. Figure-1 shows the total helix deviation for a helical gear.

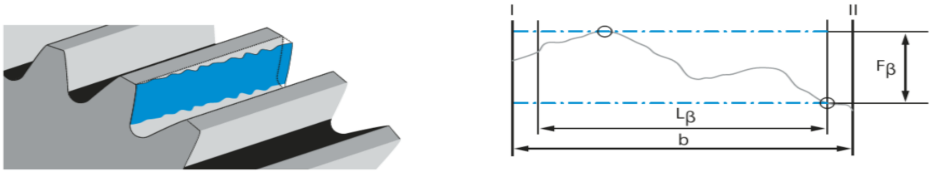

Figure 1 Total Helix deviation

Blue colour line shows the limits and the curve line in Figure1 shows the helix deviation. It must lie in between the upper and bottom limit. For this research work this is considered within limit without any deviation. Thus, a straight line. It includes helix form and helix slope deviation also which adds up to form total helix deviation.

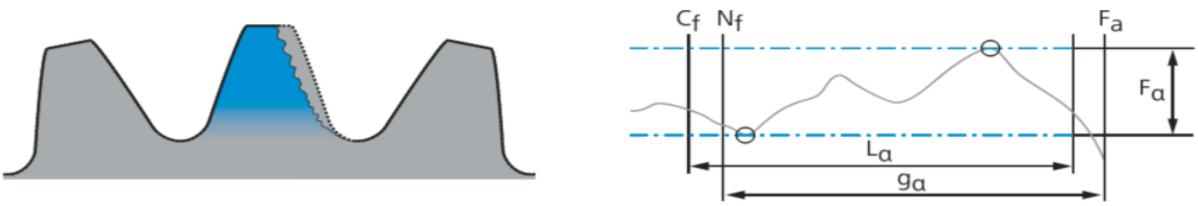

Figure 2 Total Profile deviation

Blue colour line shows the limits and the curve line in Figure 2 shows the profile deviation. It must lie in between the upper and bottom limit. For this research work this is considered within limit without any deviation. Thus, a straight line. It includes profile form and profile slope deviation also which adds up to form total profile form deviation.

Apart from the above two parameter, Cumulative pitch deviation, tooth thickness and radial runout are the other parameters which add up to form the quality of gear.

1.2 Present concern

Mixing industry uses gearbox to rotate the mixing shaft and some of the operation run continuously for 12 hours per day. Such gearboxes are either in single stage or double stage for small power rating. It has been observed that the gears inside these gearboxes deteriorate over a period. This cause to increase the dynamic loads and hence the vibration. This results in bearing failure and sometimes gears failure also. To take the necessary action it is required to study the initiation of micropitting. It is almost impossible to identify the growth zone, after the failure has occurred and sometimes difficult as well to know if micro pitting is the root cause for it.

To continue the research, work the most popular gear pair is considered as per Table-1

Parameter	**Pinion**	**Gear**
No of teeth	24	97
Normal Module	1	

Helix Angle (degree)	13-24'-8"	
Pressure Angle(degree)	20	
Rpm	160	39.6
Material-Case hardened and Ground	20MnCr5	

Table 1.-Gear Pair Data

Gear and Pinion is Case hardened and ground. The quality grade is considered as Grade -6 as per ISO:1328. This gear pair needs to be analysed for all the parameter which ISO standard asks for and then based on the finding the micropitting area need to be estimated.

1.3 Literature Review

Micropitting and related analysis has been carried globally in both analytical and experimental format on a large. Many of the experimental work were done on rollers, discs, bearing and spur gears. Application areas were more associated to wind turbine industry. This section details some of the important literatures which has helped for the current research.

A) **Heli Liu, Huaiju Liu, Caichao Zhu, Ye Zhou [1],** presented a paper on A Review on micropitting studies of steel gears. The team investigated the effect of various parameters like load, lubricant, rpm, geometry factors, surface finish and temperature. For this experiment triple roller disc configuration was used with a facility having a control over lubricant flow, temperature measurement, torque measurement, speed variation. This setup is FZG test setup. The discs were made up of AISI 52100 material with hardness in the range of 60 HRC to 63 HRC. The three discs were arranged in such a way that the line connecting their centroid shall form a triangle. There was a roller of the same material as of disc mounted between the disc. The contact area of disc was set as 1mm. The roller was rotated with power whereas the discs were inserting the pressure on it and were also free to rotate about their own axis. This experiment was conducted for different load cycles having different speeds and contact stress. Various results were plotted in the form of surface profilometry, micropits images, surface roughness for various load cycles. It was found that micropitting initiation was mostly controlled by contact pressure. This can have sufficient change by controlling the slide to roll ratio parameter. No doubt surface roughness and lubricant film was also having important contribution along with contact pressure and slide to roll ratio.

B) **M. N. Webster, C. J. J. Norbart [2],** presented a paper on Experimental investigation of micropitting using a roller disk machine. Test pieces were roller which were of material 17CrMo6 with flat and chamfered profile having hardness 58HRC and 60HRC respectively. OD of both the rollers were grounded. Idea was to generate the same environment which a gear pair have while meshing to each other. Mineral based lubricant was used for this experiment. There were two different grades of lubricant used here in such a way that the total experiment cycle can be continued with these two oils separately. Test pieced were rotate through the rollers with the help of prime mover. The results were plotted for various conditions of oil, temperature, contact pressure surface roughness, load cycles and wear volume. Since these parameters were required to be jolted down so the testing needed to stop time to time. The finding of this experiment was advising more towards low rpm cycle test where the fluid film thickness was getting decreased. Slide to roll ratio was correlated to lubricant film thickness analytically and at very low slide to roll ratio the micro pitting improvement was also observed.

C) **Dario Croccolo, Massimiliano De Agostinis, Giorgio Olmi,Nicolo Vincenzi [3],** presented a paper on a practical approach to gear design and Lubrication. Authors have collected the practical examples which can help in defining the guidelines and important parameters to design a gear pair. The team worked for a spur gear set. Two types of materials are discussed from hardening point such as 18NiCrMo5 & 41CrAlMo7. Asymmetric and symmetric tooth are also discussed. Detailed work started with the basic principle of selection of module, profile shift and gear parameters. Lubrication process and its selection is the key part of this research paper. This paper provides a detailed way of generating the drawings and technical details required to manufacture a gear.

D) **Hasan Ozturk, Mustafa Sabuncu, Isa Yesilyurt [4],** presented a paper on the Early detection of pitting Damages in gears using Mean Frequency of Scalogram. This paper discusses important points related to the defects in gears with respect to the contact ratio and its resultant effect and how to measure such transient effect. Research work concentrates on the time and Frequency domain. Test rig used in this research consists of a two-stage helical gearbox with pitted gears, AC motor with speed control at one end of gearbox and on the other end a DC motor with resistor bank. Both AC and DC motors are connected to the gearbox input and output shaft through pulley and belt system. To meet the load requirement of DC motor the gears face width were reduced from 12mm to 4mm. Vibration signals were collected from accelerometer perpendicular to each other. Various Time and Frequency domain charts are plotted to examine the difference between the healthy gears and pitted gears. Mean Frequencies were considered for monitoring the pitting failure in gears. Initial pits were not observed but the way it grows the vibration signals get amplified and visible differences were found there.

E) **A Oila , B A Shaw,C J Aylott, S J Bull [5],** presented a paper on martensite decay in micropitted gears. This research work was performed for the micropitted gears to find how the microstructure basically martensite layer changes after and during micro pitting. Two helical gears were considered with material as 16MnCr5 steel . The gears were gas carburized and the grain size were limited to size of 7 as per ASTM standard. Back-to-Back test rig was used for the micropitting test. Test cycles were considered from 5 million cycled to 50 million cycles. Mineral oil was used for the gears in the testing. Gear tooth cross section was taken for metallographic examination. Scanning Electron Microscope was used to observe the surface of the cross section. Dark etching regions, white etching bands and mechanical properties were the important analysis parameter. It was concluded that the martensite decay in gears were very much like the same parameters in bearing. It was also observed that micropitting is dependent on contact fatigue.

F) **B R Hohn , K. Michaelis [6],** presented a paper om Influence of oil temperature on gear failures. This research work provided a good information about the behavior of oil at high temperature and its associativity with the gear material. It was found that with elevated oil temperature, oil's viscosity gets reduced, and a thin film is created between the mating tooth surface. This is good in many conditions however the ill effect may be like the chemical agents inside the lubricant become free to react with the metal surface which may affect the gear material endurance limit. It was recommended that the oils shall be selected based on the cooling condition and the temperatures for which it is subjected to. Gearbox must be calculated for thermal condition to establish the max temperature value so that the oil can be selected accordingly.

G) **L. Winkelmann, O. El-Saeed, M. Bell [7],** presented a paper on the effect of Superfinishing on Gear Micropitting. This research work was on the gear surface finish. Standard FZG gear test setup was used to perform this research work. Two set of gears were considered with material of 16MnCr5 with Case Carburized condition and gear quality grade 5. The two set of gears were named as Baseline gears and Superfinished gears. Base line gears were unmodified and having the surface finish of 0.47Ra on average basis. Superfinish gears were having the surface finish with average value of 0.1 Ra. Load cycle with failure criteria was defined for both Load stage test and endurance test with defined hours. The measuring criteria was considered as Profile form deviation. It was found that the baseline gears were showing higher profile form deviation than superfinished gears thus showing micropitting earlier and in advance phase as compared to superfinished gears.

H) **Marco Antonio Muraro, Fabio Koda, Urbano Reisdorfer Jr., Carlos Henrique da Silva[8],** presented a paper on the influence of contact stress distribution and specific film thickness on the wear of Spur gears During Pitting tests. In this research work several factors were considered like relative speed, surface finish, lubrication condition and temperature for their effect on the gears during the testing. For this testing FZG test setup was used. Gear material used was AISI 8620 steel manufactured by shaving and milling operation. Whole experiment was divided in two torque regions as running in Torque value of 135Nm and steady state Torque value of 302 Nm with corresponding test temperatures of 60 degree and 90 degree Celsius respectively. Image analysis was used to identify the wear levels on the gear surfaces. It was concluded that the wear on the gear surface were dependent on lubricant film thickness and was more on milled gear. It was also found that the load sharing functions has huge influence on gear surface deterioration. Wear resistance increased with high surface finish value. On a total, it was concluded that contact stress distribution, lubricant film thickness and surface finish are the parameters responsible for micropitting.

I) **I.S. Al-Tubi, H.Long, J. Zhang, B. Shaw [9],** presented a paper on Experimental and analytical study of gear micropitting initiation and propagation under varying loading conditions. This research work includes both analytical and Experimental analysis. Idea here was to investigate the effect of varying torque on the gears for initiation of micropitting. For the gear micropitting ISO standard 15144-1 was considered with recent revision. Assessment of the micropitting was done through the quantification of pits formed during the cycle and their propagation. Analytical method was used as per the predefined ISO standard to compare the results and finding. The experiment results show the initiation of micropitting at the pinion dedendum which was getting enlarged towards addendum over a period. Analytical study concluded the effect of contact stress and lube film thickness value for the same points responsible for micropitting. Finally after combining all the findings, it was concluded that load, surface finish and lube film thickness are responsible for micropitting.

J) **Michael Hein, Thomas Tobie, Karsten Stahl [10],** presented a paper for Parametric study on the calculated risk of tooth flank fracture of case-hardened gears. This research work followed the ISO standard technical report for the analysis of the surface fracture due to various parameters as guided by the standard document. This research specifies that to avoid micropitting use of advanced process may result in other type of gear failure. This research work included various parameters as per FZG test which included material parameters, tooth flank geometry, external loads, local hertzian contact stress, normal radius of relative curvature and miscellaneous parameters. It was concluded that the guideline of ISO is very much inline with FZG test and the results were also satisfactory.

K) **Aleks Vrcek, Tobias Hultqvist, Tomas Johannesson, Par marklund, Roland Larsson [11],** presented a paper on micropitting and wear characterization for different rolling bearing steels. This research work includes the surface analysis of different bearing steels. These bearing steels are formed in the form of discs which contact to each other and are subjected to contact stress under reduced lube film thickness. Different hardness process was intimated for the ring to study the effect on micropitting. Tribo testing was used to evaluate the wear and plasticity of asperities. It was found that surface hardness difference as an important parameter for surface failure. Along with this it was also found that plain medium caron steel has better surface fatigue strength than alloy steel. Rough surface was getting deteriorated faster than the mating part and this was irrespective of the hardness.

L) **Robin Olson, Mark Michaud, Jonathan Keller [12],** presented a paper on case study of ISO/TS 6336-22 Micropitting calculation. Three different cases were considered such as High speed gear set, Wind turbine gear set and tribo gear set. All the three cases were having helical gears with defined geometrical and material parameter. The geometrical parameters for all the three cases were different and with different speed. The three cases were run at three different Torque ratings such as 265Nm, 300Nm and 400Nm respectively. For each torque value with lubricant oil M-200EP, the specific film thickness was determined. It was found that for Case-1 and Case-2 the specific film thickness was more than unity still there was micropitting which should not be there as per ISO standard recommendation. This released a conclusion that for higher specific film thickness it is difficult to estimate the micropitting.

M) **Nadine Sagraloff, Thomas Tobie, Karstem Stahl [13],** presented a paper on Suitability of the test results of micropitting tests according to FVA 54/7 for modern practical gear applications. This research work is related to the experimental investigation done for the test gears development for the micropitting test. Two sets of material were considered for the test gears as 16MnCr5 and 18CrNiMo7-6 with micro geometry, macro geometry and profile grinding method. The FZG back-to-back setup was used for this experiment. Test rig was including the test gears and slave gears and the arrangement was standard per practice. Bothe the gears with different material were case hardened. Various graphs were plotted with respect to profile deviation and load stage and endurance test. Since new approaches were used along with material and geometric change , at the end of experiment it was found that there were no significant changes in the results as per FVA 54/7 as compared to the new process.

N) **Mao Ueda, Benjamin Wainwright, Hugh Spikes, Amir Kadiric[14],** presented a paper on effect of friction on micropitting. This research work was more on determining the effect of friction on micropitting. To execute the experiment a ball on disc test rig was considered. This test rig was equipped with facility to trace the lube film thickness during the execution of experiment. To vary the Friction, oil with different content were used. Different test oil were detailed out for this experiment to analyze the results. Friction parameter was mapped with respect to the load cycles over a period of time. The total load cycle considered were 8 million cycles. Because of the friction the surface of the balls were damaged. it was visible under 200-micron vision. The pattern of defect was clearly visible as the load cycles were increasing the surface defects were also increasing. Parallelly it was affecting the surface finish of the disc also. Oil film thickness with respect to the load cycles were also plotted for different lubricating oils. It was clearly visible that with change in the content of oil to meet the suitability of pressure bearing capacity the oil film thickness was also improving.

- **Outcome of Literature survey**

  Many papers were under study for this research work, however top fourteen paper's analysis is presented in this work which is useful for further step analysis. The finding are depicted as below:

  - Contact pressure, load distribution along the contact line is important parameter for the surface fatigue.
  - Lubricating oil plays a critical role in micropitting improvement and must be selected accordingly.
  - Lubricating oil must be as per temperature of the system and need.
  - Variable load cycles for the same rpm had a proportional influence on micropitting.
  - Contact line is considered as the typical area for the load distribution analysis.
  - Designing of the gearbox per ISO recommendation meets the field criteria in actual.
  - ISO recommendation for micropitting is not so clear if the lube film thickness exceeds 1 micrometer value.
  - Slide to roll ratio plays important parameter in micropittinig on account of friction.
  - Surface finish of the contacting pair plays an important role for avoiding the micropitting. Better the surface finish lower will be the micropitting failure.
  - Most of the experiments were performed for 18CrNiMo-7-6 or 16MnCr material whereas no research work was visible for 20MnCr5 material.
  - None of the research work were found for gears in mixing applications.

- Most of the research work were aligned with did or roller arrangement very few data was found related to helical gears.
- Pattern of micropitting on the surface was varying per experiments and working conditions along with load cycles.

1.4 Refinement of process for further analysis

Based on the Problem statement and the Literature review, its not the design of gear pair set only but provision of adequate environment is also required which can control the misleading parameter. The gear pair must be placed in such housing which have negligible effect on the gear performance, lube oil must be selected per maximum temperature the gearbox is releasing while in operation. So in line with the problem statement related to gears, bearing selection, housing analysis, shaft calculation, efficiency calculations must be performed before any experimental analysis to be double sure that adequate environment is provided to the gear pair for testing. This research work will consider as part-1 of the project where the complete gearbox design will be elaborated. A detailed analysis of each parameter is required as per finding from Literature review.

1.5 Software packages in use

For designing the gears Kissys 2020 is used, housing analysis is done in Nastran, shaft and bearing calculations are also done in Kissys 2020. Python program is used to develop the lubricant film thickness.

1.6 Gear Assembly

Gearbox model is created in Kisssys as per the need of dimensions as shown in figure-3

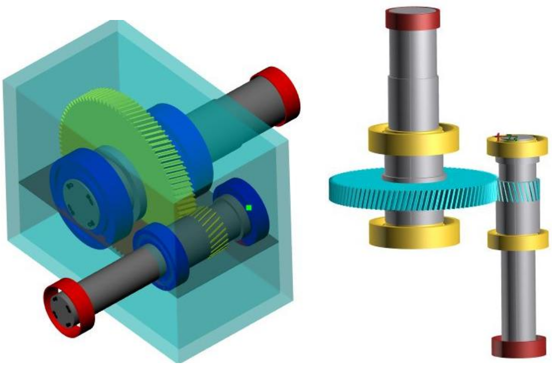

Figure 3 Gearbox Model (Kissys 2020) & Gear pair

The housing will be required to perform the thermal rating and oil level is shown inside the gearbox such that the lower portion of bearing is deep inside it.

- **Stress analysis**

Hertzian theory has been revised by adding some load modification factors to broaden design coverage and to suit the working of gears. Hertzian theory was also adopted by the newly publishing micropitting ISO Technical Report, ISO/TR 15144-1 (2010) to calculate the gear contact stresses along the path of contact, $P_{dyn,Y}$, as shown in Equation-1:

$$P_{dyn,Y} = Z_E * \sqrt{\frac{F_t * X_Y}{b * \rho_{t,Y} * cos\alpha_t * cos\beta_b}} * \sqrt{K_A * K_V * K_{H\alpha} * K_{H\beta}} \quad (1)$$

The factors mentioned inside the Equation -1 is detailed in ISO:6336

- **Micropitting Calculation**

The equation by Dowson and Higginson for the purpose of film thickness calculation has been widely used in engineering applications. The newly published micropitting Technical Report ISO/TR 15144-1 (2010) is based on the Dowson and Higginson method and can be written as Equation 2:

$$h_y = 1600\rho_{n,Y} * G_M^{0.6} * U_Y^{0.7} * W_Y^{-0.13} * S_{GF,Y}^{0.22} \quad (2)$$

$$\lambda_{GF,Y} = \frac{h_y}{R_a} \quad (3)$$

Where,

h_y is representing the Lubricant film thickness.

$\lambda_{GF,Y}$ is representing the specific film thickness

R_a represents the average roughness of the gear pair.

- **Gear Housing analysis**

Gear housing is considered with Material Aluminium 6061-T6. The housing is pre-processed in hypermesh and later checked in Nastran. The Displacement value is shown in Figure -4 and is very low, almost negligible. Corresponding stress and probability of failure for 8 million cycles were checked and are very low, looks like quite unexpected for any failure.

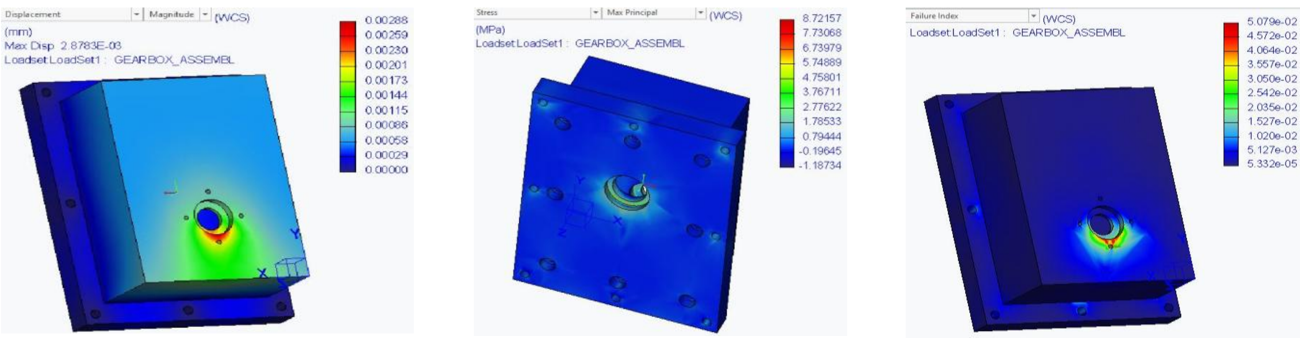

Figure 4 Gearbox Housing FEA result

1.7 Gear geometry parameter

Gear profile and tooth traces were considered as per ISO-1328 recommendation and the corresponding chart is shown below in Figure 5. Green colour and blue colour show the considered tooth profile and trace for gear pair.

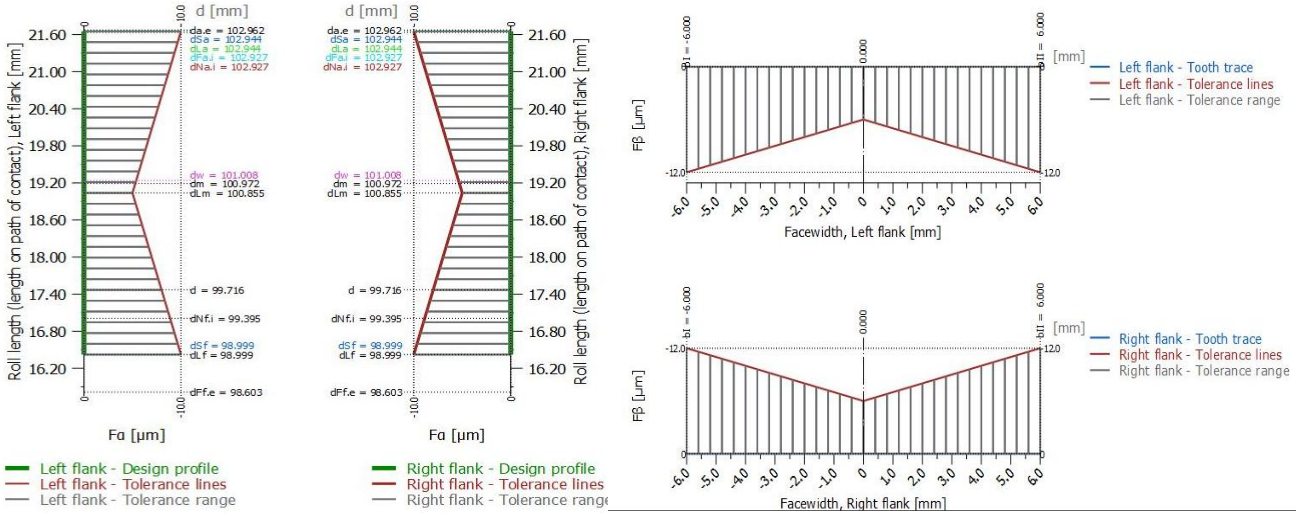

Figure 5 Gear Profile and tooth trace

1.8 Design Reliability of Gearbox

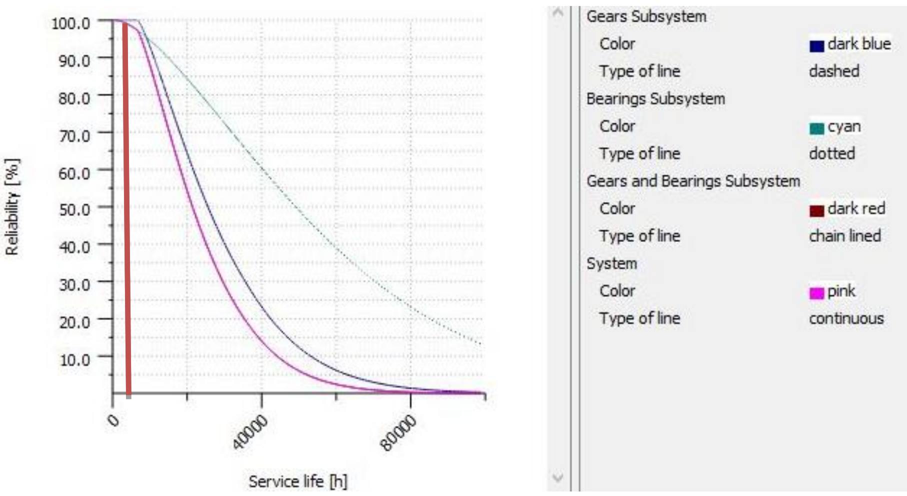

Figure 6 Reliability Graph of Gearbox

Reliability curve shows each of the component is having different reliability percentage over the no of hours in service life. This gearbox is supposed to work for 1000 hours of testing and hence from the curve it is clear that the reliability for all components will be 100%. Thick red line shown in the curve shows reliability of 100% for 5000 hours.

1.9 Thermal rating report of Gearbox

Kisssys has a thermal rating module which can calculate the various losses which the gearbox has while in operation. Heat inside the gearbox is generated because of gear churning loss, gear mess loss, bearing loss and seal losses.

Type of Calculation	Efficiency
Total Input Power (Watt)	370
Total Power Output (Watt)	358.4
Total Power losses (Watt)	11.6
Gearbox efficiency (Total with factors)	96.90%
Gearbox efficiency (Only Gear nesh)	97.60%
Power Loss Data	
Gear churning Loss (Watt)	0.7
Gear Meshing losses (Watt)	8.9
Bearing losses (Watt)	1.2
Seal Losses (Watt)	0.8
Total Power Losses (Watt)	11.6

Table 2.-Thermal Rating Data of Gearbox

Based on the Table 2 data the gear mesh loss is the maximum loss value which the subject gearbox is subjected to. The total losses value is 11.6 watt, so in order to get the system work properly the actual Power rating of gearbox need to be considered as 358.4 watt as against 370 watt.

1.10 Results and Discussions

For the given problem statement and the learning from Literature review the gear pairs are designed accurately. Various parameters which are related to micropitting is compared below.

a. Max stress Distribution in the gear pair

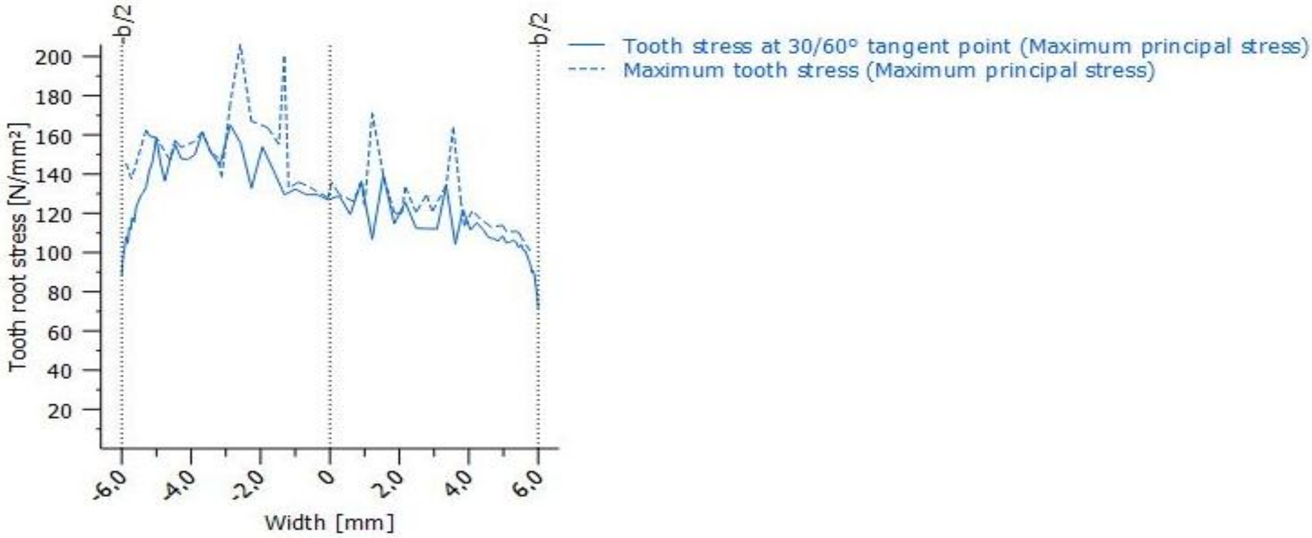

Figure 7 Maximum stress distribution in the tooth pair

Maximum stress value zone found is in the dedendum area of the Pinion. Looks like the zone would be subjected to more fatigue.

b. Specific sliding in Gear and Pinion

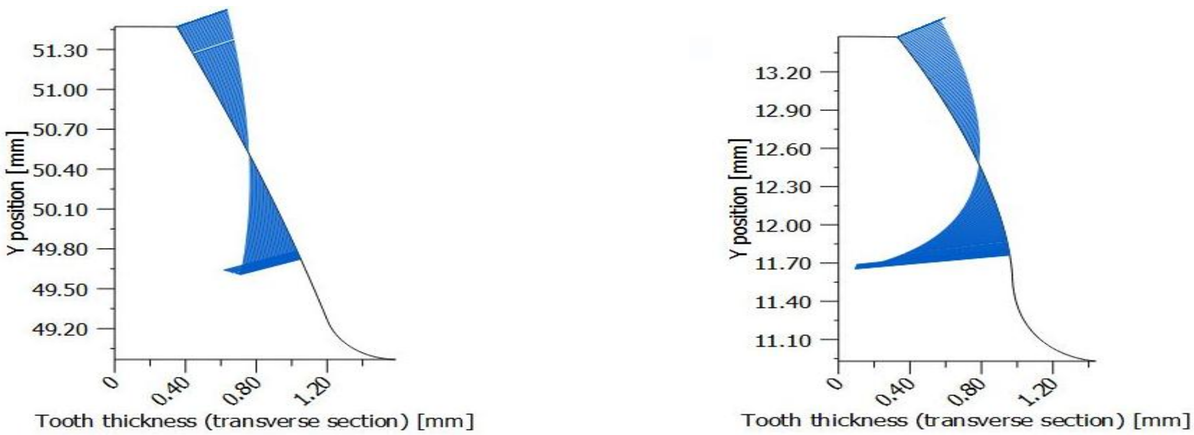

Figure 8 Specific sliding for gear and Pinion

Specific sliding value is negative below the pitch circle diameter and the value is more challenging for the pinion. This is happening because of the sliding of teeth. From the above two details pinion is more susceptible for micropitting than gear and that also below the pcd in dedendum zone.

c. Heat generated in the gear mesh.

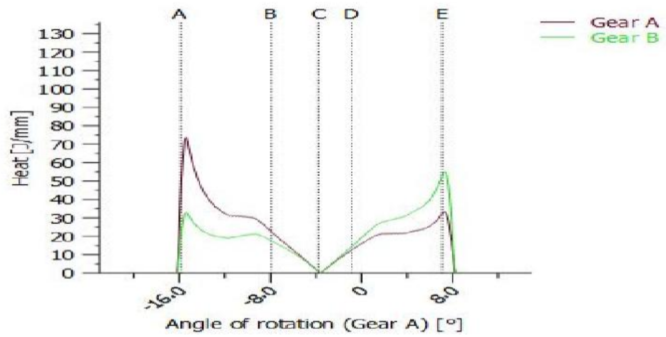

Figure 9 Heat generation for Gear (Gear-B) and Pinion (Gear-A)

Heat generation is good source of identification of friction. Per last point friction was more in pinion and below pcd in dedendum zone. Point C in the Figure-8 is pcd and negative values are below pcd. It is very clear that there is high friction in dedendum zone causing high heat generation in Pinion. This point is also showing the chances of micro pitting will be more towards the pinion dedendum area.

d. Lube Film thickness (Pinion).

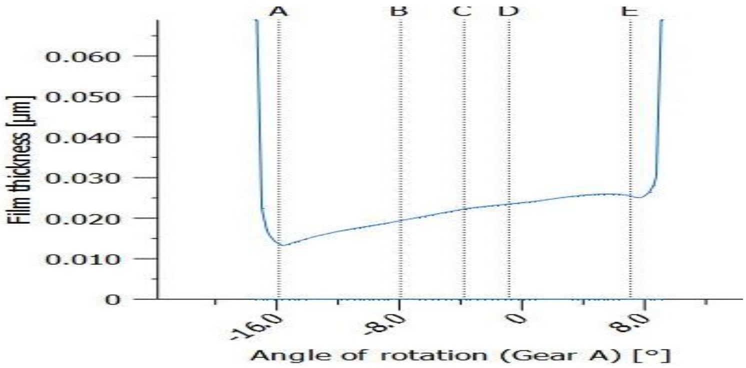

Figure 10 Lube film thickness Pinion (Gear-A)

Lube film thickness is very low in dedendum zone where the friction is high, and temperature is also high. Thus, supporting the low film thickness reason in dedendum zone.

e. Stress distribution for Gear and Pinion teeth

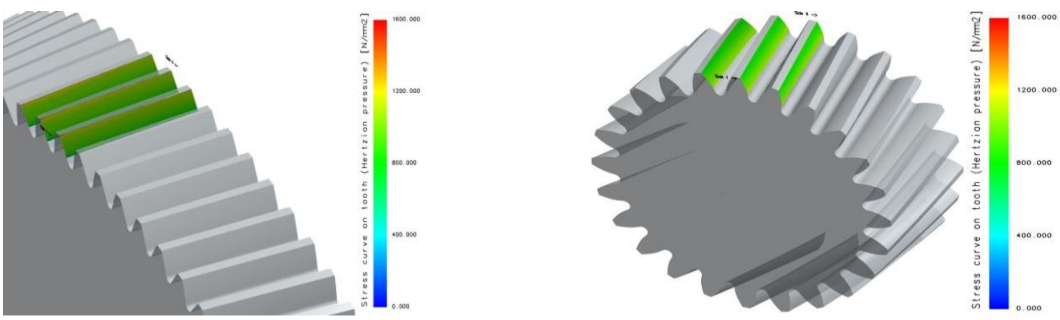

Figure 11 Stress distribution on gear and pinion teeth

Stress distribution looks uniform through out the tooth face width so that's the idea condition and there is no misalignment.

f. Micropitting safety factor

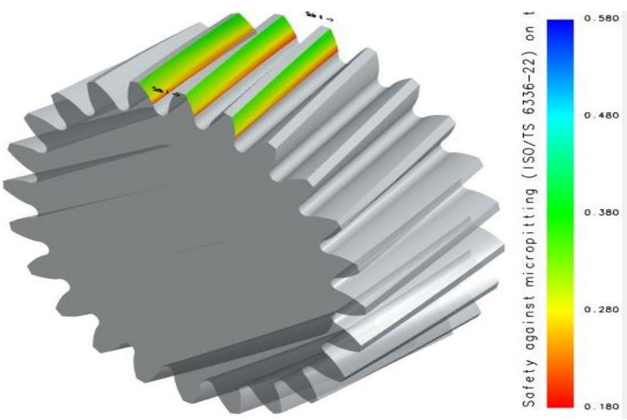

Figure 12 Stress distribution on gear and pinion teeth

As per previous points it is very clear that the micropitting is subjected to be in the dedendum zone of pinion. Figure-11 is also showing the same thing with very low factor of safety as against micropitting.

- Results find above are very much in line with the literature review finding. Friction has once again come as an important parameter for micropitting in the concerned area.
- Lubricant film thickness is lower in the zone where the temperature is high and is also inline with the literature review finding.
- Lubricant film thickness is lower than 1 micrometer thickness and the micropitting will be as per expected zone as per the literature review data.

1.11 Conclusion and Future scope

Gearbox is designed based on the exact guidelines per ISO standard, the detailed analysis shows that micropitting will occur in pinion at dedendum zone instead of having reliable design. Geometry parameters were defined properly and the profile with trace diagram shows exactly what is required as per global standard requirement

A good Future scope could be to perform experimental analysis to be double sure of the results of this analysis. Experimental setup should be applied with variable load over a period of time to capture the effect on surface of gears and other associated parameters.

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