A Project Report

HEAT GENERATION IN CRACKED GEAR PAIR DURING RUNNING CONDITION

Submitted in Partial Fulfilment of the Requirements for the Award of the Degree of

Bachelor of Technology

In

Mechanical Engineering

Submitted by

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CERTIFICATE

This is to certify that, **Divyanshu Srivastava**, Roll No. **1701070**, Enrolment No. **170594** and **Vivek Kumar**, Roll No. **1701037**, Enrolment No.**170431** have carried out the project entitled "**HEAT GENERATION IN CRACKED GEAR PAIR DURING RUNNING CONDITION**" as their 8th semester project under the supervision of Dr. Sankar Kumar Roy, Assistant Professor, National Institute of Technology, Patna. This report is bonafide work done by them for the partial fulfilment of the requirements for the award of the degree of B. Tech in Mechanical Engineering.

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DECLARATION

I hereby declare that this project work entitled "**Heat Generation in Cracked Gear Pair During Running Condition**" was carried out with assistance from **Dr. Sankar Kumar Roy**, Assistant Professor, Department of Mechanical Engineering, National Institute of Technology, Patna. To the best of my knowledge, the matter embodied in the report has not been to any other University/Institute for the award of any Degree or Diploma.

Date:

Place:

Divyanshu Srivastava (1701070) …………………..

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ABSTRACT

Gear transmission systems are very important system in the field of Mechanical Engineering. There are different types of gear available as per the requirement of the work. This thesis concentrates on the investigations regarding the frictional situation in the gear. Effects of friction on the dynamic response. Also, if there is any defect in the gear, say a common defect-tooth crack, what will be the effect of that crack on the stresses developed, temperature change, heat generated, heat flux etc. Heating of gear due to friction is also area of concern in gear transmission. All this detection, analysis was carried out using Finite Element Analysis (FEA), which is very important for engineers as it saves lot of time, money and reduces the number of prototypes as compared to the situation when these things are carried out practically. The modelling was done in CATIA V5 and analysis of the designed component was carried out in ANSYS 2021 to find the corresponding values of stresses, temperature change, heat reaction etc.

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ABBREVIATIONS

Symbol	**Meaning**
FEA	**F**inite **E**lement **A**nalysis
FEM	**F**inite **E**lement **M**ethod
RPM	**R**evolutions **P**er **M**inute

CONTENTS

CHAPTER 1: INTRODUCTION

The gear drives are often called as mechanical drives. Mechanical drives are defined as a mechanism, which helps in transmitting mechanical power over a certain distance usually involving a change in speed and/or torque. The gear transmission systems are widely used in many fields, notably machinery fields, which are employed for transmitting power and changing speed. The necessary condition for a particular gear system is its steady operation. Therefore, the dynamic characteristics and mechanism of a gear failure are a vast subject of interest in the dynamic field.

1.1 Types of gears:

- **Spur Gear**: In case of spur gears, the teeth are cut parallel to the axis of shaft. As the teeth are parallel to the axis of the shaft, spur gears are use only when the shafts are parallel.
- **Helical Gear**: In case of helical gears, the teeth are cut at an angle with the axis of the shaft. The magnitude of helix angle of pinion and gear is same; however, the hand of helix is opposite.
- **Bevel Gear**: They have the shape of a truncated cone. The size of the gear tooth including the thickness and height, decreased towards the apex of the cone. Bevel gears are normally used for the shafts, which are at right angles to each other.
- **Worm Gear**: The worm gears consist of a worm and a worm wheel. The worm is in the form of threaded screw, which meshes with the matching wheel. Worm gear drives are used for the shafts, the axes of which do not intersect and are perpendicular to each other.

1.2 What is a gearbox?

The most common definition of gearbox is that it basically consists of a gear train, or a mechanical unit or component having series of integrated gears within a housing. In fact, as cleared from its name; a box containing gears. In the most basic sense, we can say, the function of a gearbox is like any system of gears, it changes torque and speed between a driver like a motor and a load.

Fig 1. A typical gearbox shown here is a right-angle flange-mounted gearbox from Neugart USA.[8]

1.2.1 Single Stage gearbox

In single stage gearbox, there is only one reduction, i.e., suppose input speed is 100 rpm, therefore in single stage it'll be reduced once in a single step, from 100 rpm to 50 rpm(2:1).

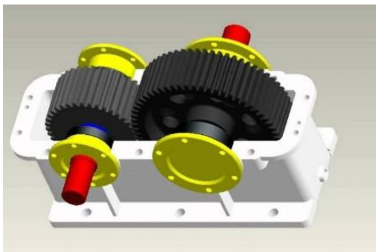

Fig 2. Single Stage Gearbox [9]

1.2.2 Multi Stage gearbox

In a multi stage gear box, there is a successive reduction, i.e., suppose input speed is 1000 rpm, it'll be reduced from 1000 rpm to 5000 rpm in one stage, in another stage it'll be reduced to 3000 rpm and so on.

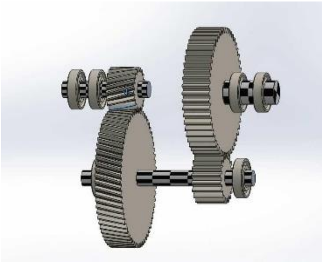

Fig 3. Multi Stage gearbox [10]

The gearbox failure is very much related to gear tooth, including pitting failure, bending failure, crack and broken tooth, which ultimately lead to a complete damage of the gear box. Therefore, it is necessary to analyse the dynamic behaviour of the gear transmission system and effect of its parameters on it. In order to intensify the performance, credibility and dynamic stability of the gear transmission system, the effect of dynamic parameters have been the focus of the research for quite sometime now.

Meanwhile, **sliding friction** between the tooth surfaces has been reported to be one of the main reasons for power loss, unnecessary heat generation, high temperature in gear transmission as well as major source of unsought vibration and noise. Heat generated, deformation, stresses developed, temperature rise, due to friction; all this affects the performance of the gearbox. A fundamental understanding of gear friction is essential as it impacts

- gear scuffing failures due to excessive heat generation and gear contact fatigue lives and associated failure modes of spalling and micro-pitting,
- load-dependent (mechanical) gear mesh power losses, and
- a class of gear vibrations along the direction of the relative sliding and the damping effects along the line of action.

This thesis will only focus on **Simple Pinion-Gear Pair.**

1.3 OBJECTIVES

The objectives of this major project are described below:

- To design two spur gears, a pinion and a gear, in CATIA V5 and do its dynamic analysis in ANSYS 2021.
- Incorporate a crack in one of the teeth of gear and see the effect of stresses developed in healthy gear pair and cracked gear pair and see the heat generation in case of healthy and cracked gear pair.
- To check temperature rise because of excessive heat generation due to friction after 10 revolutions, 50 revolutions and 100 revolutions after doing dynamic analysis in healthy and cracked gear pair.

CHAPTER 2: LITERATURE REVIEW

M Vaishya and **R Singh**[1-3] developed a spur gear pair model with periodic tooth stiffness variation and sliding friction based on an assumption that the load is shared equally among all the teeth in contact. However, the assumption of equal load sharing gives us a simplified expressions and analytically possible solution, but as far as realistic model is concerned, it may not be feasible.

Wei Li, **Pengfei Zhai** and **Iei Ding**[4] paid attention on the heating problem of gear due to friction. Tooth surface temperature field of spur gear or helical gear is compared and their thermal characteristic is studied. Further they derived a calculation formula to find out frictional heat flux and convective heat transfer coefficient which take different surfaces of gear tooth in consideration. They built finite element parametric model for thermal analysis and that model realized the automatic parametric model., loading and generation of temperature field by ANSYS Parametric Design Language (APDL) program.

Khaldoon F. Brethee, **Fengshou Gu** and **Andrew D. Ball**[5], did research on frictional effect on dynamic response of gear systems and diagnostics of the tooth breakage. In this they worked on meshing model, gear tooth meshing process which tells us that the relative contact motions between two compressed elastic bodies, here gear teeth, are the origin of internal excitations of vibration in gearing. Further they worked on varying meshing stiffness, Varying friction excitations between tooth surfaces which tells us that friction forces and the nonlinearity excitation between tooth contact surfaces are another considerable source of vibration. To further carry out their research, they worked on dynamic model and method of its solution, here they presented their models in terms of studying the influence of tooth modifications on gear dynamic behaviour.

Vijay Karma and **AK Agrawal**[6], used analytical approach in their research. Calculated all the stiffness values, viz., pinion tooth stiffness, gear tooth stiffness and single tooth mesh stiffness, by using a computer program in MATLAB. Their research was done for ideal spur gear, however they proposed idea to perform the analysis by incorporating defects in spur gear profile such as - tooth crack.

Zheng Li and **Ken Mao**[7], did research and came to conclusion that in static analysis, the friction can increase values, but due to reliable friction there is a slight decrease in noise. Further they researched on how in dynamic analysis, the friction decreases the harmful responses to the dynamic excitation and also the transient responses are weakened and the transmission error result line becomes steadier and more regular. To further carry out their research, they focused on frictional effects on bending tensile stress where the moment when the frictional shear stress disappears embroils that the gear teeth are getting contacted at pitch point, and the frictional effects becomes opposite from there on.

CHAPTER 3: FINITE ELEMENT ANALYSIS

3.1 Introduction to Finite Element Analysis

Finite Element Analysis (FEA) was developed in 1943, who used Ritz method of numerical analysis and minimization of variational calculus to obtain approximate solutions for system of vibration. It is the simulation of the physical phenomenon using a mathematical technique which is referred to as the Finite Element Method (FEM). This process is one of the cores of Mechanical Engineering, as well as many other things related to it. It is also one of the main principles used in the development of simulation software, which are used by engineers to cut short the number of physical prototype and run virtual experiments to optimise their time and also save expenses.

FEA consists of computer model of a required component on which constraints are imparted and then it’s analysed for the specific results. It is used in the design of the new products and processing of the existing product.

All real-life objects are continuous. This means there is no physical gap between any two consecutive particles. As per material science, any object is made up of small particles, particles of molecules, molecules of atoms, and so on and they are bonded together by the force of attraction. Solving a real-life problem with the continuous material approach is difficult. The basis of all numerical methods is to simplify the problem by discretizing (discontinuation) it. In other words, nodes work like atoms and with gap in between is filled by an entity called an element. Calculations are made at the nodes and results are interpolated for the elements. All the numerical methods including the Finite Element Method follow the discrete approach. Meshing (nodes and elements) is nothing but the discretization of a continuous system with infinite degree of freedoms to a finite degree of freedoms. The basic idea of FEA is to make calculations at only limited (Finite) number of points and then interpolate the results for the entire domain (surface or volume). Any continuous object has infinite degrees of freedom and it’s just not possible to solve the problem in this format. Finite Element Method reduces the degrees of freedom from infinite to finite with the help of discretization or meshing (nodes and elements). The Finite Element Method only makes calculations at a limited (Finite) number of points and then interpolates the results for the entire domain (surface or volume). If in case there is a structural failure in a particular model, then FEA may be used for help to determine modification in the design to meet the new condition.

FEA is a good choice for analysing problems over complicated domains (like cars and oil pipelines), when the domain changes (as during a solid-state reaction with a moving boundary), when the desired precision varies over the entire domain, or when the solution lacks smoothness. FEA simulations provide a valuable resource as they remove multiple instances of creation and testing of hard prototypes for various high-fidelity situations.

There are generally two types of analysis which are commonly used in the industry: 2-D modelling and 3-D modelling. While 2-D modelling is very simple and allows the analysis to be performed on comparatively normal computer, but it doesn't give very accurate results. 3-D modelling however is not simple unlike the former, gives more accurate results but at the cost of ability to run on all computers faster.

To run an FEA simulation, first of all a mesh is generated which contains millions of small elements which make up for the whole component. This the way of interpreting a 3-D object into series of mathematical nodes that can be analysed. The quality and sizing of this mesh can be altered depending upon how complex or a simple simulation is required. Each of these small elements are subjected to calculations, with these mesh refinements combine to produce the final result of the whole structure. These approximate calculations are generally polynomial, with interpolations occurring across small elements, which means that values can be determined at some points but not all. The points where values can be determined are known as nodal points and are generally found at the boundary of the element.

3.2 Advantages of FEA/FEM

From the above discussions, it is evident that the Finite Element Analysis has some advantages. These are:

- Better **Visualization** of Failure Location
- Lower down the **Design cycle time**

- Decrease the **Number of prototypes**
- Cut the **Testing cost**
- **Optimum design** can be achieved faster

In this project work, designing of the component is done on **CATIA V5** and analysis is done on **ANSYS 2021**.

3.3 MESHING

FEM uses Lagrangian or Eulerian meshing criteria. To handle the deformation of a material, Lagrangian mesh is redefined in almost each step. Pinion and gear meshing are very important for accurate process simulation. A finer mesh will give finer granularity. If the number of elements is increased then solution time is also increased. Element order of the mesh is kept linear, adaptive sizing is used while generating the mesh. Major number of elements in the mesh are **Tetrahedron** and some of them are **Wedge (Pyramid).**

3.4 BOUNDARY CONDITION

The boundary condition helps the user to determine the interaction of component with other objects in simulation. The boundary conditions which are used very often in explicit dynamic analysis are: end time which is very important without this simulation cannot run, number of steps, current step number etc.

3.5 LOADING

To get the required results like deformation, stresses, angular velocity, strain energy etc. some inputs are given which is called as loads. Loads can be of any type like forces, pressures, velocity, acceleration, temperature etc. In explicit dynamic analysis of pinion and gear, load is given as the angular velocity to the pinion and remote displacement to the gear in the direction of its axis, by setting one DOF free while keeping other 5 constrained and setting the behaviour of the body to rigid rather than deformable (pre-set condition).

CHAPTER 4: MODELLING AND ANALYSIS

4.1 Modelling in CATIA V5

The model of the pinion and gear was designed in **CATIA V5** by taking the optimum parameter of pinion and gear like module(**m**), number of teeth(**z**), pressure angle and rest other parameters were calculated using module(**m**) and number of teeth(**z**), as stated below:

Pitch circle radius, $\mathbf{R_p}$=m*z/2

Base circle radius, $\mathbf{R_b}$=0.94*R_p

Addendum circle radius, $\mathbf{R_a}$=R_p+m

Dedendum circle radius, $\mathbf{R_d}$=Rp-1.25*m

Fillet radius, $\mathbf{R_f}$=0.4*m

4.1.1 Design of Pinion

Smaller gear in two mating gears is called pinion. To design pinion following parameters were taken into consideration:

Parameters	**Values**
Number of teeth(**z**)	20
Module(**m**)	3 mm
Pitch circle radius, $\mathbf{R_p}$	30 mm
Base circle radius, $\mathbf{R_b}$	28.2 mm
Addendum circle radius, $\mathbf{R_a}$	33 mm
Dedendum circle radius, $\mathbf{R_d}$	26.25 mm
Fillet radius, $\mathbf{R_f}$	1.2 mm
Face width	40 mm

Table 1. Design Parameters of Pinion

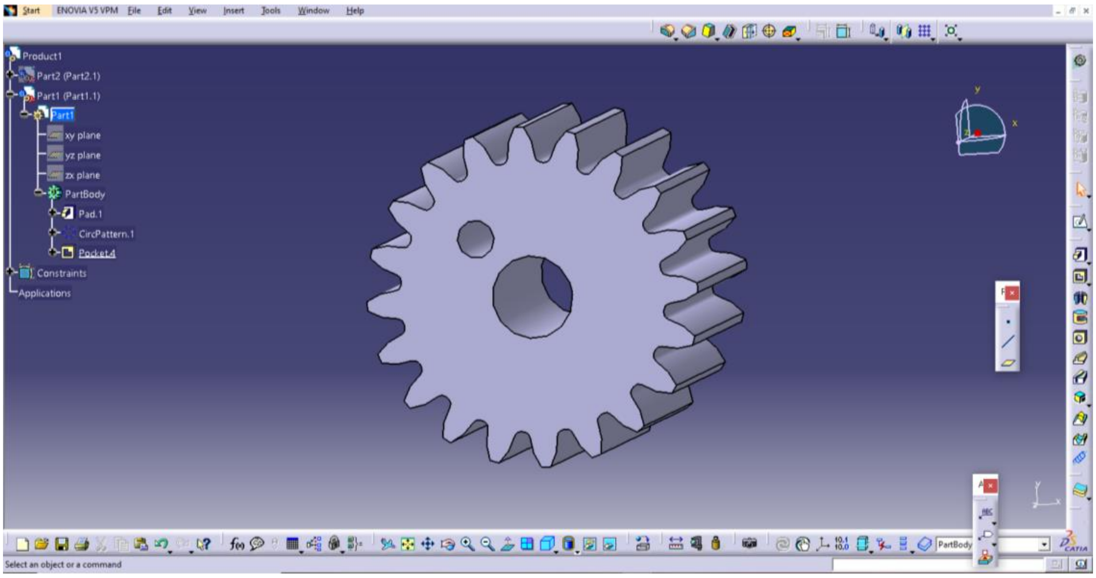

Fig 4. Pinion Design

4.1.2 Design of Gear

Larger part in two mating gears is called gear. To design the gear following parameters were taken into consideration:

Parameters	**Values**
Number of teeth(**z**)	41
Module(**m**)	3 mm
Pitch circle radius, $\mathbf{R_p}$	61.5 mm
Base circle radius, $\mathbf{R_b}$	57.81 mm
Addendum circle radius, $\mathbf{R_a}$	64.5 mm
Dedendum circle radius, $\mathbf{R_d}$	57.75 mm
Fillet radius, $\mathbf{R_f}$	1.2 mm
Face width	40 mm

Table 2. Design Parameters of Gear

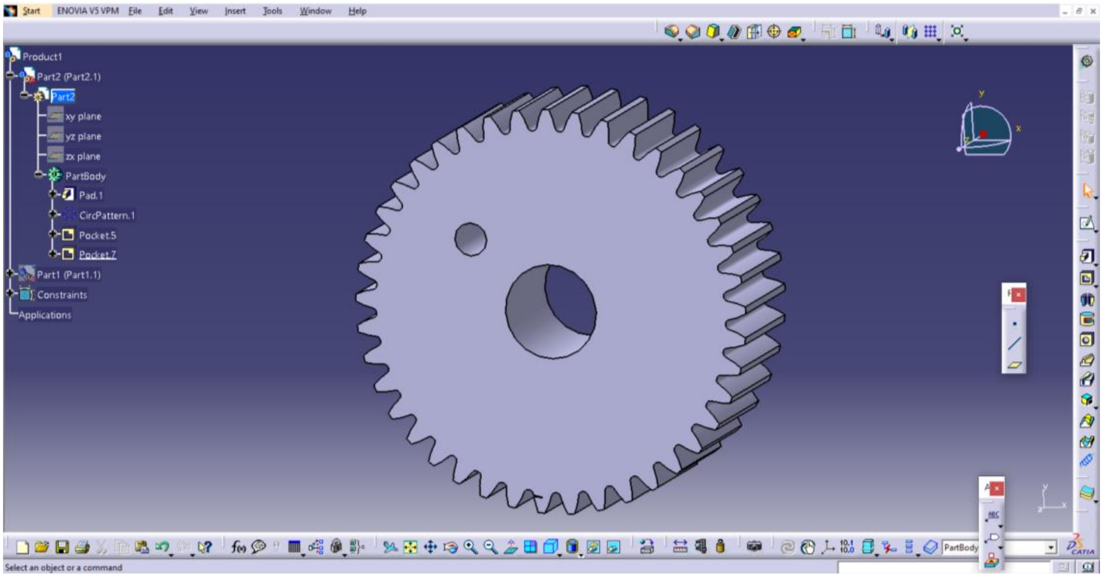

Fig 5. Gear Design

4.1.3 Assembling of the model

Assembly of pinion and gear is done in CATIA V5 using proper assembly constraints and separation. The final result achieved is shown in figure below.

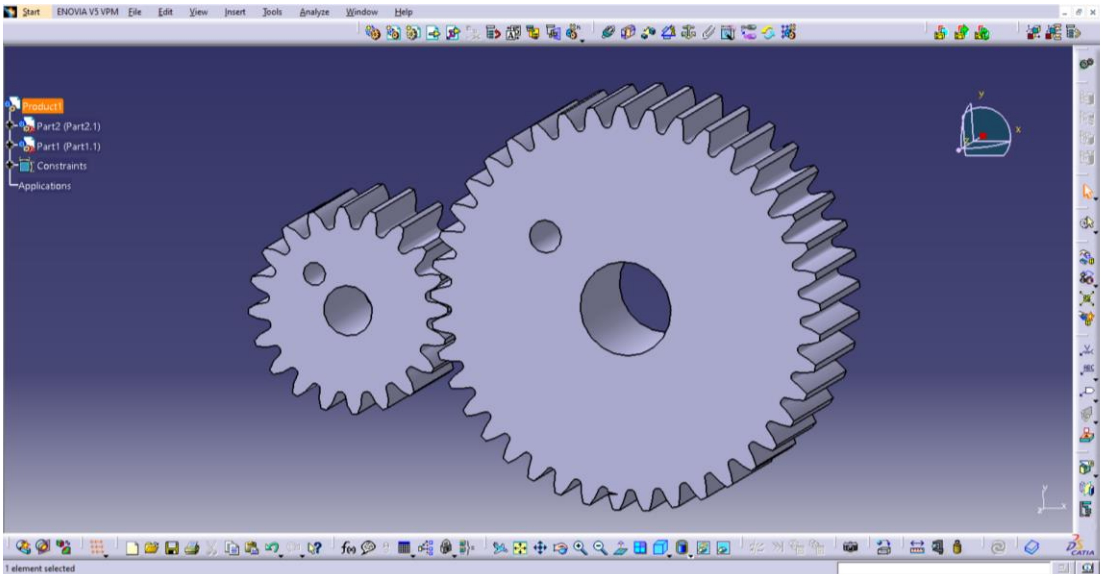

Fig 6. Assembled model

4.1.4 Modelling Crack in Gear

To carry out required analysis, a crack was modelled of depth **3.091 mm** in gear in one of the teeth which is in contact with the pinion, as shown below.

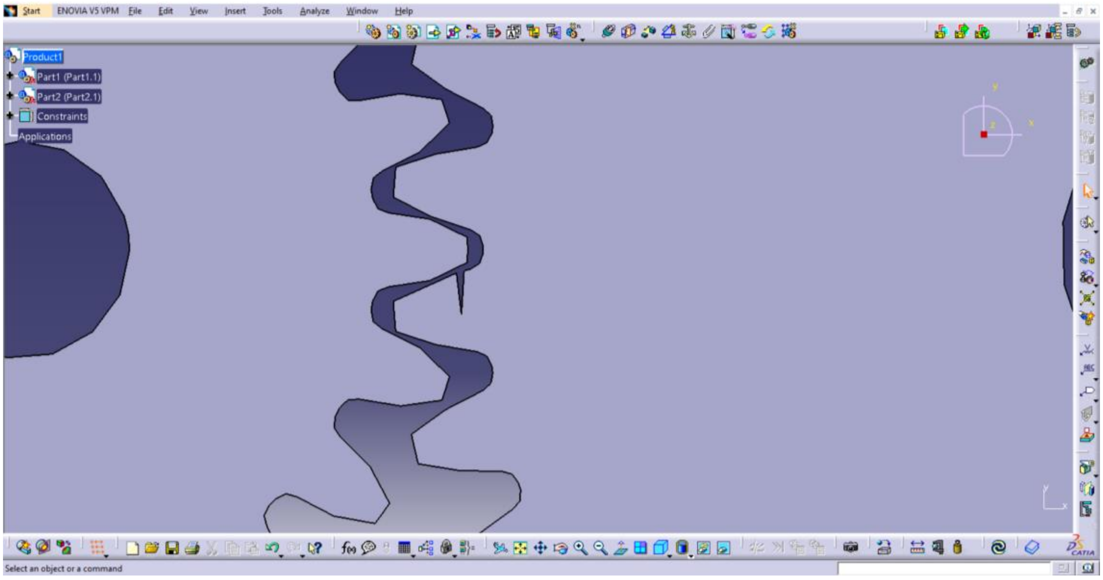

Fig 7. Modelling a Crack in Gear

4.2 Analysis of the component in ANSYS

Analysis of the component was carried out in ANSYS 2021. To see the effect of friction in the gear and pinion explicit dynamic analysis is carried out and further transient thermal analysis was carried out to see the temperature rise in the component and heat generation arose as a result of dynamic analysis.

4.2.1 Explicit dynamic analysis of Healthy Gear Pair

In ANSYS 2021, explicit dynamic analysis was carried out with proper meshing, boundary and input condition

Input Speed= 100 rpm

End time= 0.0001 s

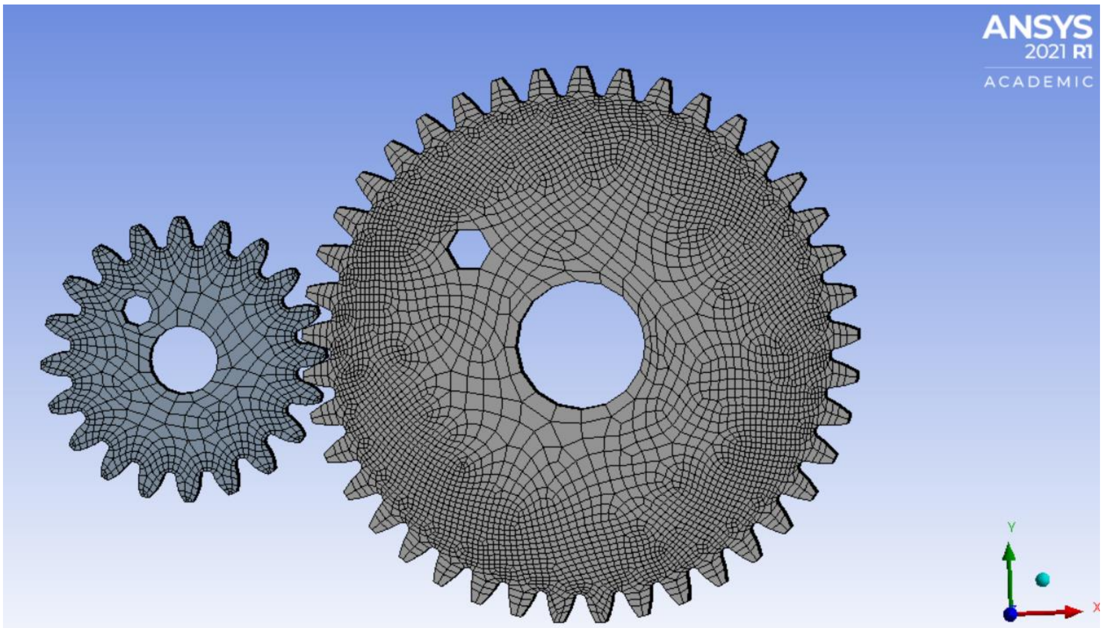

Fig 8. Meshed view of the Healthy Gear Pair

After doing the dynamic analysis of healthy gear pair, result of stress developed due to it is shown in the figure below.

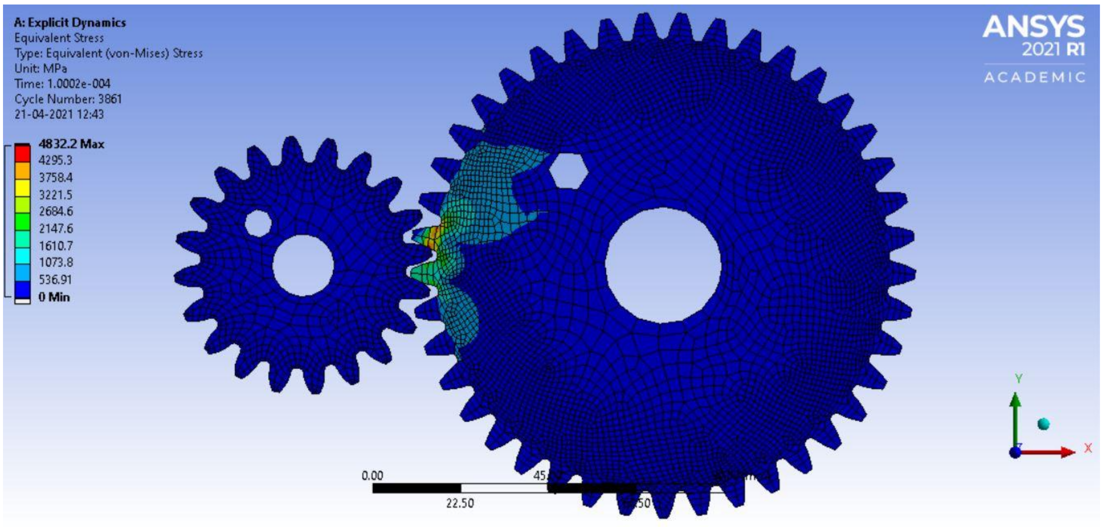

Fig 9. Stress developed in healthy gear pair

4.2.2 Explicit dynamic analysis of Cracked Gear Pair

In ANSYS 2021, explicit dynamic analysis was carried out for cracked gear pair with same meshing, boundary and input condition as in the case of healthy gear pair, and results are shown below.

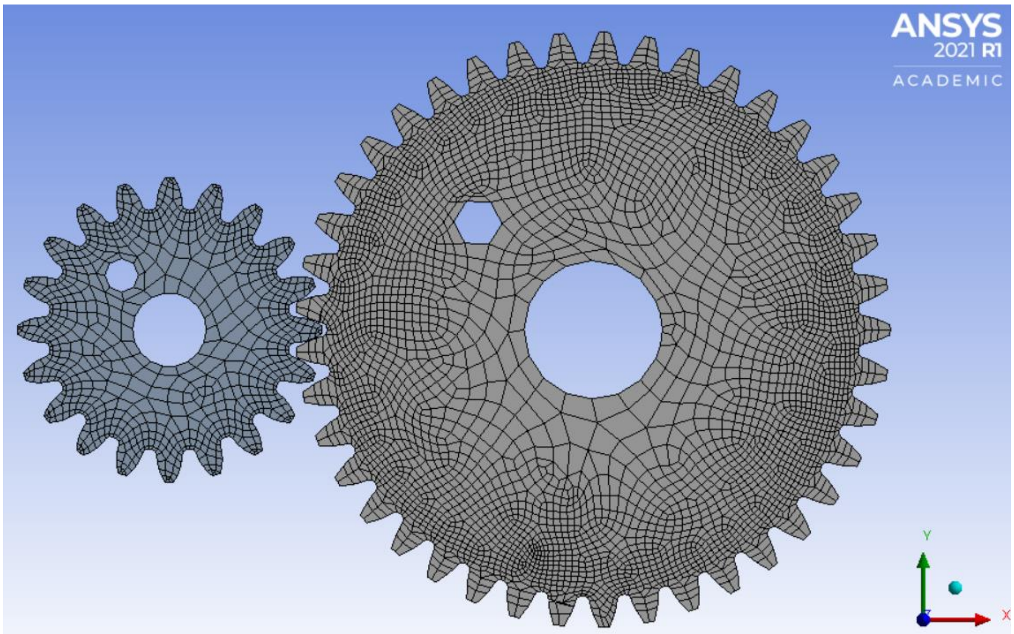

Fig 10. Meshed view of cracked gear pair

After doing the dynamic analysis of cracked gear pair, result of stress developed due to it is shown in the figure below.

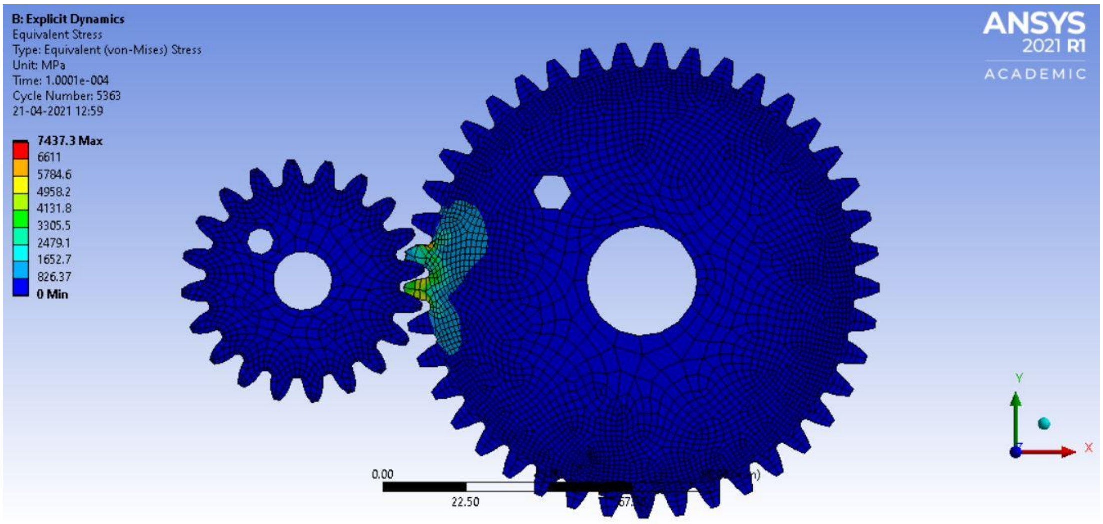

Fig 11. Stress developed in the cracked gear pair

4.2.3 Transient thermal analysis of healthy and cracked gear pair

After doing the dynamic analysis of the healthy gear pair, transient thermal analysis was incorporated in the explicit dynamic analysis in project schematic of ANSYS workbench window, to get the temperature rise, heat flux due to friction.

Initial temperature of the component = 22 ^{o}C

Since the material is structural steel, therefore heat flux for steel which is 23518.32 W/m^2, was given as input condition.

Also, the other input condition was to insert convection with film coefficient of stagnant air – simplified case and ambient temperature as 22 ^{o}C.

In the dynamic analysis, the input speed was given as 100 rpm, but due some limitation of the system on which analysis was performed, to do the transient thermal analysis smoothly input speed was set to 10 rpm.

After setting all the condition, analysis was carried out and temperature output was checked after 10 revolutions, 50 revolutions and 100 revolutions.

The result of the analysis is shown below in the figure.

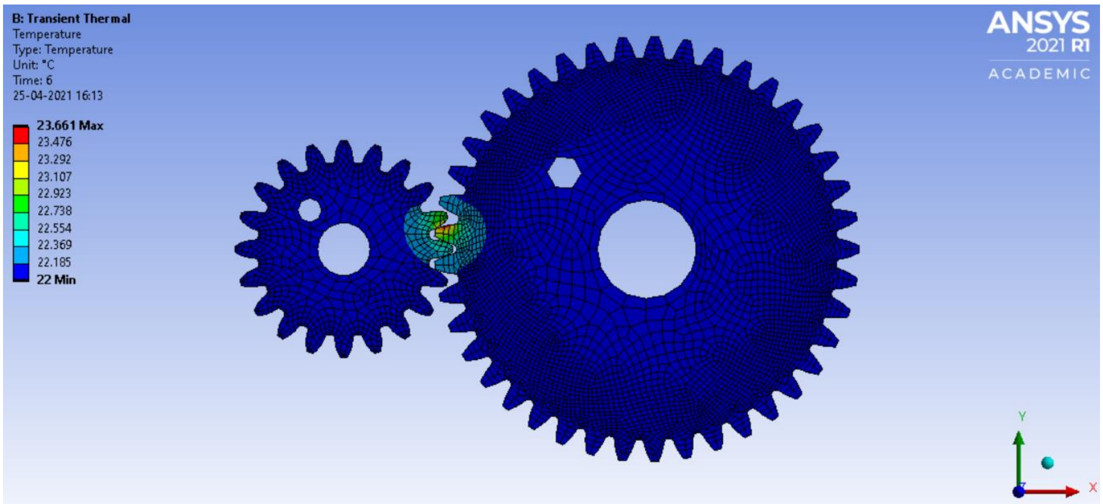

Fig 12. Temperature change after 100 revolutions

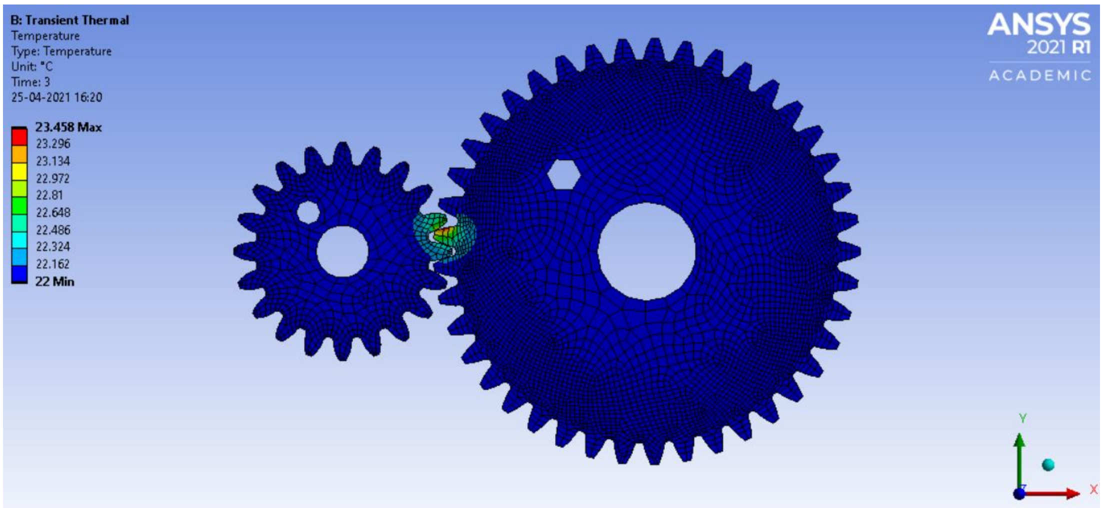

Fig 13. Temperature change after 50 revolutions

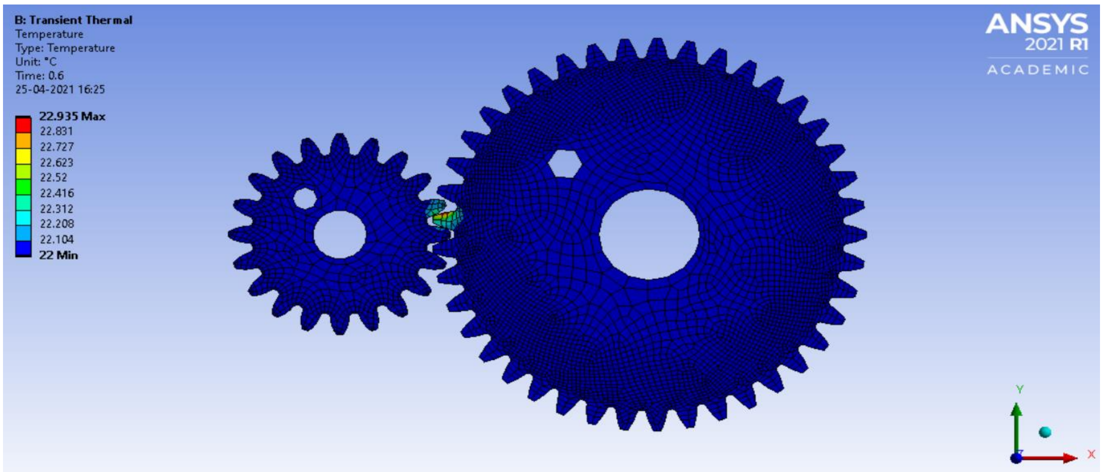

Fig 14. Temperature change after 10 revolutions

After doing the analysis of healthy gear pair to get the temperature change for 10, 50 and 100 revolutions, same analysis was done for cracked gear pair too and temperature change was checked for 10 revolutions, 50 revolutions and 100 revolutions.

Further analysis was done on both healthy and cracked gear pair to get the heat flux, as shown in the figures below.

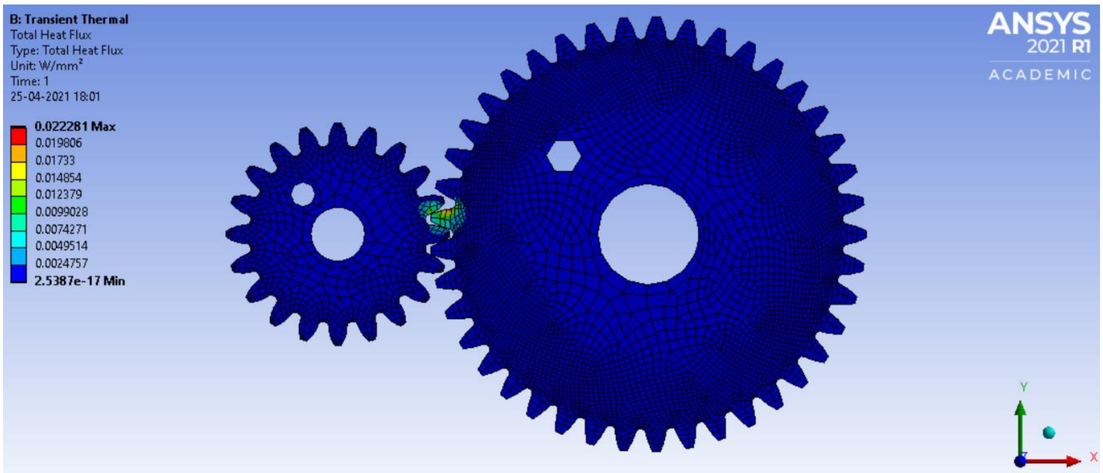

Fig 15. Heat Flux in Healthy gear pair

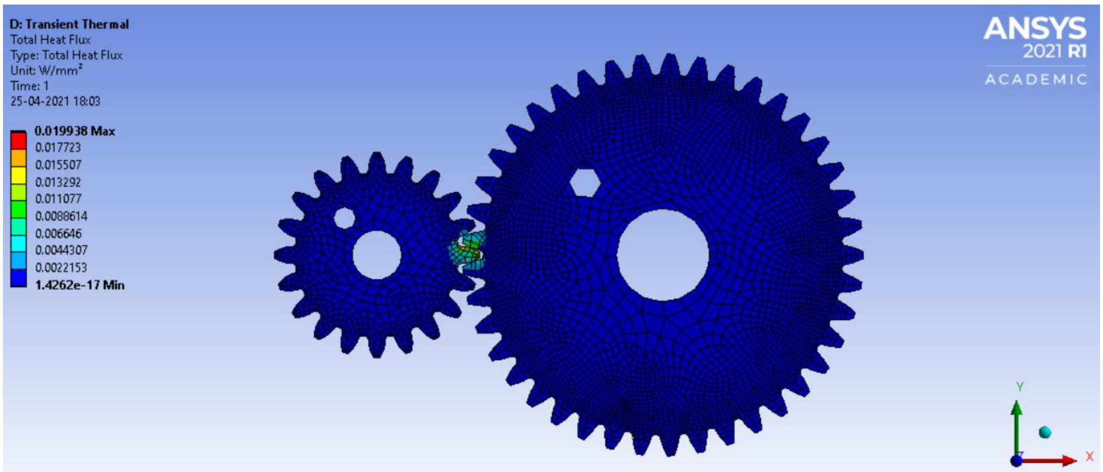

Fig 16. Heat Flux in Cracked gear pair

CHAPTER 5: RESULTS AND DISCUSSION

No research work is complete without result and some discussions about it. All the findings need to be justified properly. So, in this chapter, whatever the analysis has been done, whatever outcomes have come, everything is discussed and justified.

5.1 Results and Discussions

- Firstly, after doing the explicit dynamic analysis the stresses values have been different for healthy and cracked gear pair.

  In cracked gear pair, the stress at the crack point is more than that of healthy gear pair as it's clearly evident from figure 11. Simple reason for this is due to stress concentration, which says that if there is any irregularity or crack in the component then stresses in the vicinity of that irregularity is higher than nominal stress.

  As a result of this, strain energy is high and strain energy to heat is also high.

- Moving on, further carrying out explicit dynamic analysis followed by transient thermal analysis, temperature change was checked after 10 revolutions, 50 revolutions and 100 revolutions.
  The results for 100 revolutions are shown in the graph below

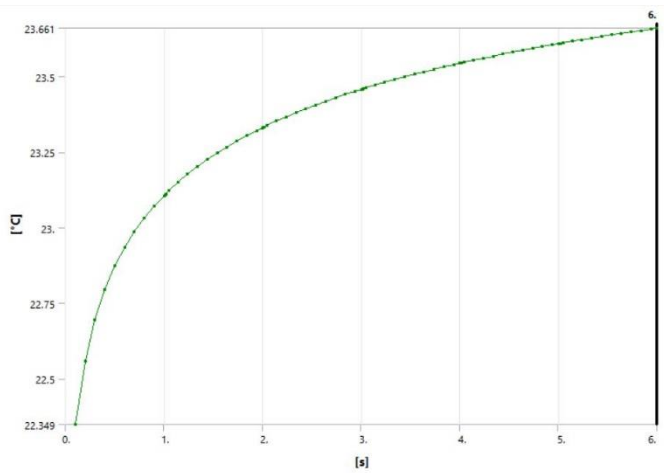

Fig 17(a). Temp v/s time graph for 100 revolutions for healthy gear pair

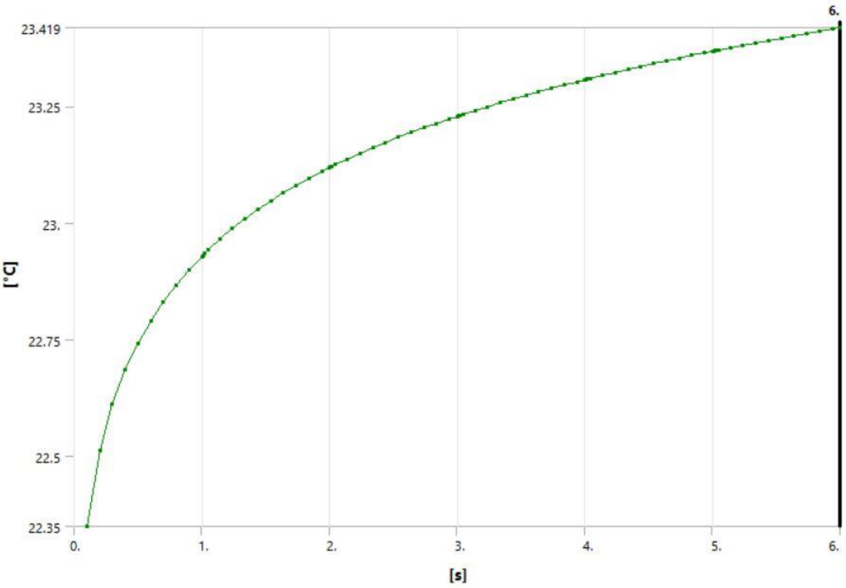

Fig 17(b). Temp v/s time graph for 100 revolutions for cracked gear pair

As shown above in figure 17(a) and Figure 17(b), the temperature change in healthy gear pair is more than the temperature change in cracked gear pair for 100 revolutions. In healthy gear pair temperature was found to be **23.661 ºC**, where as in cracked gear pair temperature was found to be **23.419 ºC**, slightly more than the healthy pair.

- Further analysis was carried out for 50 revolutions, for both cracked and healthy gear pair. The results are shown below in the graph

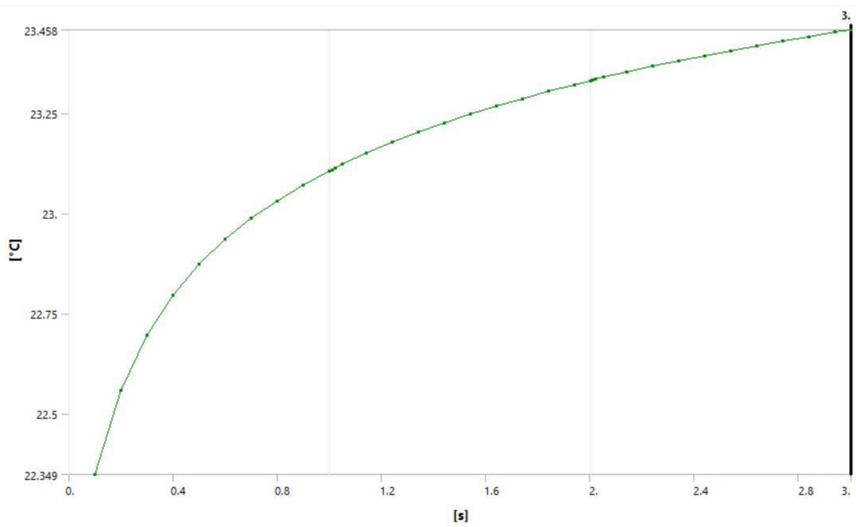

Fig 18(a). Temp v/s time graph for 50 revolutions for healthy gear pair

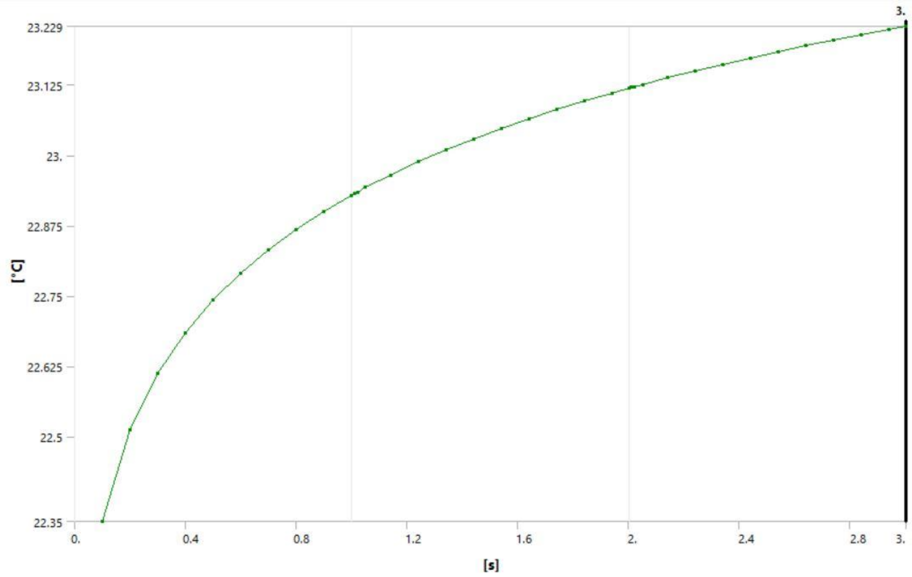

Fig 18(b). Temp v/s time graph for 50 revolutions for cracked gear pair

As shown in above figure 18(a) and 18(b), the temperature change in healthy gear pair is again more than the temperature change in cracked gear pair for 50 revolutions. In healthy gear pair temperature was found to be **23.458 ºC**, where as in cracked gear pair temperature was found to be **23.229 ºC**, slightly more than the healthy pair.

- Again, transient thermal analysis was carried out after dynamic analysis to check the temperature change after 10 revolutions for healthy as well as cracked gear pair. The results are shown in the graph below.

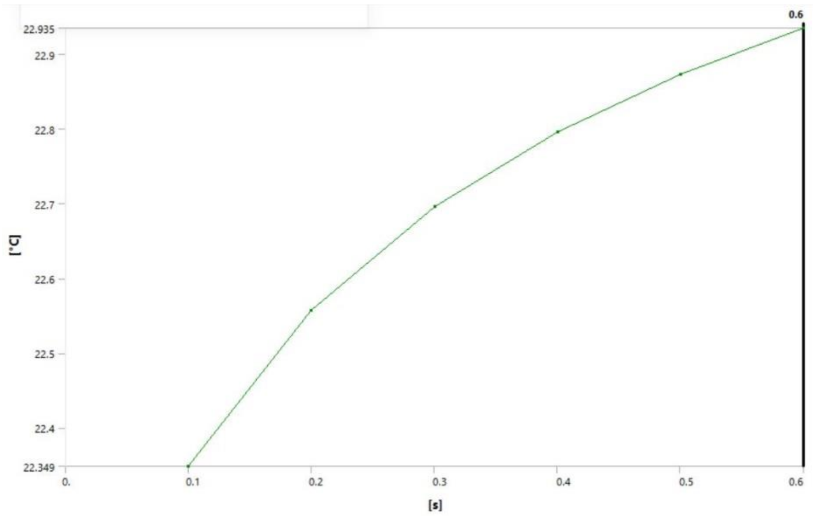

Fig 19(a). Temp v/s time graph for 10 revolutions for healthy gear pair

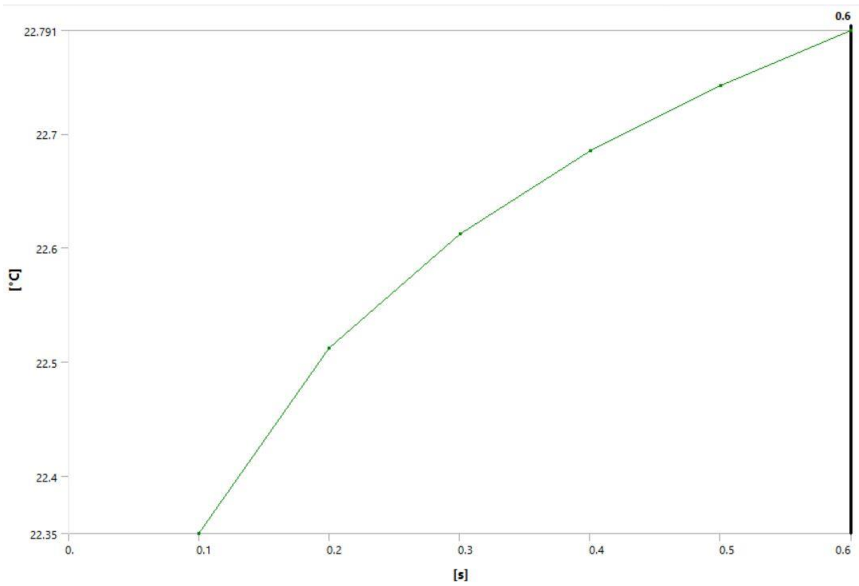

Fig 19(b). Temp v/s time graph for 10 revolutions for cracked gear pair

As shown above in figure 19(a) and 19(b), once again it was seen that the temperature change in healthy gear pair is more than the temperature change in cracked gear pair for 10 revolutions. In healthy gear pair temperature was found to be **22.935 ºC**, where as in cracked gear pair temperature was found to be **22.791 ºC**, slightly more than the healthy pair.

- As discussed above, it's clearly evident from all the above graphs that at higher revolutions temperature change is more than that at lower revolutions. For instance, in healthy gear pair for 100, 50 and 10 revolutions the temperature change are **23.661 ºC**, **23.458 ºC** and **22.935 ºC** respectively. Also, in cracked gear pair for 100, 50 and 10 revolutions the temperature change are **23.419 ºC, 23.229 ºC** and **22.791 ºC.**

  This is mainly due to as speed increases, heat generation also increases, therefore increasing temperature change.
- Since, in case of 100 and 50 revolutions temperature change is very minute, so to make things clearer the values are represented in tabular form below.

Time(s)	Temperature (^oC)
1	23.106
2	23.331
3	23.458
4	23.544
5	23.609
6	23.661

Table 3: Temp. Change for 100 revolution(healthy)

Time(s)	Temperature (^oC)
0.5	22.873
1	23.106
1.5	23.247
2	23.331
2.5	23.406
3	23.458

Table 4: Temp. Change for 50 revolution(healthy)

Time(s)	Temperature (^oC)
1	22.929
2	23.125
3	23.233
4	23.310
5	23.371
6	23.458

Table 5: Temp. Change for 100 revolution(cracked)

Time(s)	Temperature (^oC)
0.5	22.743
1	22.929
1.5	23.047
2	23.119
2.5	23.184
3	23.229

Table 6: Temp. Change for 50 revolution(cracked)

- Further, in transient thermal analysis a reaction probe was inserted to check the heat reaction for healthy as well as for cracked gear pair. The result in the form of graph of Heat(watt) and time(sec) is plotted in ANSYS 2021 and shown below.

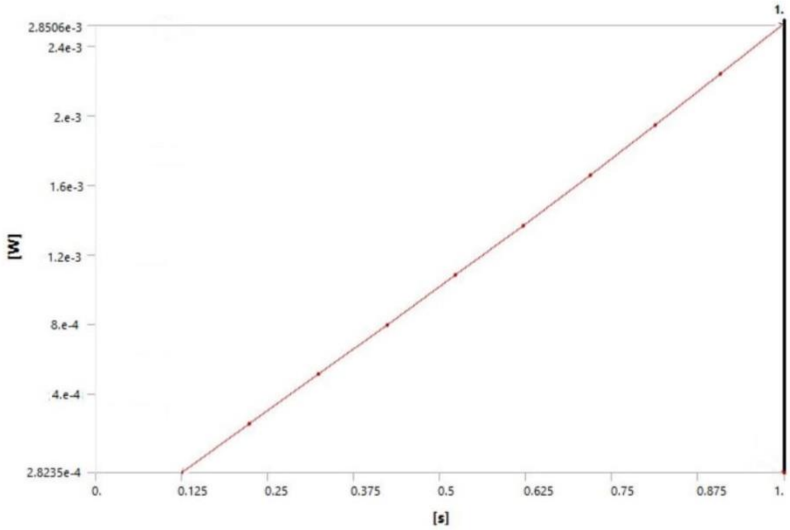

Fig 20. Heat v/s Time graph for heathy gear pair

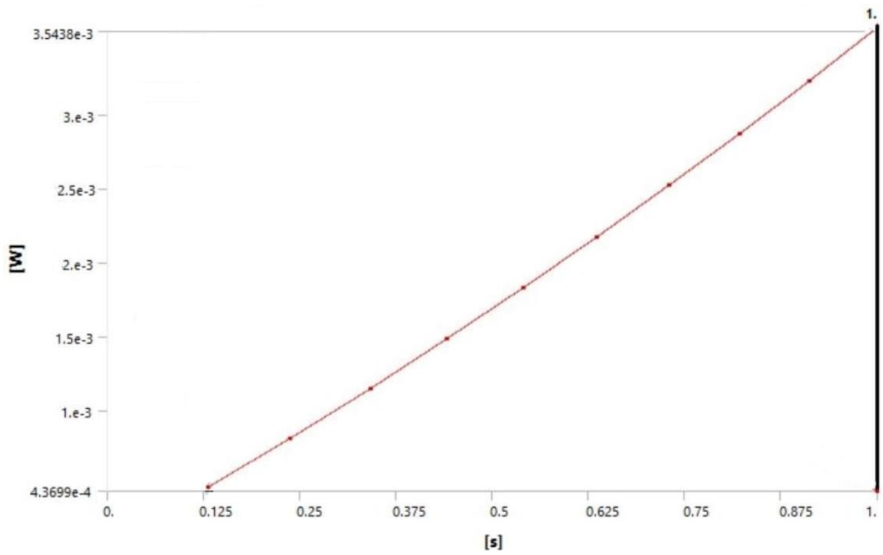

Fig 21. Heat v/s time graph for cracked gear pair

- As shown in Fig. 20 and Fig. 21, heat generation increases with increase in time but in case of cracked gear pair it is more than that of healthy gear pair. This is mainly because air movement within extremely narrow cracks is very slow due to existence of fluid velocity boundary layer, here velocity profile of the air within the crack approaches zero in all directions, hence there is negligible heat convection within the cracks. Since this is heat is revolving in the crack itself, very less heat is lost to the environment, hence heat generation is more in presence of crack.

CHAPTER 6: CONCLUSIONS

The following conclusions can be made from all above discussions:

- Stress values for healthy gear pair and cracked gear pair are different for same boundary and input condition in ANSYS 2021, more in cracked gear pair.
- Temperature change increases with increase in number of revolutions because of heat generation due to friction.
- For same number of revolution temperature change in healthy gear pair is slightly more than that of cracked gear pair.
- Heat generation is more in cracked gear pair as compared to healthy gear pair.
- Temperature of the pinion is more than the gear.

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