COMPUTER AIDED ENGINEERING OF GEAR BOX

A thesis submitted in partial fulfillment of the
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IN
CAD/CAM & ROBOTICS

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CERTIFICATE

This is to certify that the thesis titled, **"Computer Aided Engineering of Gear Box"** being submitted by **Mr. Vineet Shibe,** Roll No. 8028117 in partial fulfillment of the requirements for the award of degree of **Master of Engineering in CAD/CAM & Robotics at Thapar Institute of Engineering & Technology** (Deemed University), Patiala, is a bonafide work carried out by him under my guidance and supervision.

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ABSTRACT

Gears have wide variety of applications. They form the most important component in a power transmission system. Advances in engineering technology in recent years have brought demands for gear teeth, which can operate at ever increasing load capacities and speeds. The gears generally fail when tooth stress exceeds the safe limit. Therefore, it is essential to determine the maximum stress that a gear tooth is subjected to, under a specified loading. Analysis of gears is carried out so that these can be prevented from failure.

When failure occurs, they are expensive not only in terms of the cost of replacement or repair but also the cost associated with the downtime of the system of which they are a part. Reliability is thus a critical economic factor and for designer to produce gears with high reliability they need to be able to accurately predict the stress experienced by the loaded gear teeth.

The major problems being faced in the gearbox manufactured by Kay Kay Industrial Corporation, Patiala are interference, surface fatigue and fracture. In order to analyze the exact failure point and the stress levels at which gear is failing, the modeling and stress analysis of the gear box has been done in Pro-E & ANSYS respectively, taking various constraints and boundary conditions imposed by the company. The necessary design modifications have also been made to rectify these problems.

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In chapter 1 a brief introduction of gears, types of gear tooth failures, conventional & new method of gear design and finite element analysis have been discussed.

In chapter 2 definition of the problem, methodology used, constraints applied and approach for the problem has been elaborated.

In chapter 3 results of stress analysis of existing & modified gearbox has been discussed. Introduction to structural (static) analysis, structural (static) analysis procedure and steps involved in carrying out analysis using ANSYS has been explained.

In the end, chapter is devoted to highlight important conclusions of the research work and scope of further work has been discussed.

For references '[ ]' and for bibliography '{ }' with proper numbering has been used.

CHAPTER 1
INTRODUCTION

1.1 Introduction of Gears

Gears are the most common means of transmitting motion and power in the modern mechanical engineering world. They form vital elements of mechanisms in many machines such as automobiles, metal cutting machine tools, rolling mills and transmitting machinery. Toothed gears are used to change the speed and power ratio as well as direction between an input and output shaft.

1.1.1 Advantages of Gear Drives

Advantages of gear drives over other transmission means are :

- They give positive drives and constancy of speed ratio without any slippage.
- The drive is very compact due to short center distances used in such drives.
- High efficiency, reliable service and simple operation.
- Maintenance is inexpensive and if properly lubricated and operated, gear drives have the longest service life as compared to other mechanical drives.
- Gear drives can be used where precise timing is desired.
- Gear drives can drive much heavier loads than other drives due to their unlimited sizes.
- Gear drives can be used for wide range of transmitted power, i.e., from one-tenths of a KW to tens of thousands of KW.

1.1.2 Disadvantages of Gear Drives

Advantages of gear drives over other transmission means are :

- The manufacturing is complex. Special tools and equipment are needed to manufacture them.
- Due to errors and inaccuracy in their manufacturing, the drive may become noisy accompanied by vibrations at high speeds.
- They are not suitable for large center distances because the drive will become bulky.

1.2 Types of Gear Tooth Failures

The gears generally fail when tooth stress exceeds the safe limit. When failure occurs, they are expensive not only in terms of the cost of replacement or repair but also the cost associated with the downtime of the system of which they are a part. So, it is important to understand various problems that can occur in gears.

The types of gear tooth failures can be categorized into following classes:

- Wear
- Scoring
- Interference
- Surface Fatigue
- Plastic Flow
- Fracture
- Process Related

1.2.1 Wear

Wear occurs when the film of lubricant that exists between the mating surfaces of the teeth is not sufficient to prevent surface-to-surface contact. Other factors responsible for wear, such as abrasive particles in the lubricant, corrosion of tooth surfaces, aberrations in the tooth surfaces themselves that penetrate the lubricant film, relative surface roughness of the tooth flanks, and the amount of contamination in the lubricant.

Depending on the extent and the cause of wear, it can be of following types:

- Polishing Wear
- Moderate Wear
- Excessive Wear
- Abrasive Wear
- Corrosive Wear

1.2.2 Scoring

Scoring is generally observed on high-speed, high-load gearing. Most often these gears are operating with low-viscosity, synthetic lubricants. If the combination of load, sliding velocity, and inlet oil temperature reaches a critical value, the oil film separating the mating surfaces is destroyed, and metal-to-metal contact occurs. If the surface pressure and sliding velocity are high enough, instantaneous welding of the asperities will then occur. As the gears continue to rotate, the welds break. This phenomenon is known as Scoring.

Depending on the extent and the cause of scoring, it can be of following types:

- Frosting
- Light Scoring
- Moderate Scoring
- Destructive Scoring
- Localized Scoring

1.2.3 Interference

Interference of one tooth with another, can wreak havoc on the operation of the system. A wide variety of conditions, such as operating on tight centers, insufficient involute, thermal expansion, misalignment and insufficient or incorrect profile modifications can cause interference.

Depending on the region of interference, it can be of following types:

- Tip Interference
- Root Interference

1.2.4 Surface Fatigue

Surface fatigue is a time-dependent phenomenon; thus its effects may not be apparent for a considerable period of time. The surface of a gear tooth is subjected to varying load. This condition is referred to as fatigue. When the fatigue capacity of the material is exceeded, it will fail. It generates substantial quantities of chips in their later stages of progression.

Depending on the extent of surface fatigue, it can be of following types:

- Initial Pitting
- Destructive Pitting
- Spalling
- Case Crushing

1.2.5 Plastic Flow

Plastic flow does progress with time and can ultimately be catastrophic. It is not strictly a fatigue phenomenon. Very heavy loads, usually combined with relatively slow speed rotation can cause gear materials to flow plastically.

Depending on the specific conditions encountered, plastic flow may take any of several forms:

- Cold Flow
- Hot Flow
- Rippling
- Ridging

1.2.6 Fracture

Fracture is a much more insidious type of failure. It produces no debris in its early stage, gives little warning, and usually results in either immediate loss of serviceability or greatly reduced power transmitting capacity.

All the failure modes discussed above are progressive, i.e. the time between failure initiation & complete loss of serviceability is frequently quite long. This is of particular importance in the design of devices such as helicopters, elevators, cranes, and so forth in which a complete failure to transmit rotation may result in human injury or death. For

these reasons, gears are generally designed with a larger margin of safety when considering the fracture modes.
Depending on the way in which the fracture occur, it can be of following types:

- Classical Bending Fatigue
- Overload
- Random Fracture
- Root/Rim/Web
- Resonance

1.2.7 Process Related

There are many types of failures that occur even before the gears are placed in service. The very best design, on paper, can be a total disaster if it is not faithfully executed in the manufacturing phase.

Process Related failure can be of following types:

- Quench Cracks
- Case/Core Separation
- Grinding cracks
- Nicks, Scratches, and Such
- Electric Arcing
- Grinding "Burns"
- Improper Edge Breaks
- Tool Marks

1.3 Conventional Method of Gear Design

The designs of most gears were derived from concepts applicable many years ago. Designing of gears is done on the basis of thumb rule. One of the greatest bottlenecks in gear development is prototype testing. In this type of development process, a concept is translated into detailed engineering drawings. Then, service loads and stresses had to be estimated. The various non-avoidable variations were all taken together using a 'factor of safety', perhaps better expressed as a 'factor of ignorance'.

After a lengthy design review, a hardware prototype is built & tested. Any problems are then fed back to engineering, where the design is modified. These changes are translated into new components & the prototype re-tested. This cycle is repeated until satisfactory performance is achieved. This build-and test process is both expensive & time consuming.

1.4 New Method of Gear Design

New advances in computer technology have made finite element stress analysis a routine tool in design process has given rise to computer-aided design (CAD) using solid-body modeling.

Some benefits of CAD are productivity improvement in design, shorter lead times in design, more logical design process & analysis, fewer design errors, greater accuracy in design calculations, standardization of design, more understandability and improved procedures for engineering changes.

1.5 Finite Element Analysis (FEA)

It is widely accepted method of accessing product performance without the need for physical building and testing. It also shortens prototype development cycle times & facilitates quicker product launch. FEA consists of a computer model of a material or design that is loaded and analyzed for specific results. It is used in new product design, and existing product refinement.

1.5.1 Advantages Of FEA

- The inherent advantages of finite element analysis are as under:
- Easy to model irregular shapes
- Possible to evaluate different materials
- Can apply general load conditions
- Large numbers and kinds of boundary conditions are possible in FEA
- Different sizes of elements can be used where necessary
- Cheap and easy
- Dynamic effects, nonlinear behaviors and nonlinear materials can be examined
- Reduce the number of prototypes required in the design process

1.5.2 Steps Required For Development Of FEA Model

- Steps required for development of finite element model are as under:
- Assigning material and its properties to various parts.
- Discretize and choose element types.
- Choose a displacement function.
- Derive the element stiffness matrix and equations.
- Generate global or total equations from the element equations and introduce loads and boundary conditions.
- Solving for elemental strains and stresses and interpretation of the model

1.6 Role of CAD & Solid Modeling in Gear Design and Analysis

CAD techniques give the design engineer a powerful tool for graphical and analytical tasks. Modern CAD systems are based on ICG in which the computer is employed to create, transform and display geometric data.

CAD helps in :-

- Creating conceptual product models
- Editing, refining the model to improve aesthetics, ergonomics and performance
- Analyze stress, static deflection and dynamic behavior for different mechanical and thermal loading configurations and carry out quickly any necessary design modifications to rectify deficiencies in the design.
- Study the product from various aspects such as material requirements, cost, value, value engineering, manufacturing processes, standardization, simplification, variety reduction, service life, servicing and maintenance aspects.

CHAPTER 2
PROBLEM DEFINATION

2.1 Definition of the Problem

Kay Kay Industrial Corporation, Patiala is the leading manufacturer of gearbox, which is used in various utensil and sugar mill machinery. The major problems being faced in the gearbox manufactured by the above firm are given as under :-

- Interference
- Surface Fatigue
- Fracture

The gears fail when tooth stress exceeds the safe limit. Therefore, it is essential to determine the maximum stress that a gear tooth is subjected to, under a specified loading. Analysis of gears is carried out so that these can be prevented from failure. When failure occurs, they are expensive not only in terms of the cost of replacement or repair but also the cost associated with the downtime of the system of which they are a part.

2.2 Methodology Used

The modeling and stress analysis of the gearbox has been done in Pro-E and ANSYS respectively, taking various constraints and boundary conditions imposed by the company. The necessary design modifications have also been made to rectify the problems being faced by the firm.

2.3 Constraints

There were various constraints or restrictions that were imposed by the firm.

- **Material :-** The gears were made of forged steel having specification EN24 as it is most economical.

- **Type of Gear :-** Type of gear cannot be other than double helical gear.

- **Helix Angle and Pressure Angle :-** The helix angle and pressure angle were fixed at 15° and 20° respectively.

- **Pitch Circle Diameter :-** The pitch circle diameters of the gears mounted in the gearbox were fixed.

- **Number of Gears :-** The number of gears mounted in the gearbox was fixed.

2.3.1 Inputs Given

- Initial design or drawing of the gearbox was given.

- The value of the horsepower of the motor driving the gearbox was also given.

- The gears were made of forged steel having specification EN24.

2.3.2 Freedom Provided for the gearbox

Design modifications in the gears can be done considering factors such as strength and stiffness.

2.4 Approach for the Problem

The following steps are used for solving of the problem :-

Step I : Modeling of all the parts of the gearbox correctly.

Step II : Assembly of all the parts of the gearbox.

Step III : Drawings of all the parts and assembly.

Step IV : Stress analysis (von mises) of all the gears mounted in the gearbox.

Step V : Design modifications to be made to reduce the stresses below the safe or allowable stress limit.

For the above steps the CAE softwares Pro-E & ANSYS are to be used.

CHAPTER 3
STRESS ANALYSIS OF GEAR BOX

3.1 Stress Analysis of Existing Gear Box

As discussed in the previous chapter, the following steps are used for problem solving.

3.1.1 Model Generation

Proper modeling of the parts is very important for getting accurate results of analysis. Creating the parts and its dimensioning scheme are important steps.

The components of the gearbox were modeled in the part mode of Pro-E. The gearbox consists of the following parts :-

- Double helical gears of dimensions as given in the table below :

Diameter (mm)	Number of teeth	Module (mm)
204	18	10
234	17	12
446	29	14
636	60	10
675	52	12

- Shaft of diameter 75mm and of length 1100mm.

- Gear housing of length 1674mm, breadth 1086mm and height 1141 mm.

These parts of the gearbox are shown in figures 3.1 to 3.7.

3.1.2 Assembly of the Gear Box

The assembly of all the components of the gearbox was done in the assembly mode of Pro-E. The placement (or assembly) constraints were used to rigidly bind the components of the gearbox to their respective positions in the assembly.

The assembly of the gearbox is shown in figures 3.8 to 3.11

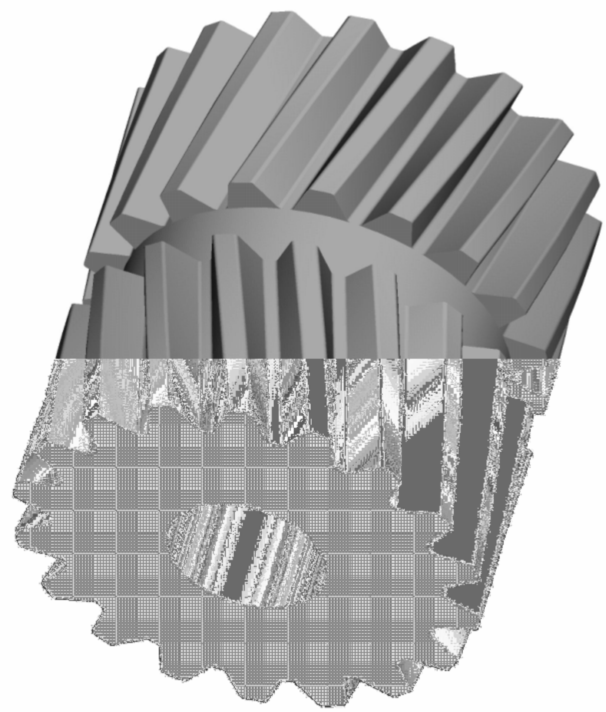


Figure 3.1 3-D Model of double helical gear of diameter 204mm

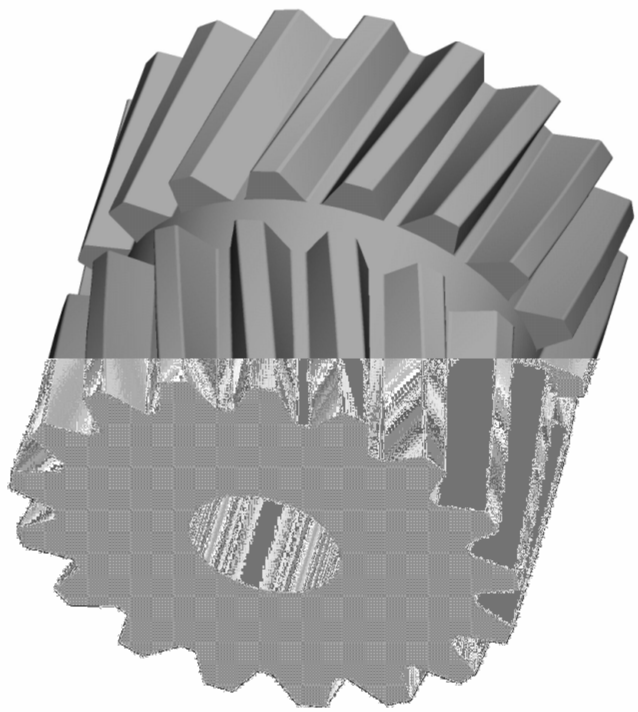


Figure 3.2 3-D Model of double helical gear of diameter 234mm

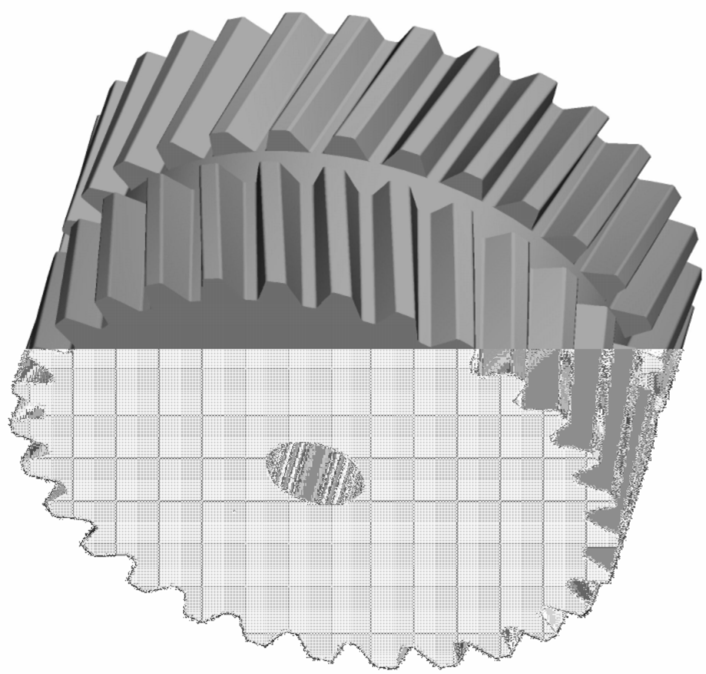


Figure 3.3 3-D Model of double helical gear of diameter 446mm

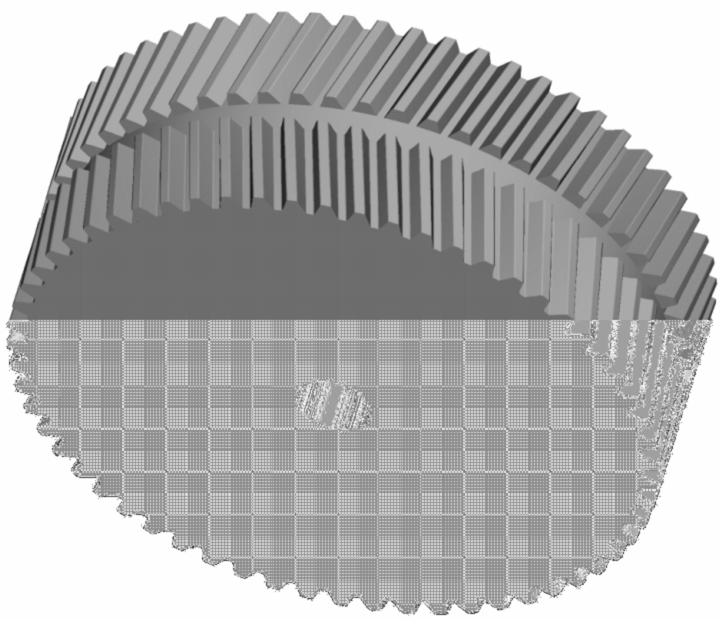


Figure 3.4 3-D Model of double helical gear of diameter 636mm

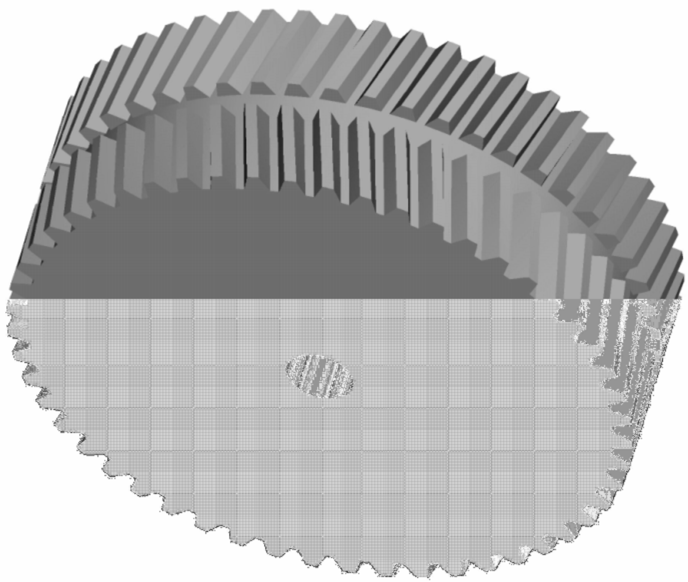


Figure 3.5 3-D Model of double helical gear of diameter 675mm

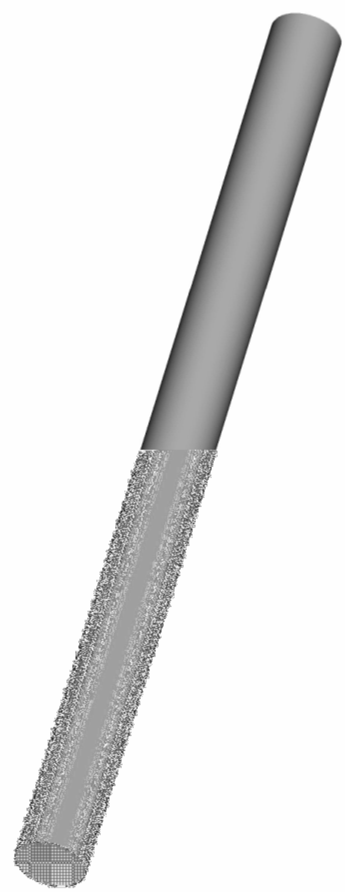


Figure 3.6   3-D Model of shaft

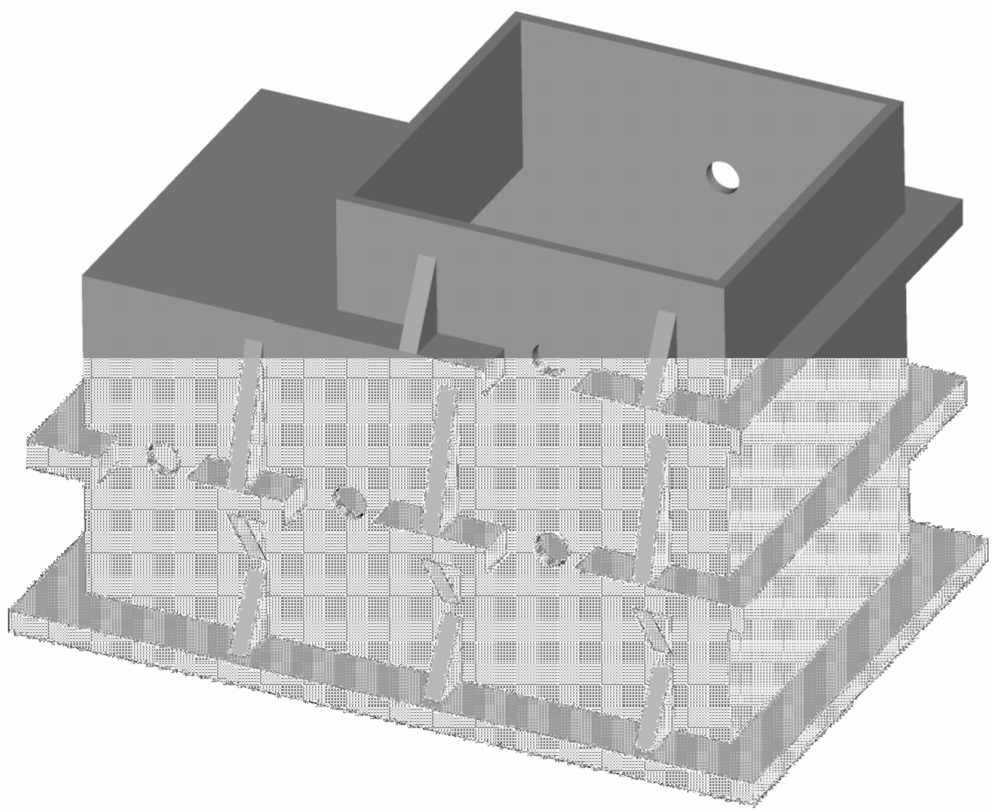


Figure 3.7 3-D Model of gear housing

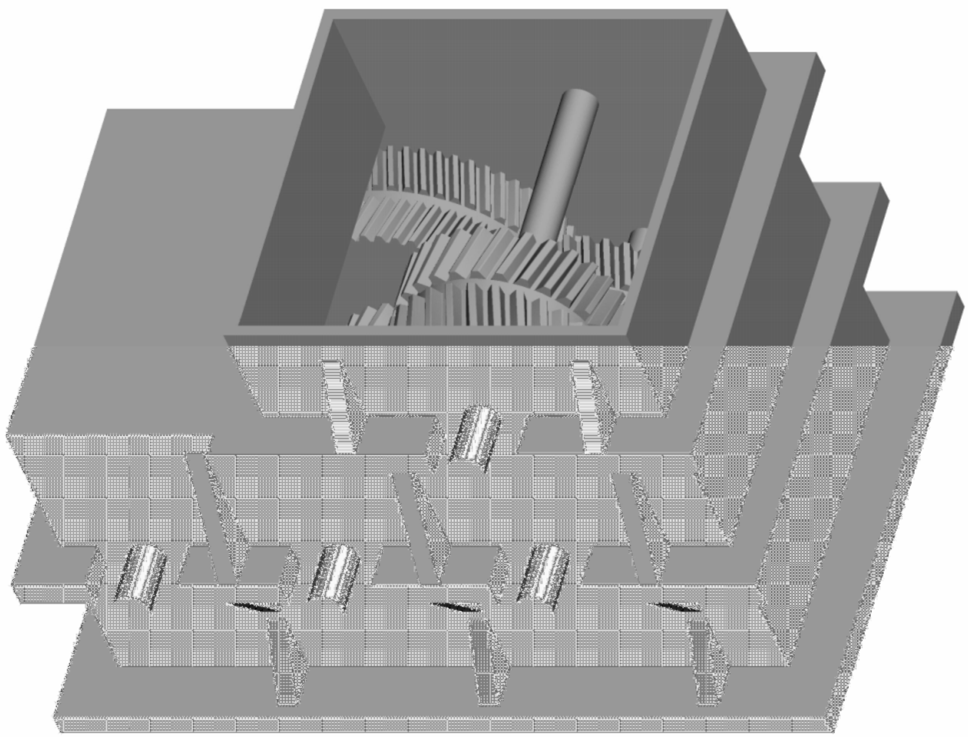


Figure 3.8 Assembly of the gearbox (Default View)

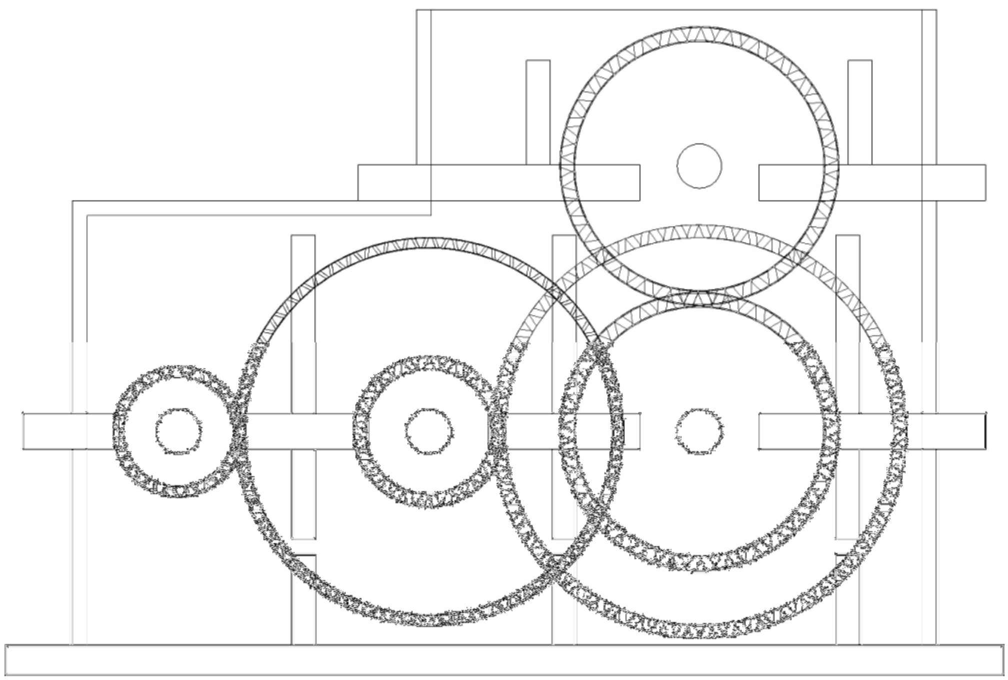


Figure 3.9 Assembly of gearbox (Front View)

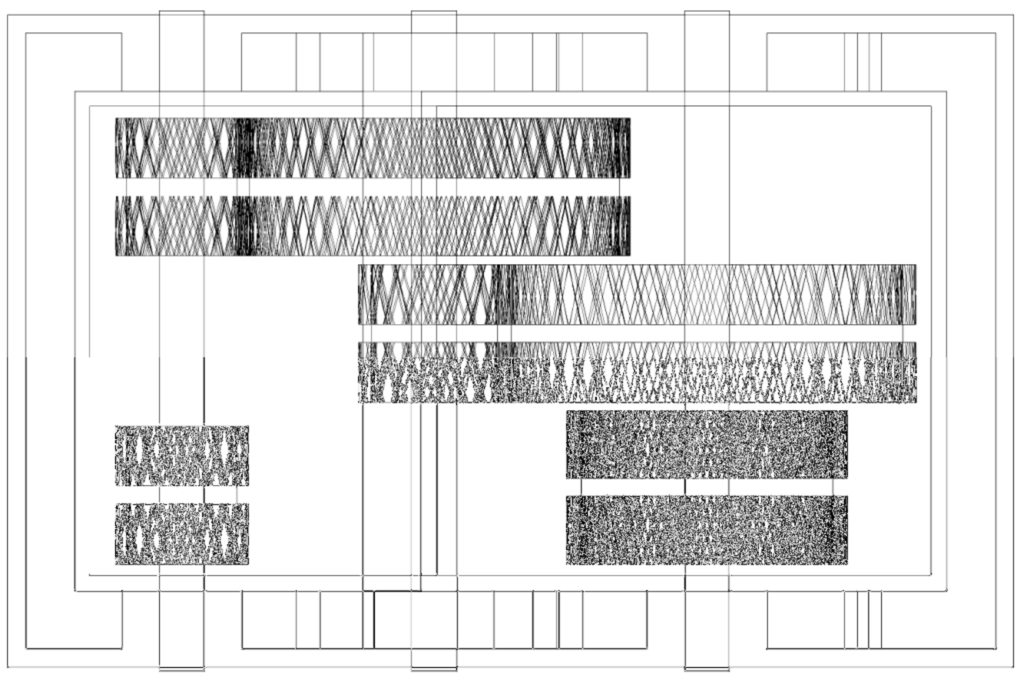


Figure 3.10 Assembly of gearbox (Top View)

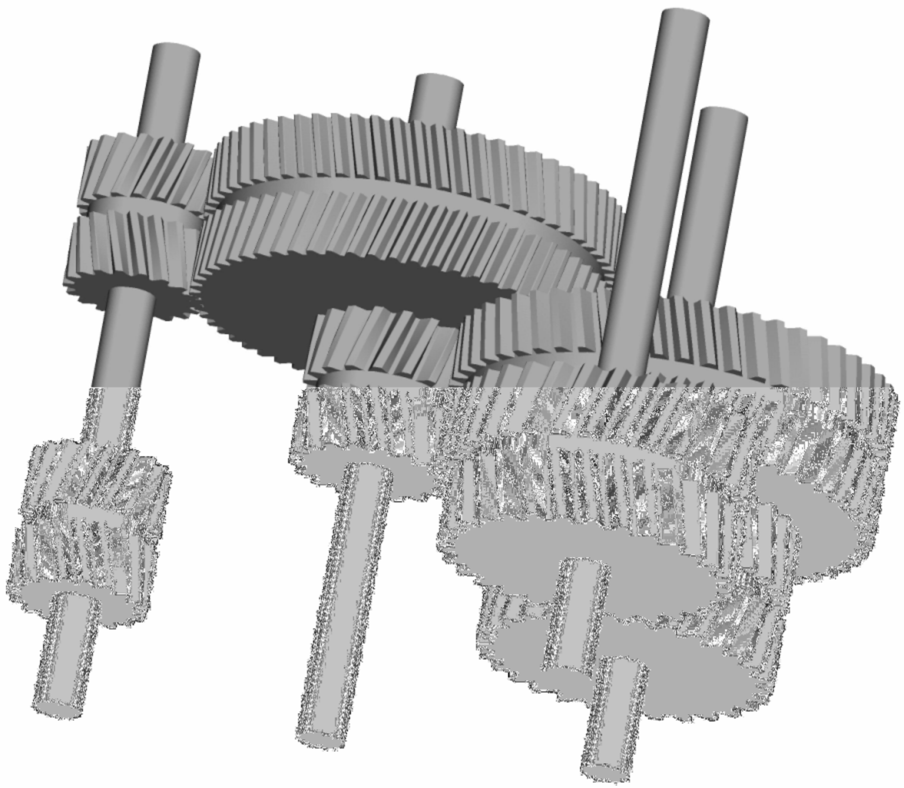


Figure 3.11 Assembly of the gearbox with hidden gear housing

3.1.3 Drawings of Parts and Assembly

The drawings of the parts of the gearbox and its assembly were generated in the drawing mode of Pro-E. Different drawing views of the parts and assembly were also created and are shown in figures 3.12 to 3.19.

3.1.4 Introduction to Structural (Static) Analysis

With the widespread adoption of CAE approach to design, finite element analysis became integrated with the design and analysis procedure.

Structural (Static) analysis is used to analyze parts and assemblies to find :-

- Maximum Stresses
- Deformed Shapes (Deformation)

3.1.5 Structural (Static) Analysis Procedure

The analysis of a structure during its design process is accomplished by the solution of the partial differential equations that describe the given model. The structural (static) analysis involves the following procedure :-

- **Pre-Processing**

  It includes the description of the geometry or model, the physical characteristics of the model and the mesh generation.

- **Solution**

  It involves the application of the finite element analysis.

- **Post-Processing**

  It includes the visualization and interpretation of the results of the solution.

3.1.6 Flowchart for Structural (Static) Analysis Procedure

PRE-PROCESSING	• Definition of type of analysis • Material properties • Element type used • Description of the geometry or model in order to generate mesh (number of nodes or element edge length) • Loads and boundary conditions

SOLUTION	• Run analysis to obtain solution (stresses & displacements)

POST-PROCESSING	• Graphical display of stresses and displacements for quick and easy interpretation of results.

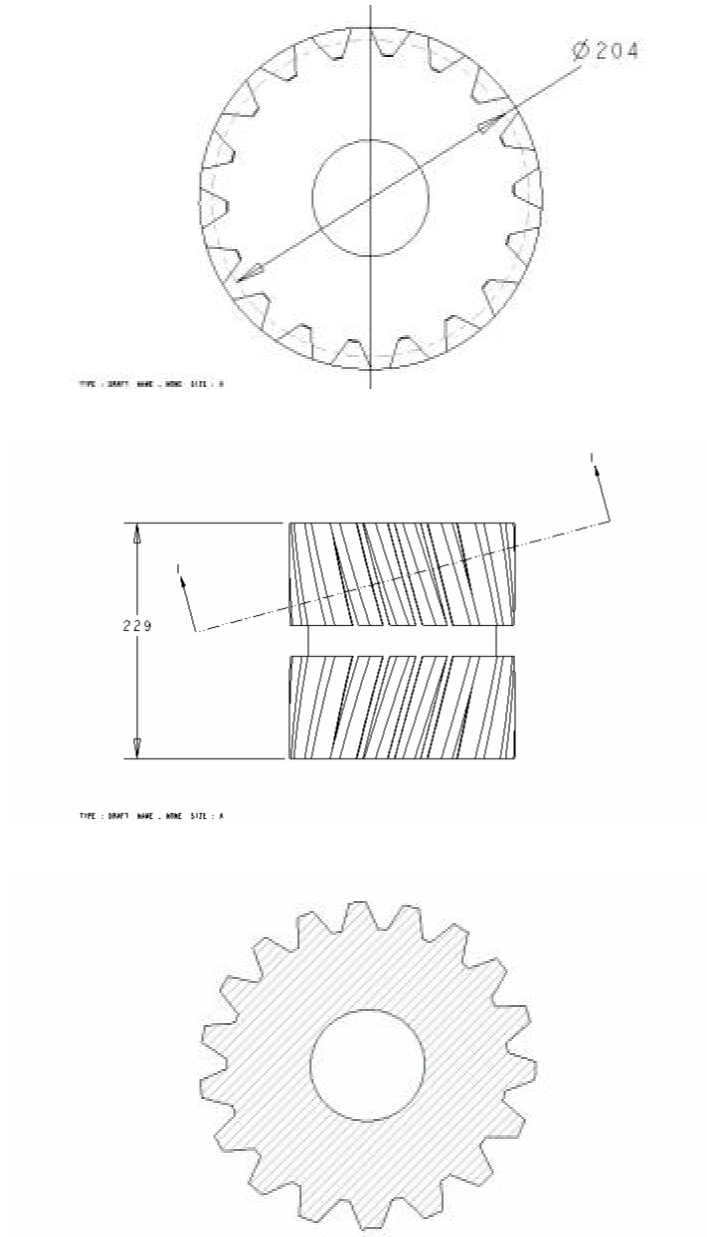


Figure 3.12 Drawing of double helical gear of diameter 204mm

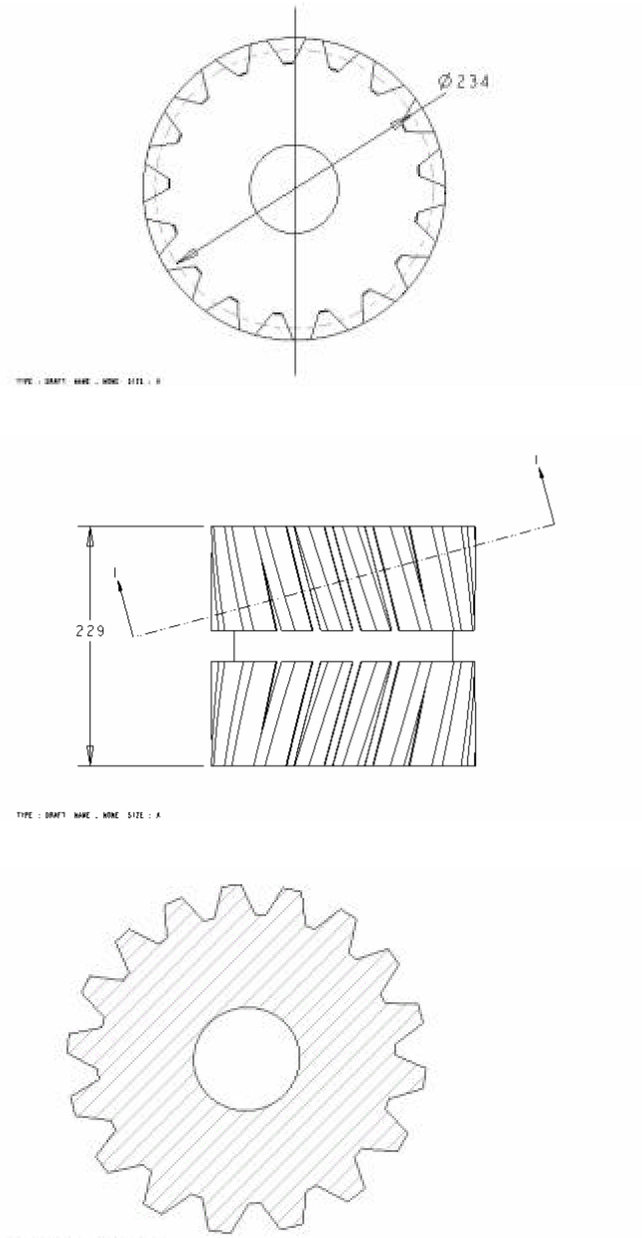


Figure 3.13 Drawing of double helical gear of diameter 234mm

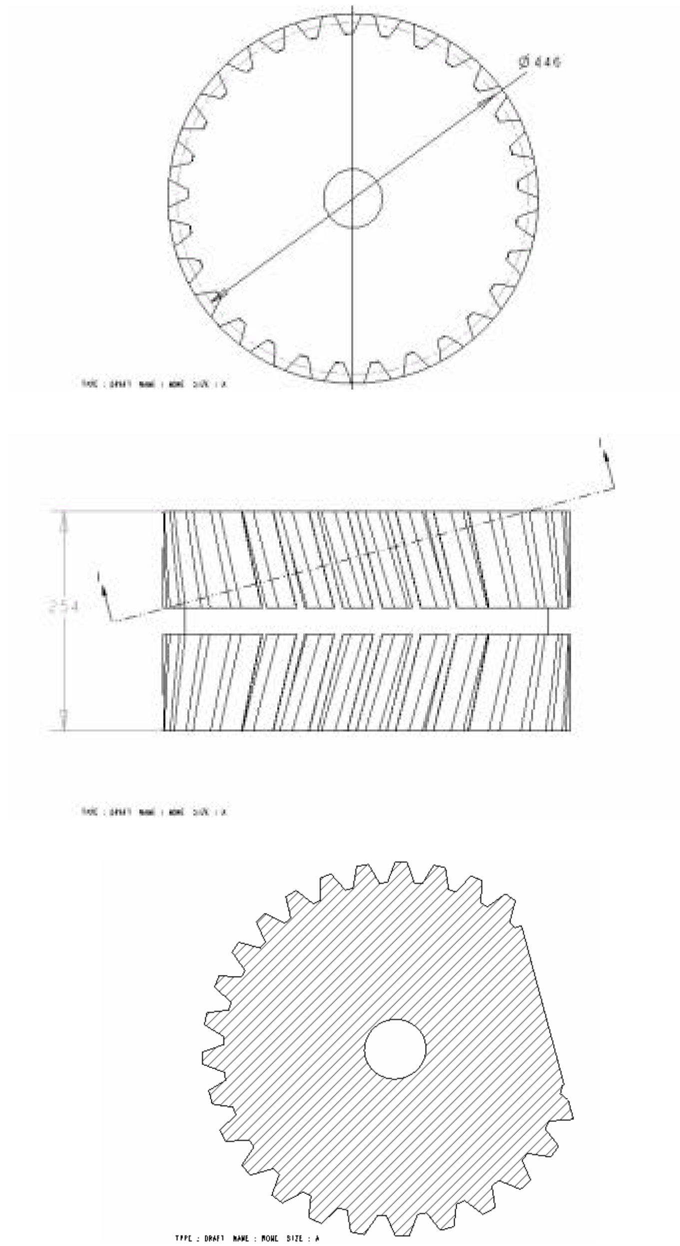


Figure 3.14 Drawing of double helical gear of diameter 446mm

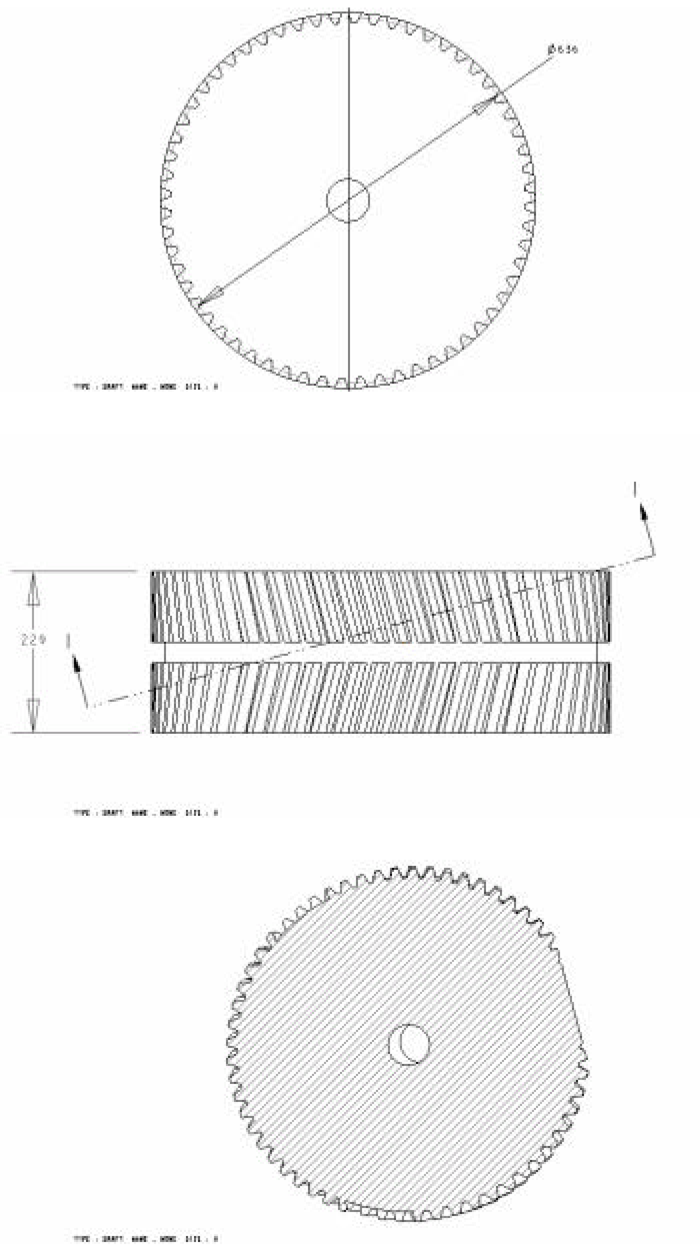


Figure 3.15 Drawing of double helical gear of diameter 636mm

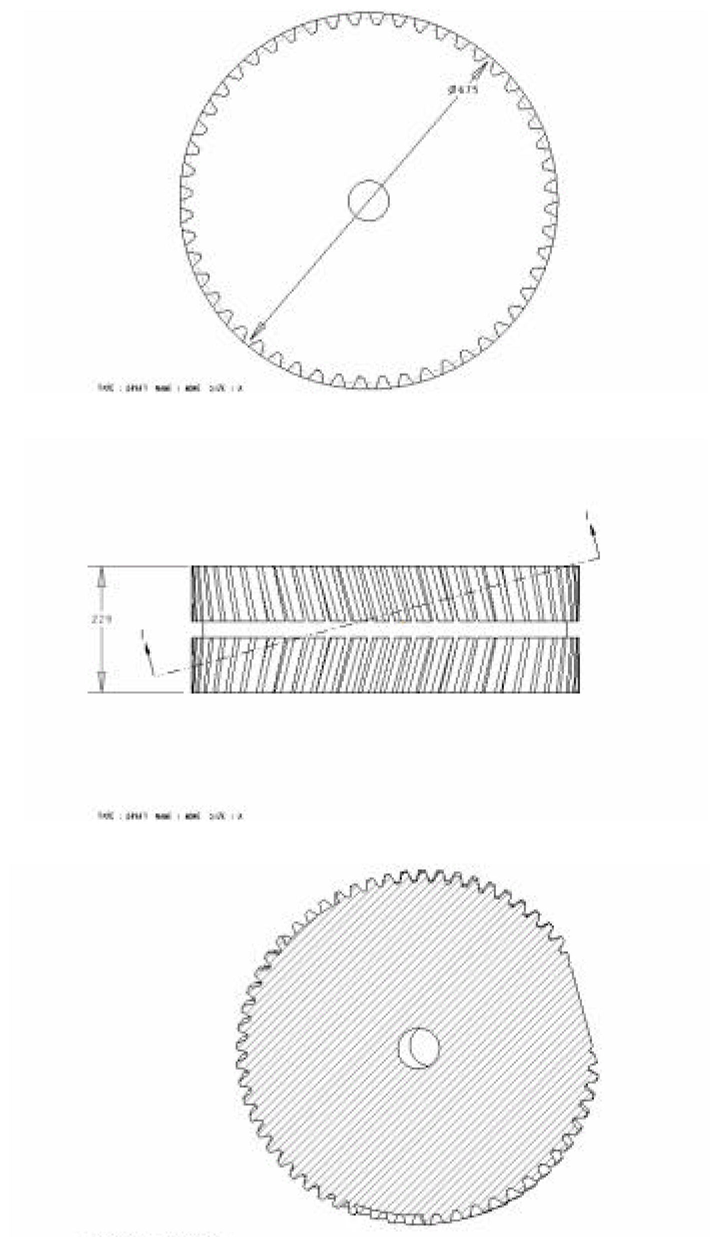


Figure 3.16 Drawing of double helical gear of diameter 675mm

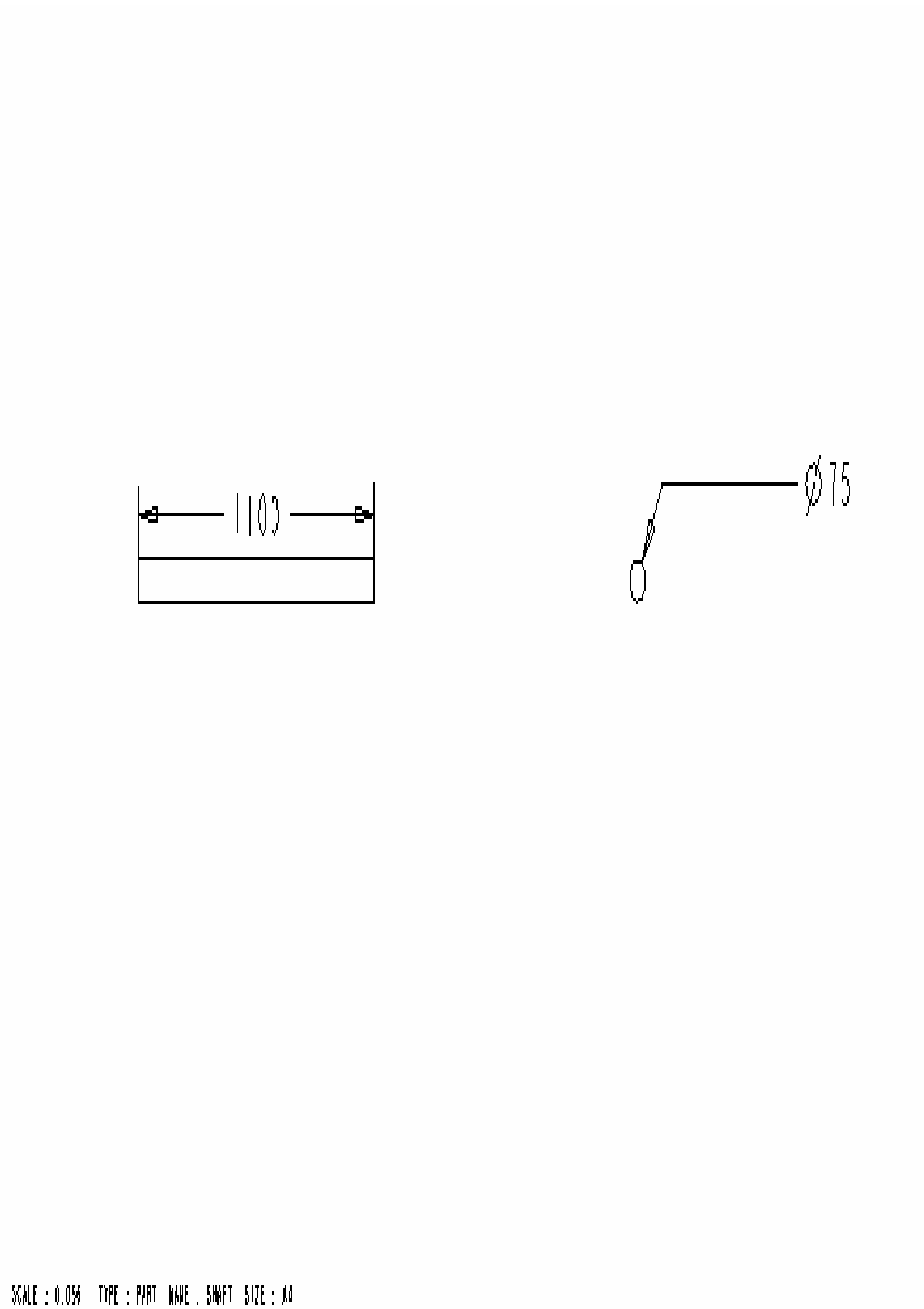


Figure 3.17 Drawing of shaft

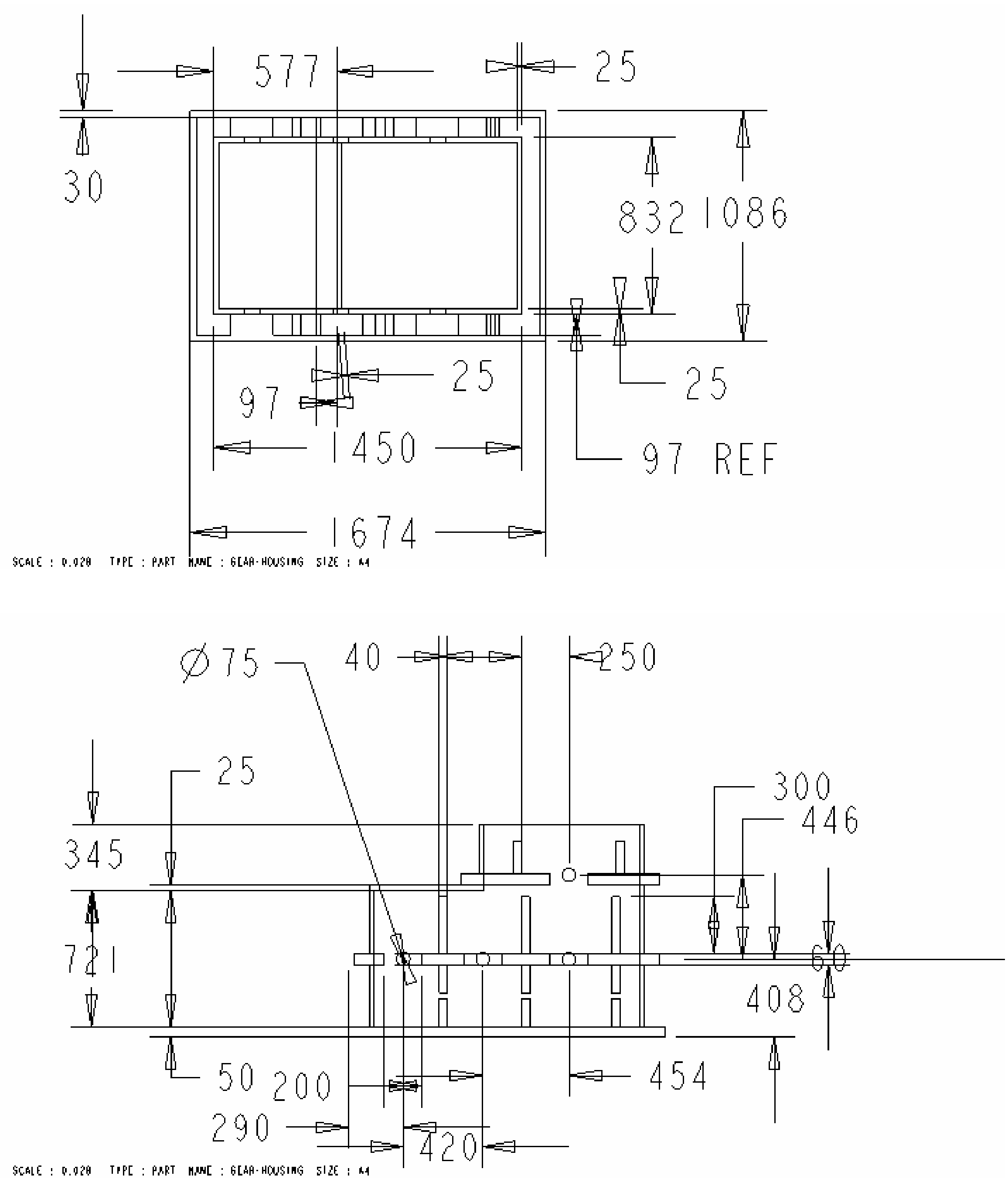


Figure 3.18 Drawing of gear housing

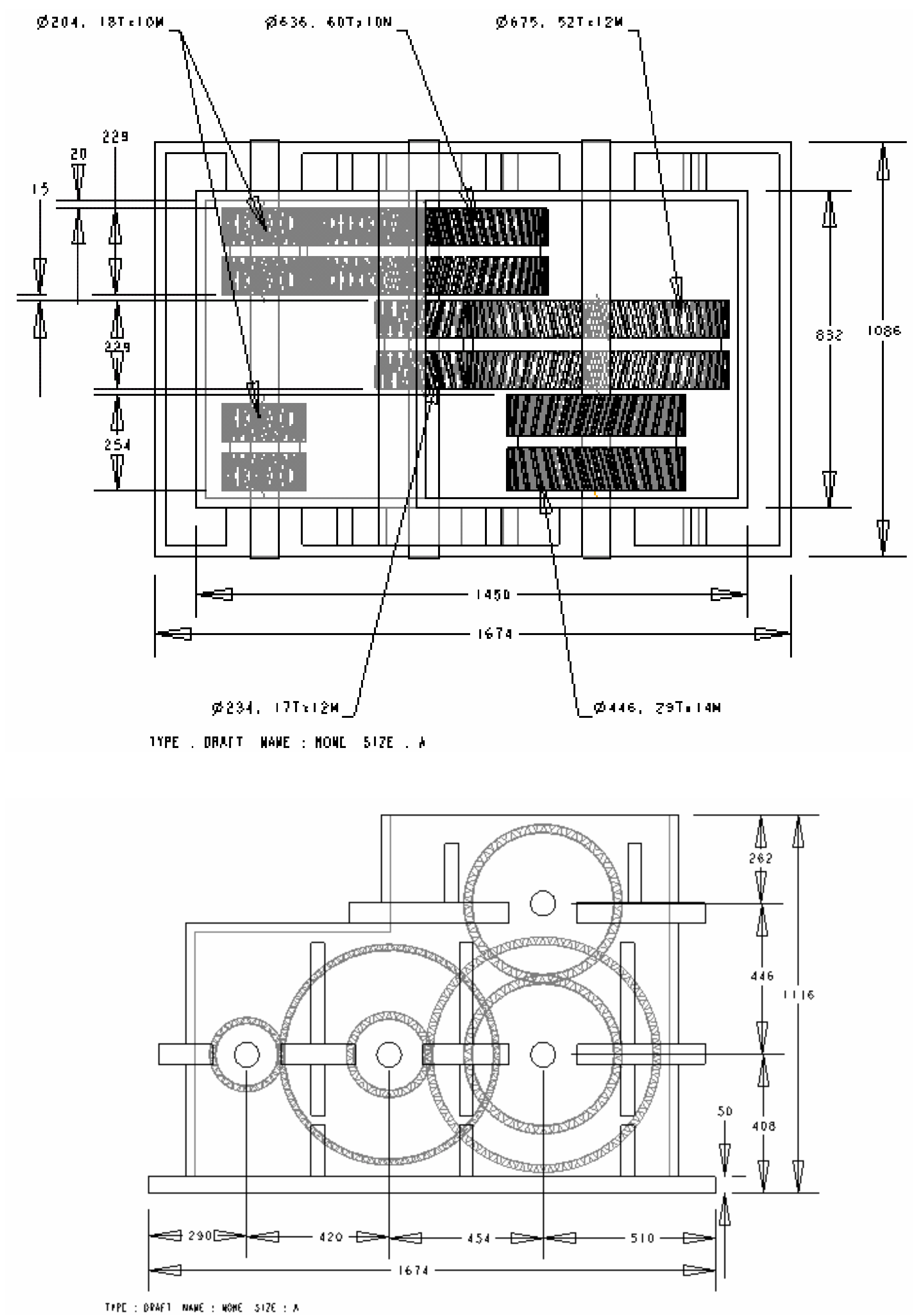


Figure 3.19 Drawing of assembly of the gearbox

3.1.7 Steps Involved in Carrying Out Analysis Using ANSYS

ANSYS is a computer aided engineering tool that allows us to simulate the physical behavior of a part or assembly, to understand and improve mechanical performance of a design. It enables us to analyze and optimize the designs for structural, thermal and dynamic requirements.

The steps involved in carrying out analysis using ANSYS are given below :-

- **Import the model**
  The model of the gear whose analysis was to be done was imported from the Pro-E file in which it was created.

- **Assign material properties**
  Material assigned to the gears in analysis was forged steel of specification EN24. The material properties[a] of EN24 are given in appendix.

- **Define the element type**
  The element type was defined as solid 92 having tetrahedral shape.

- **Define the element edge length**
  The element edge length was defined as 7-10mm in order to generate a mesh. The alternate method to generate a mesh is to define the number of nodes.

- **Apply loads**
  The loads acting on the gear tooth were defined.

- **Apply constraints/boundary conditions**
  The gear was fixed to the shaft such that it rotates with the rotation of the shaft.

- **Define the analysis type**
  The type of analysis was defined as structural (static) analysis.

- **Run the analysis**
  After the analysis was defined completely, it was required to run the analysis.

- **Review the results**
  Once the analysis had run successfully, it was important to review the results.

After reviewing the results, it was found that the stresses were not within the permissible/safe limit. The results of the stress analysis of the existing gearbox are shown in figures 3.20 to 3.24.

[a] *see appendix*

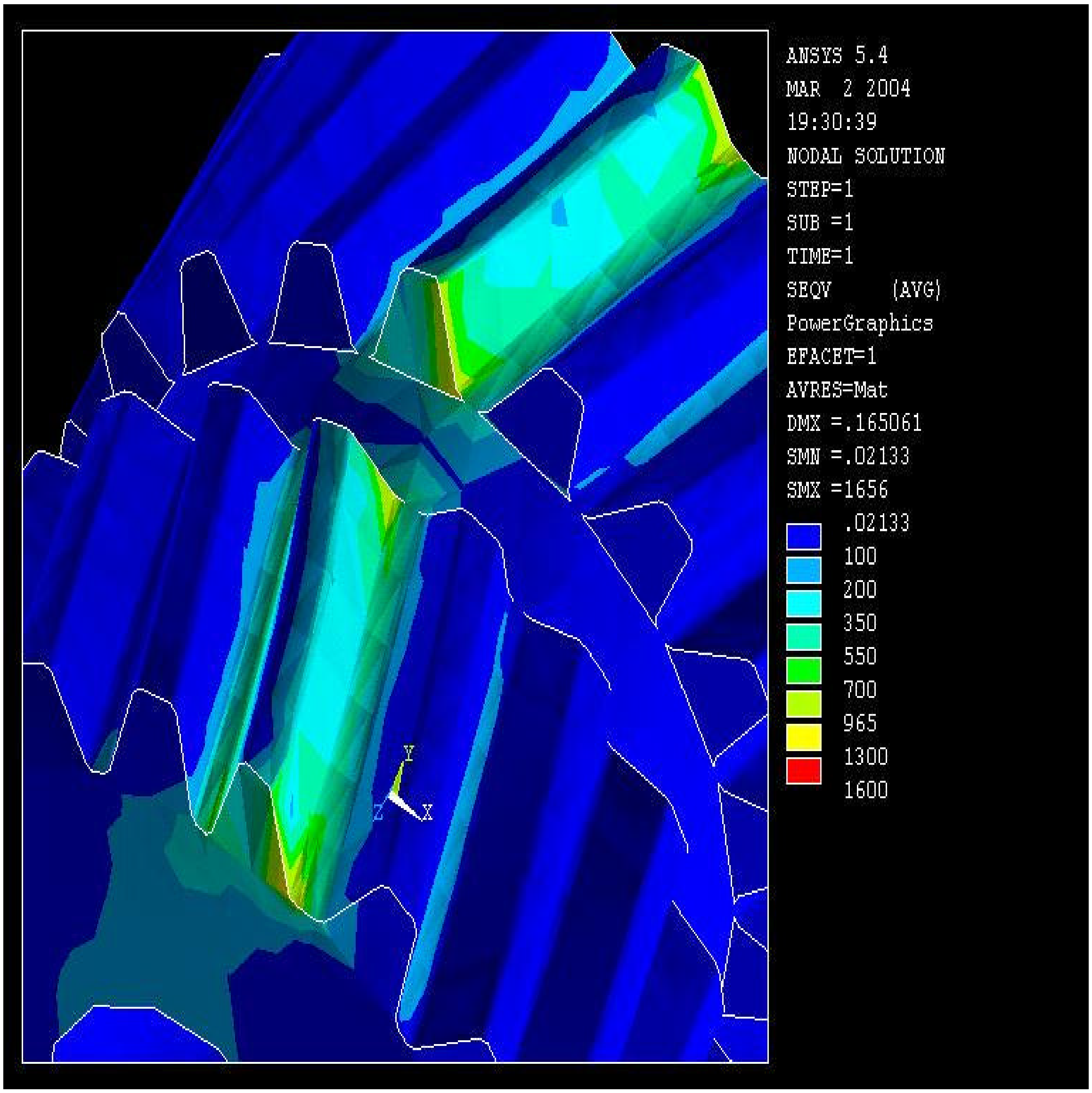


Figure 3.20 Stress analysis of double helical gear of diameter 204mm

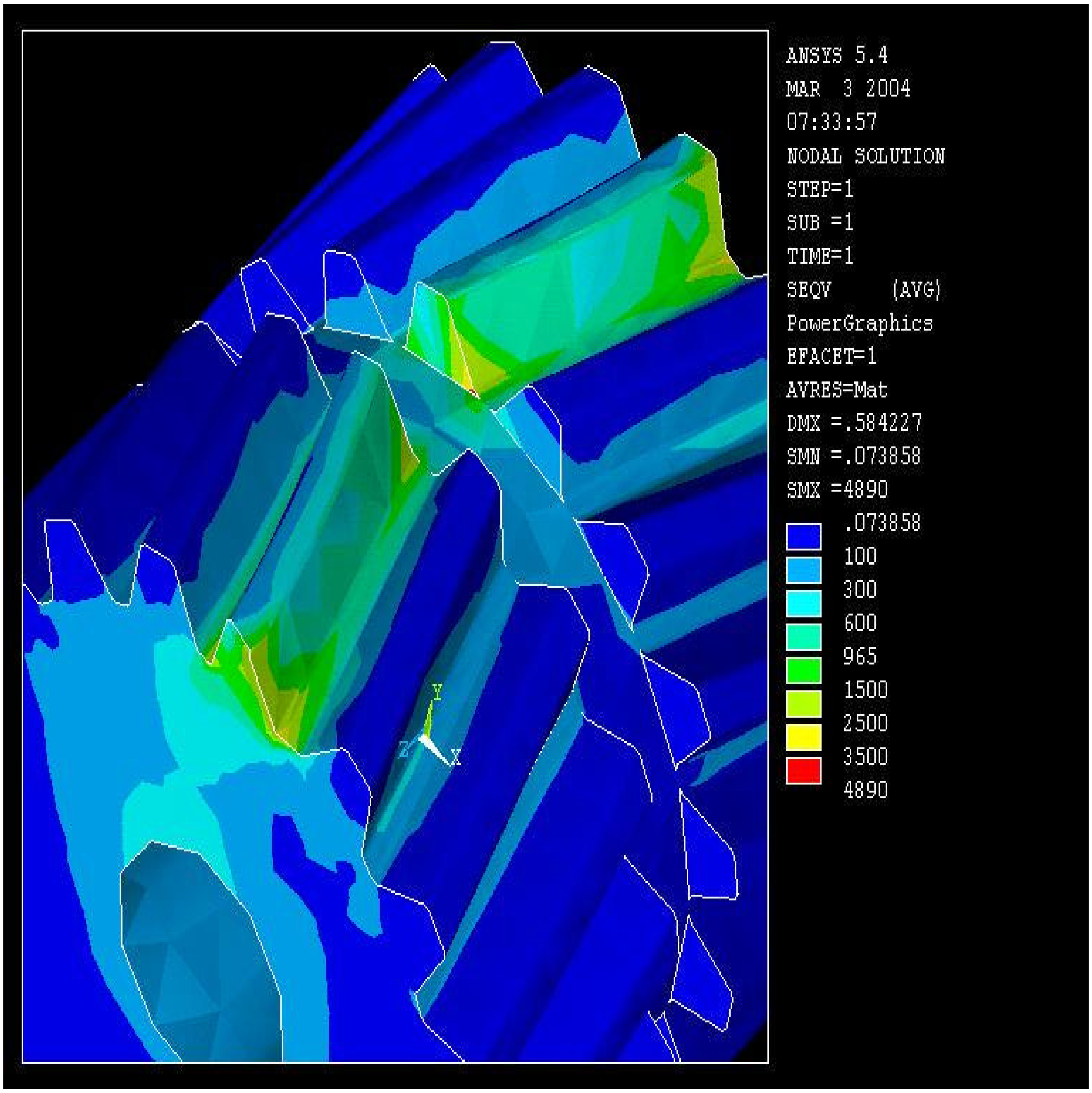


Figure 3.21 Stress analysis of double helical gear of diameter 234mm

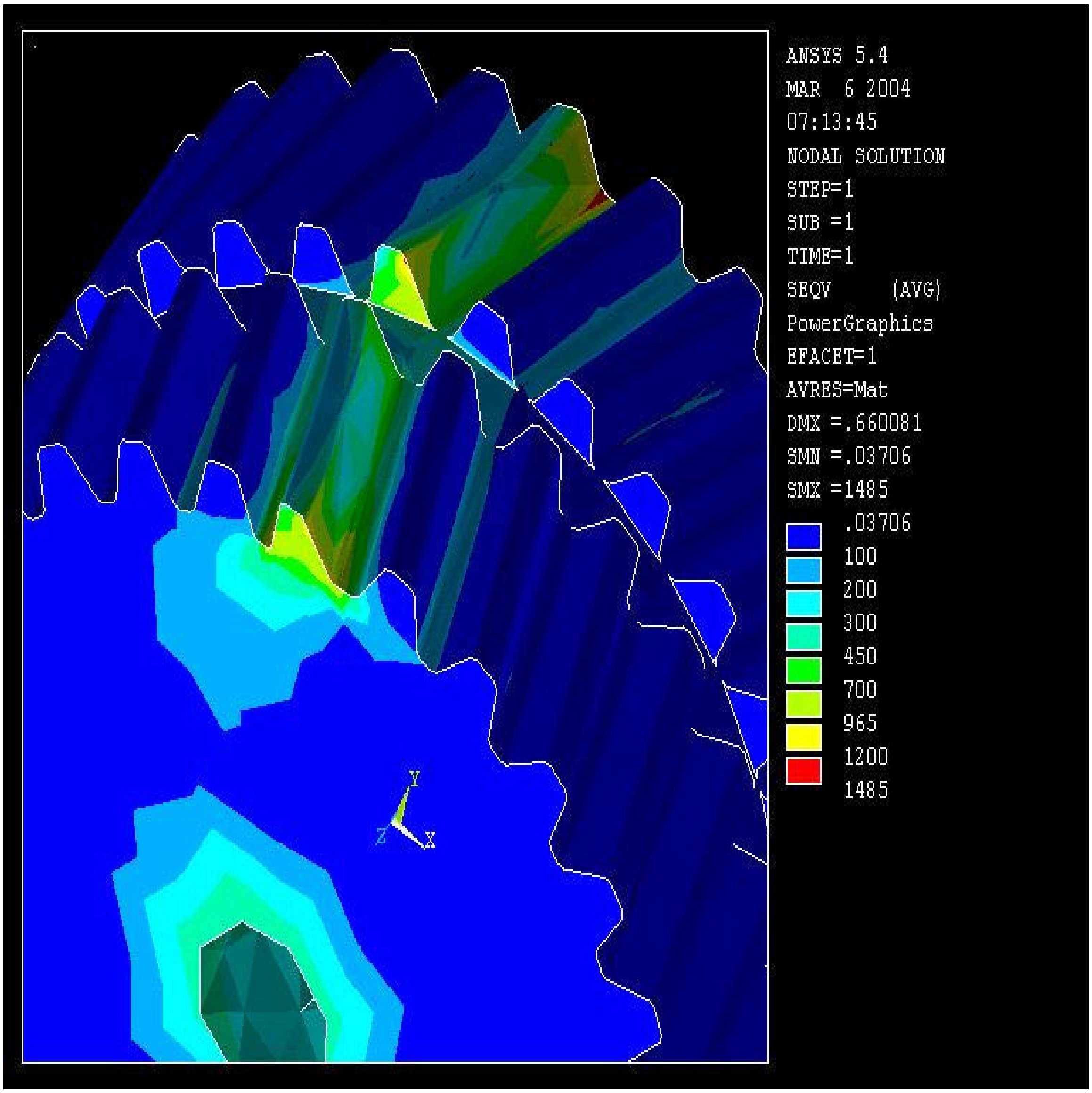


Figure 3.22 Stress analysis of double helical gear of diameter 446mm

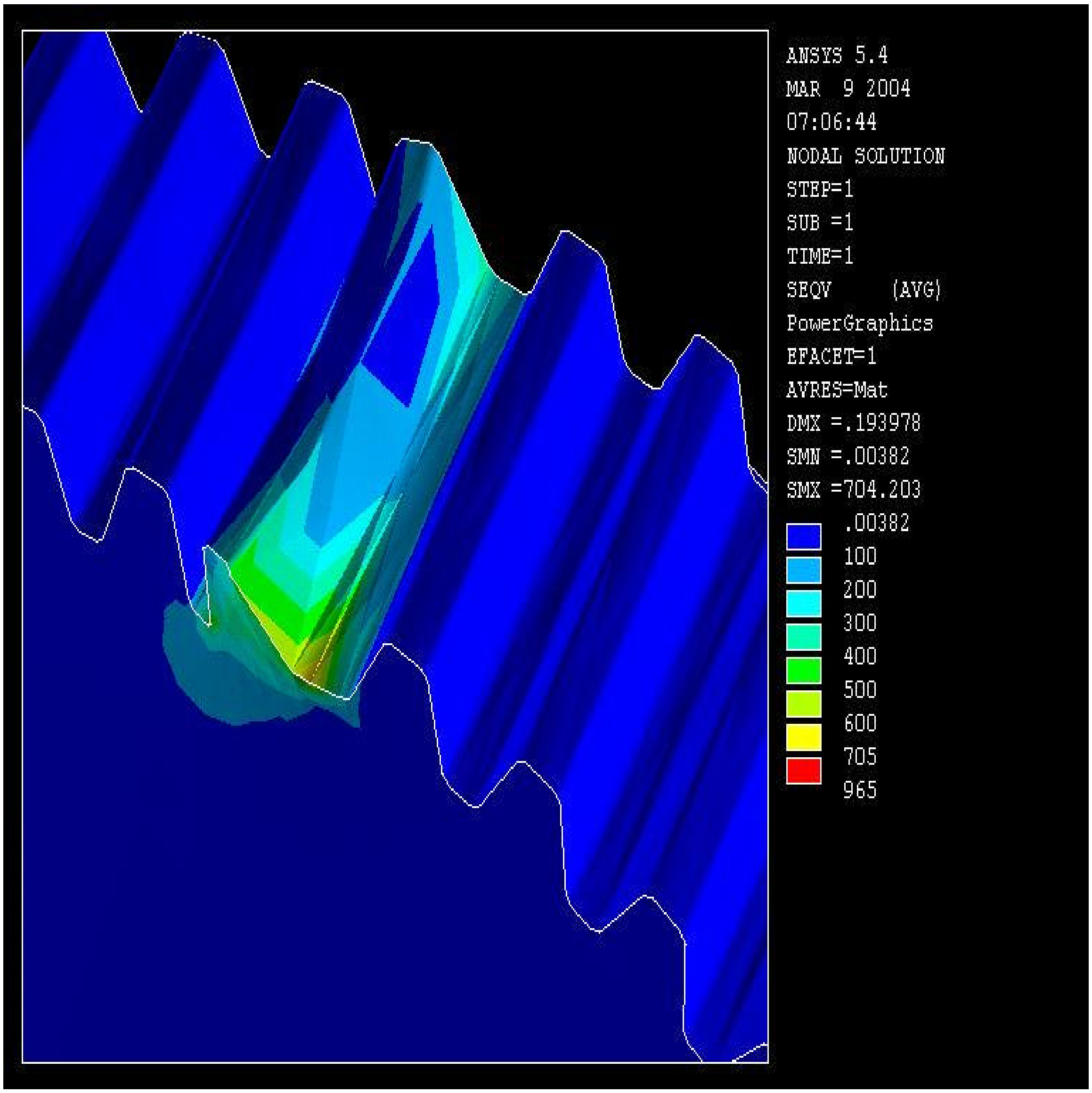


Figure 3.23 Stress analysis of double helical gear of diameter 636mm

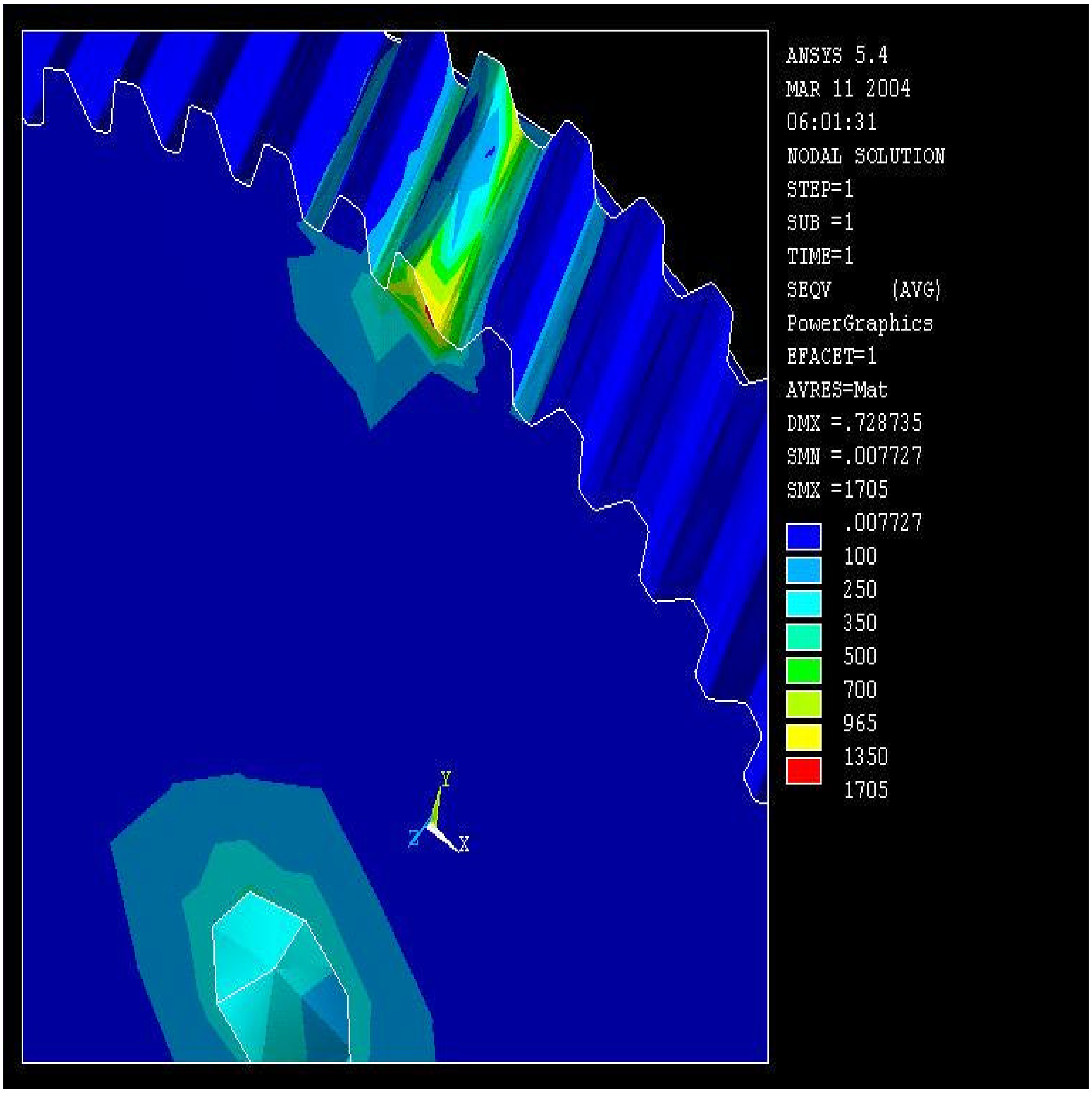


Figure 3.24 Stress analysis of double helical gear of diameter 675mm

3.2 Stress Analysis of Modified Gear Box

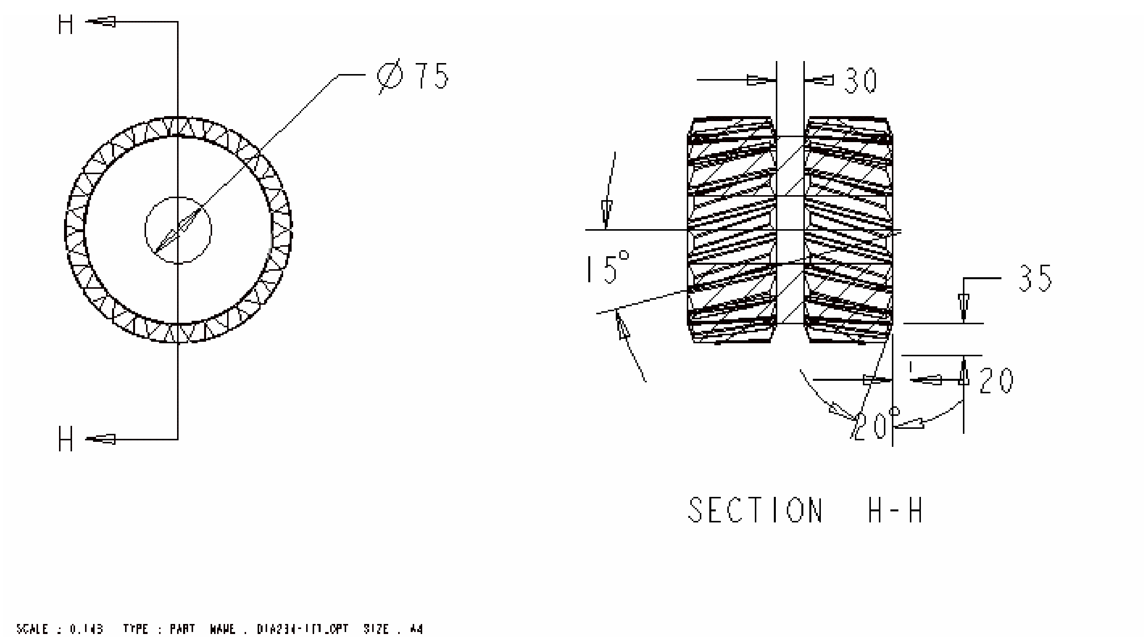
As the results of stress analysis of the existing gearbox were not within permissible/safe limit, so it was considered necessary to do design modifications in the existing gearbox, which is the main problem of the industry.

3.2.1 Design Modifications Undertaken

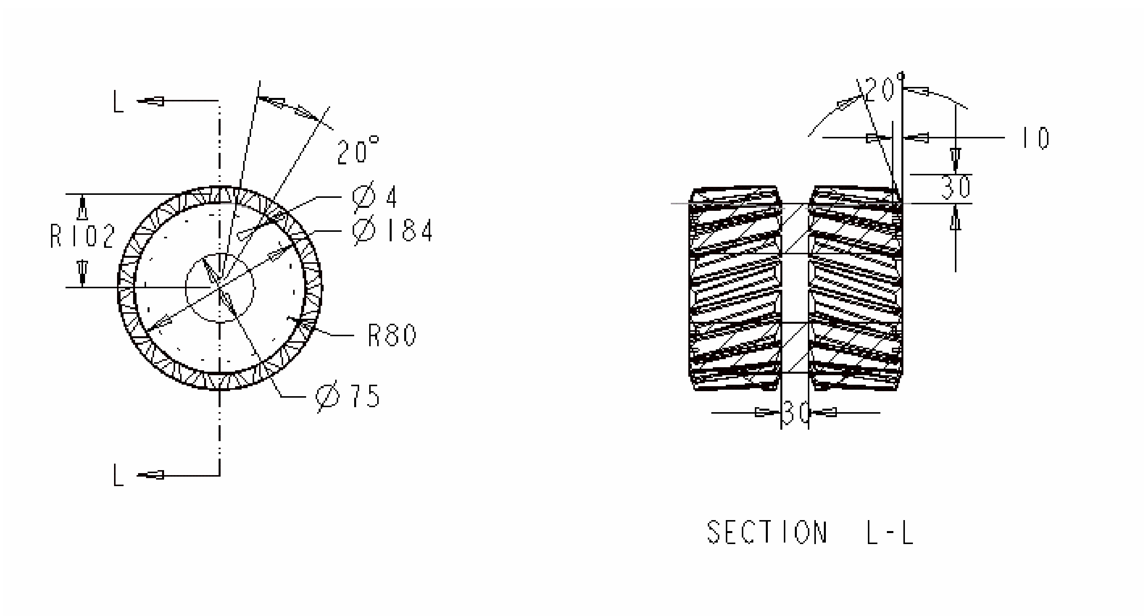
After extensive reviewing and studying the basic concepts of the stress, gears etc. some design modifications were made in order to reduce the stresses to the safe limit. The following design modifications are suggested in the existing gearbox :-

- The edges of the gear teeth were tapered by an angle of 20°.
- Making a groove in the gear wheel.
- Making a hole at the roots of the gear teeth.

Drawings of the modified parts of the gearbox are shown in figures 3.25 to 3.29 and the results of the stress analysis of the modified gearbox are shown in figures 3.30 to 3.39.

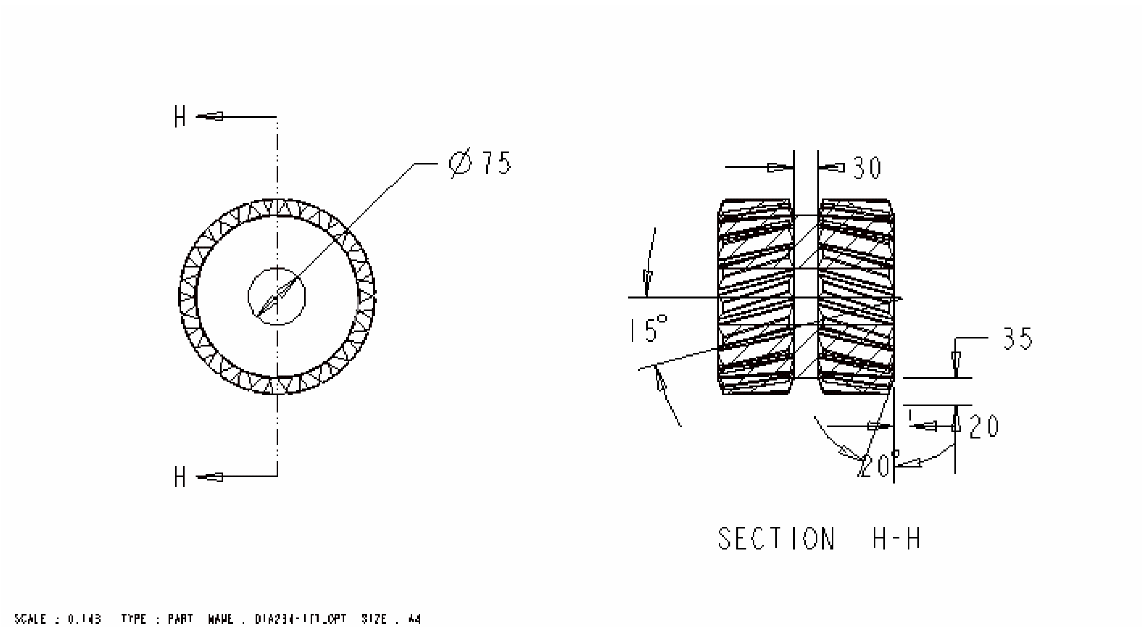


Modification: Taper on the edges of the gear teeth

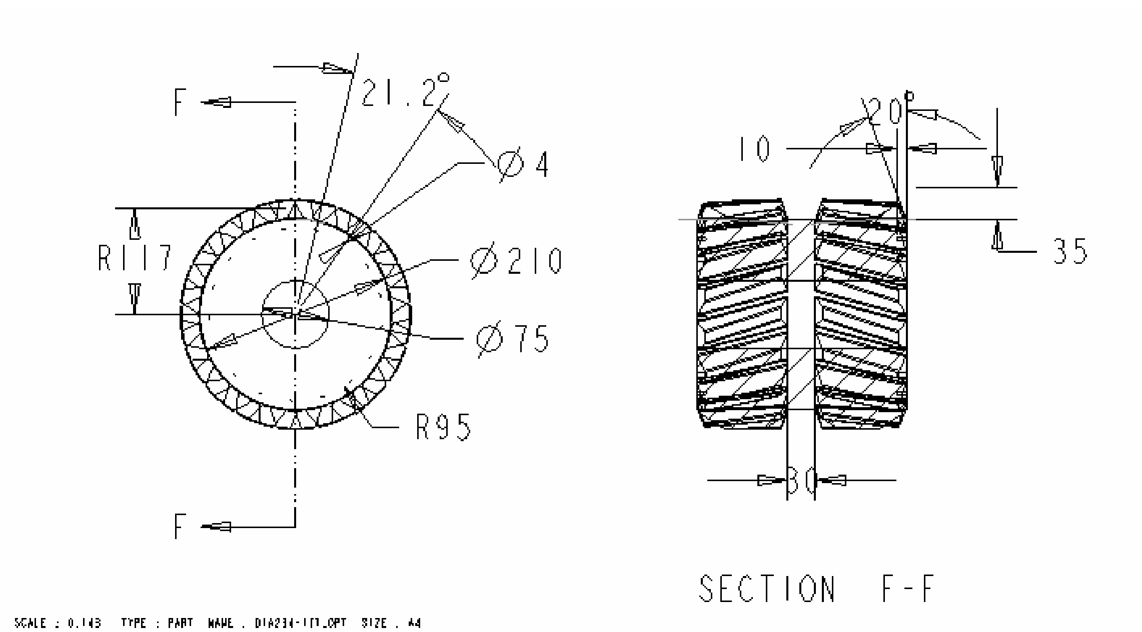


Modification: Hole at the roots of the gear teeth

Figure 3.25 Drawing of modified double helical gear of diameter 204mm

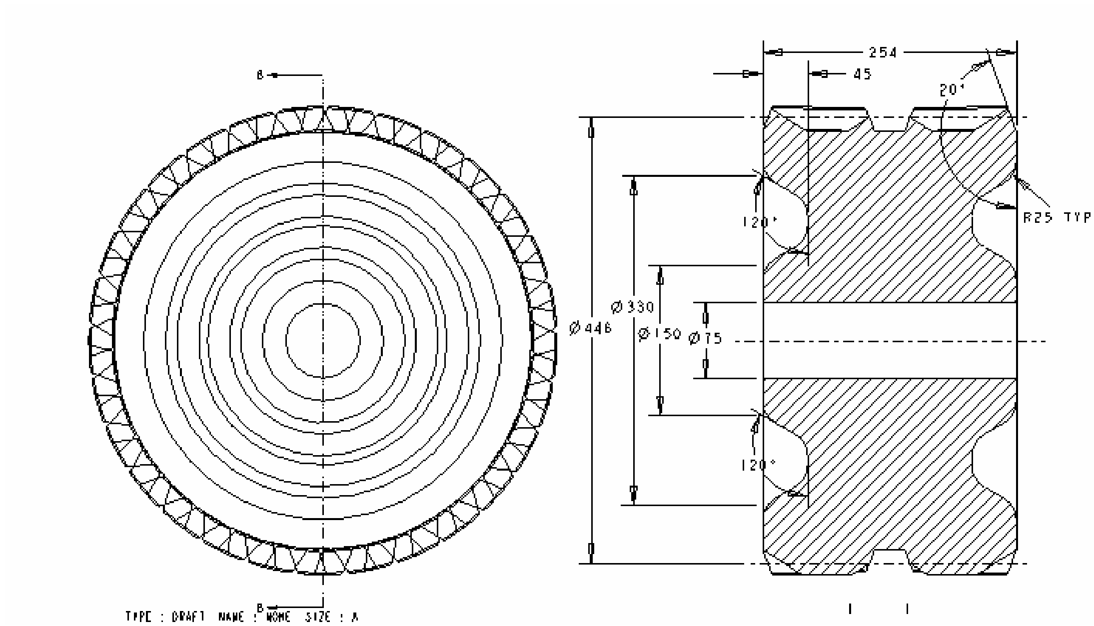


Modification: Taper on the edges of the gear teeth

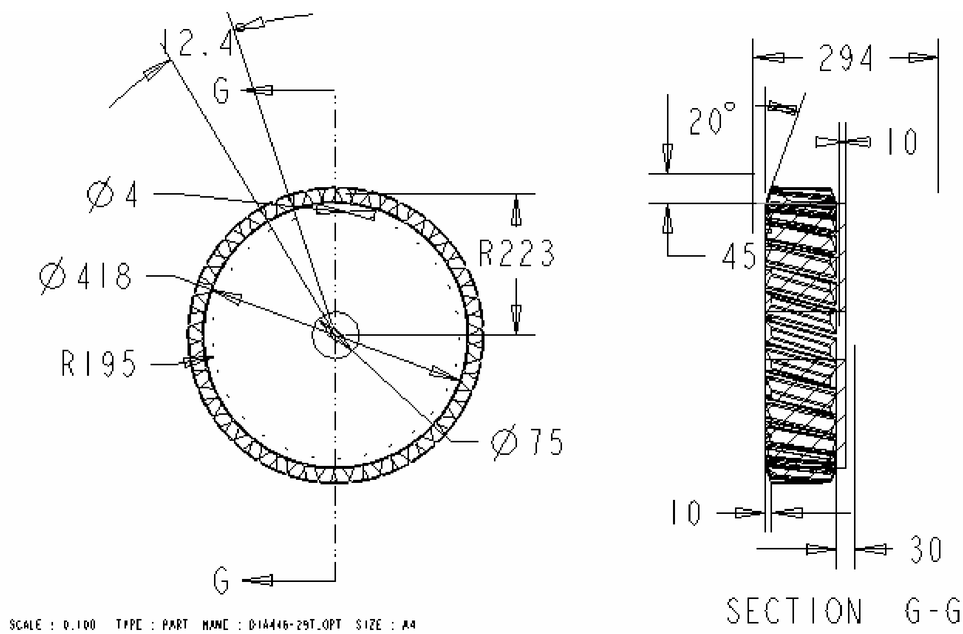


Modification: Hole at the roots of the gear teeth

Figure 3.26 Drawing of modified double helical gear of diameter 234mm

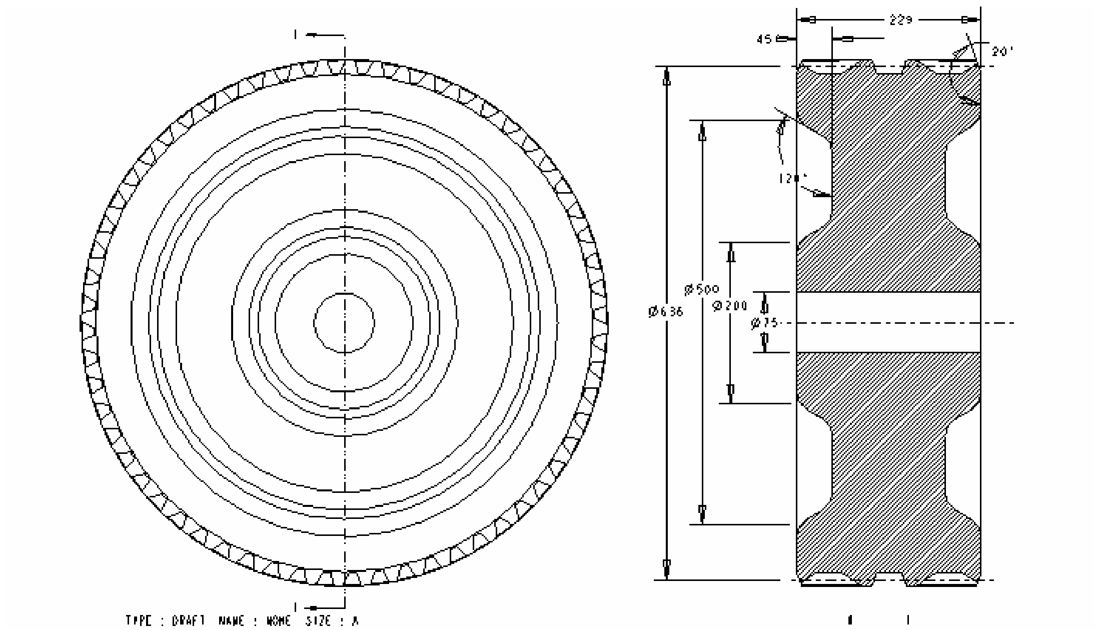


Modification: Taper on the edges of the gear teeth & groove in the gear wheel

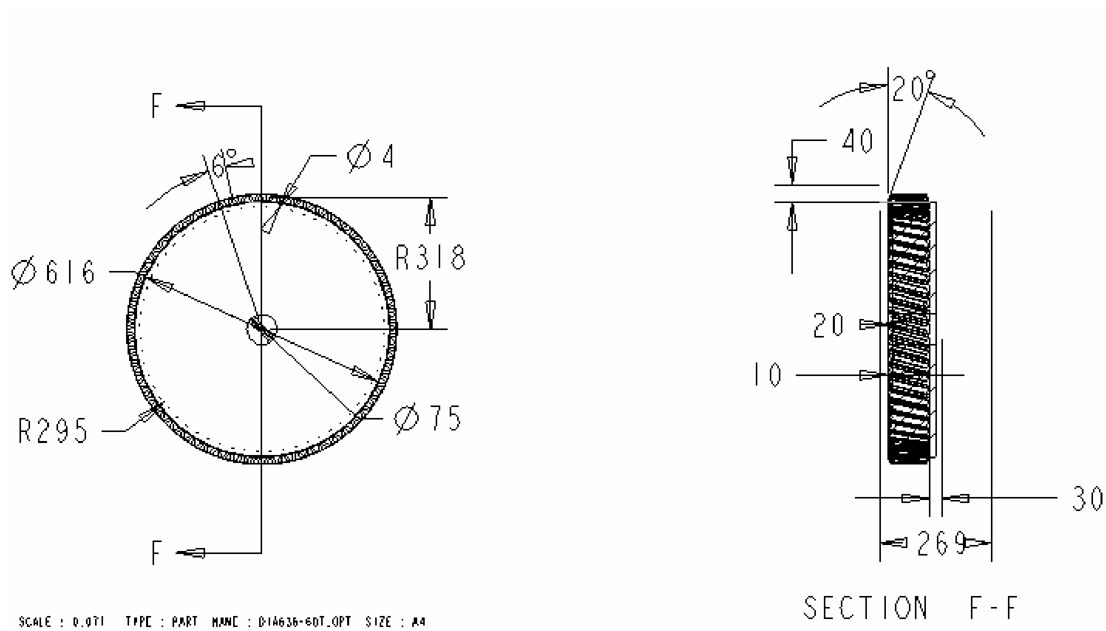


Modification: Hole at the roots of the gear teeth

Figure 3.27 Drawing of modified double helical gear of diameter 446mm

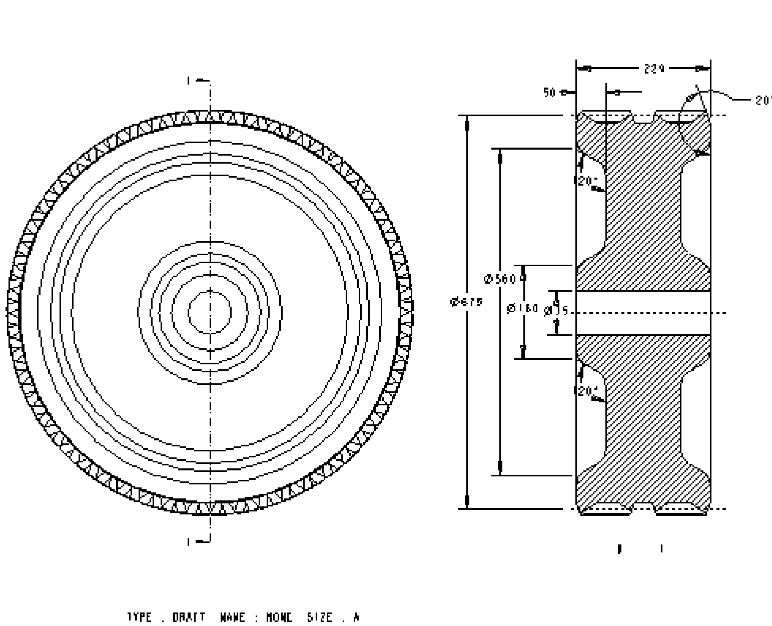


Modification: Taper on the edges of the gear teeth & groove in the gear wheel

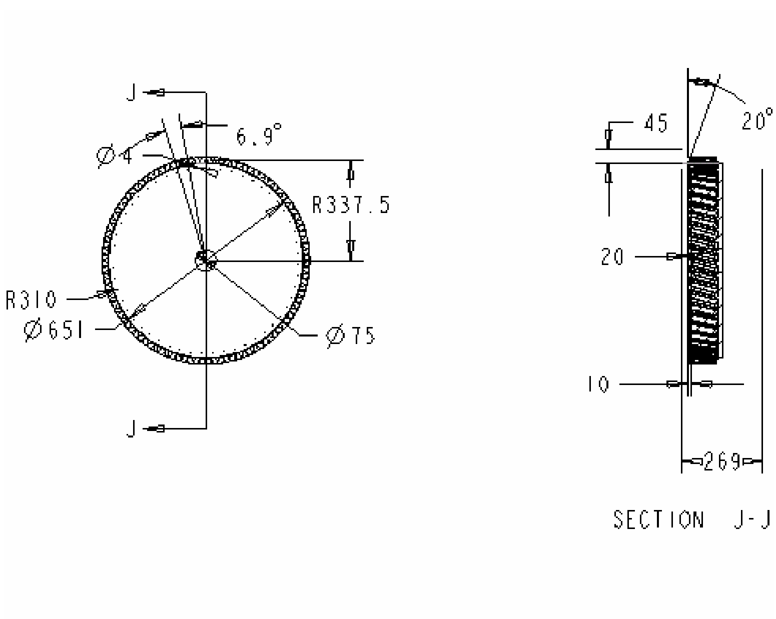


Modification: Hole at the roots of the gear teeth

Figure 3.28 Drawing of modified double helical gear of diameter 636mm



Modification: Taper on the edges of the gear teeth & groove in the gear wheel



Modification: Hole at the roots of the gear teeth

Figure 3.29 Drawing of modified double helical gear of diameter 675mm

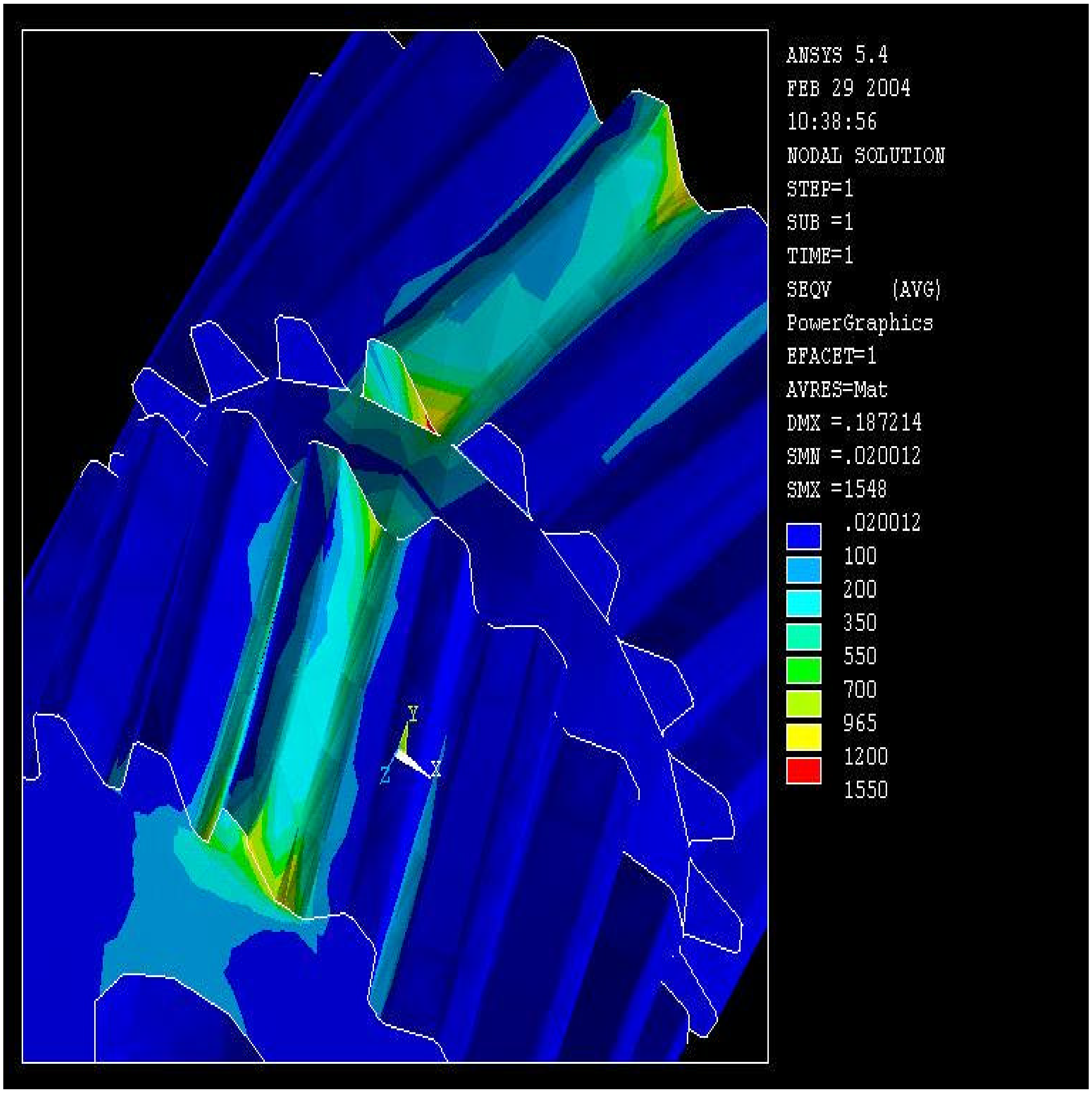


Figure 3.30 Stress analysis of modified double helical gear of diameter 204mm (Taper on the edges of the gear teeth)

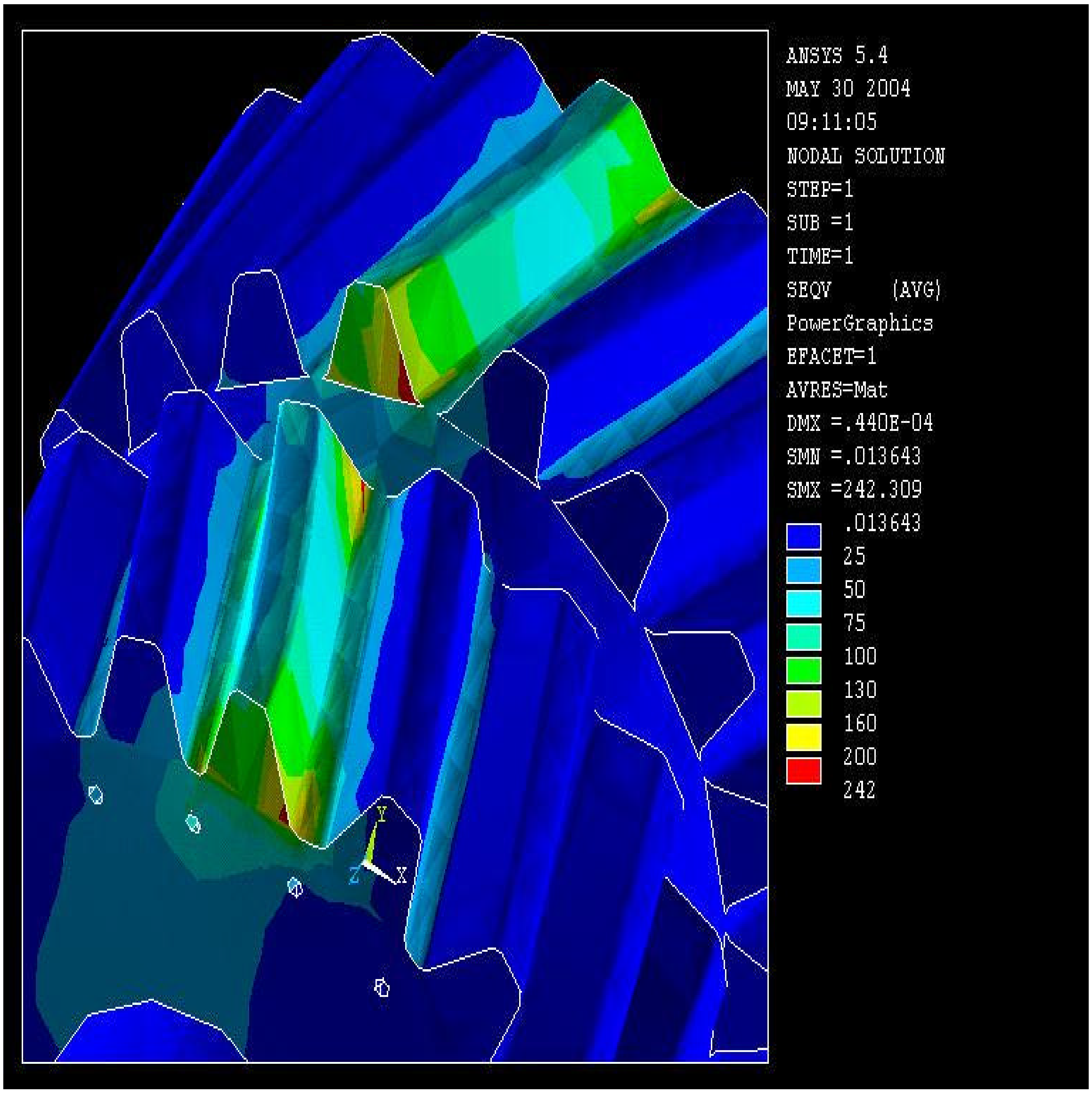


Figure 3.31 Stress analysis of modified double helical gear of diameter 204mm (Hole at the roots of the gear teeth)

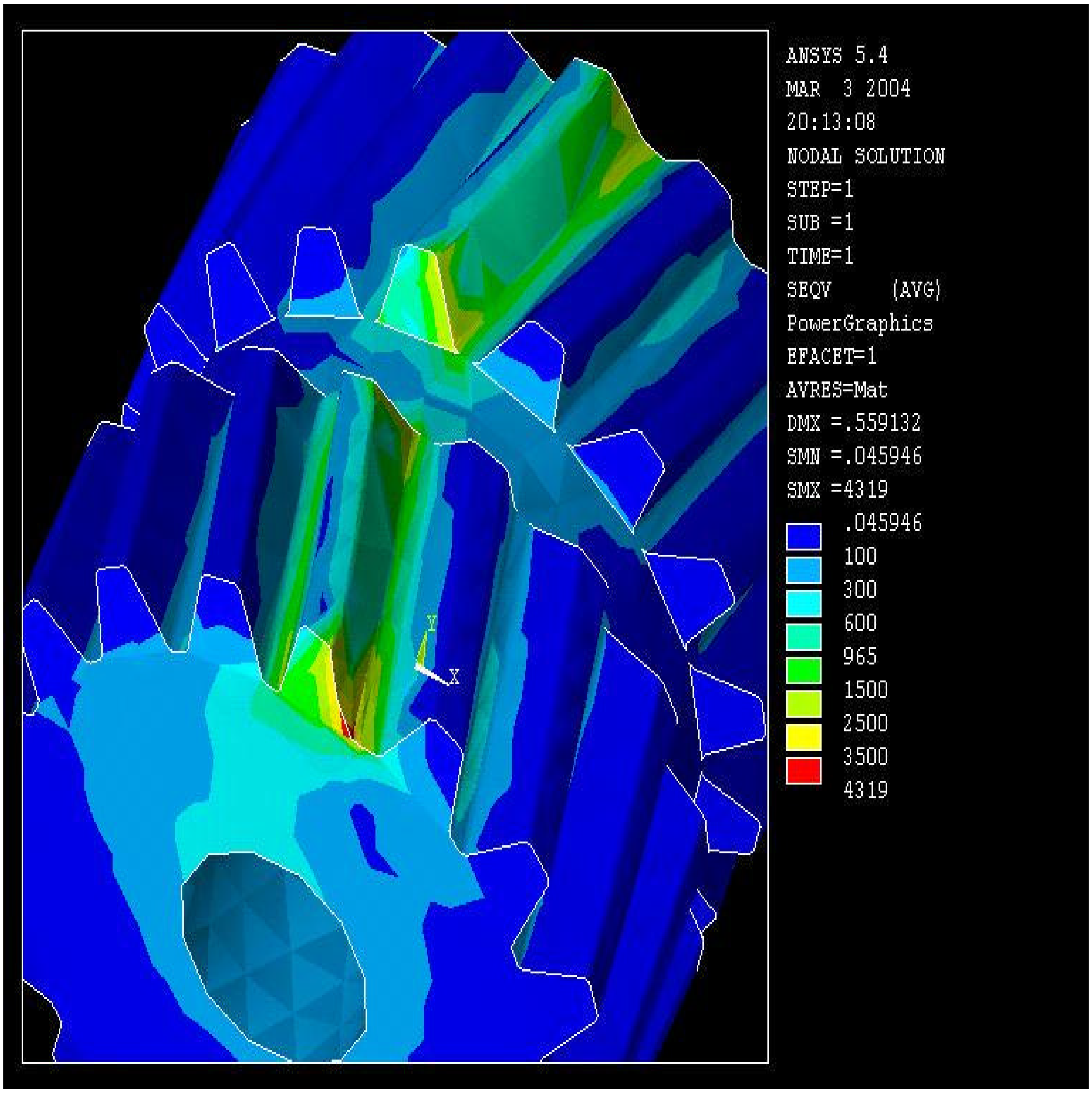


Figure 3.32 Stress analysis of modified double helical gear of diameter 234mm (Taper on the edges of the gear teeth)

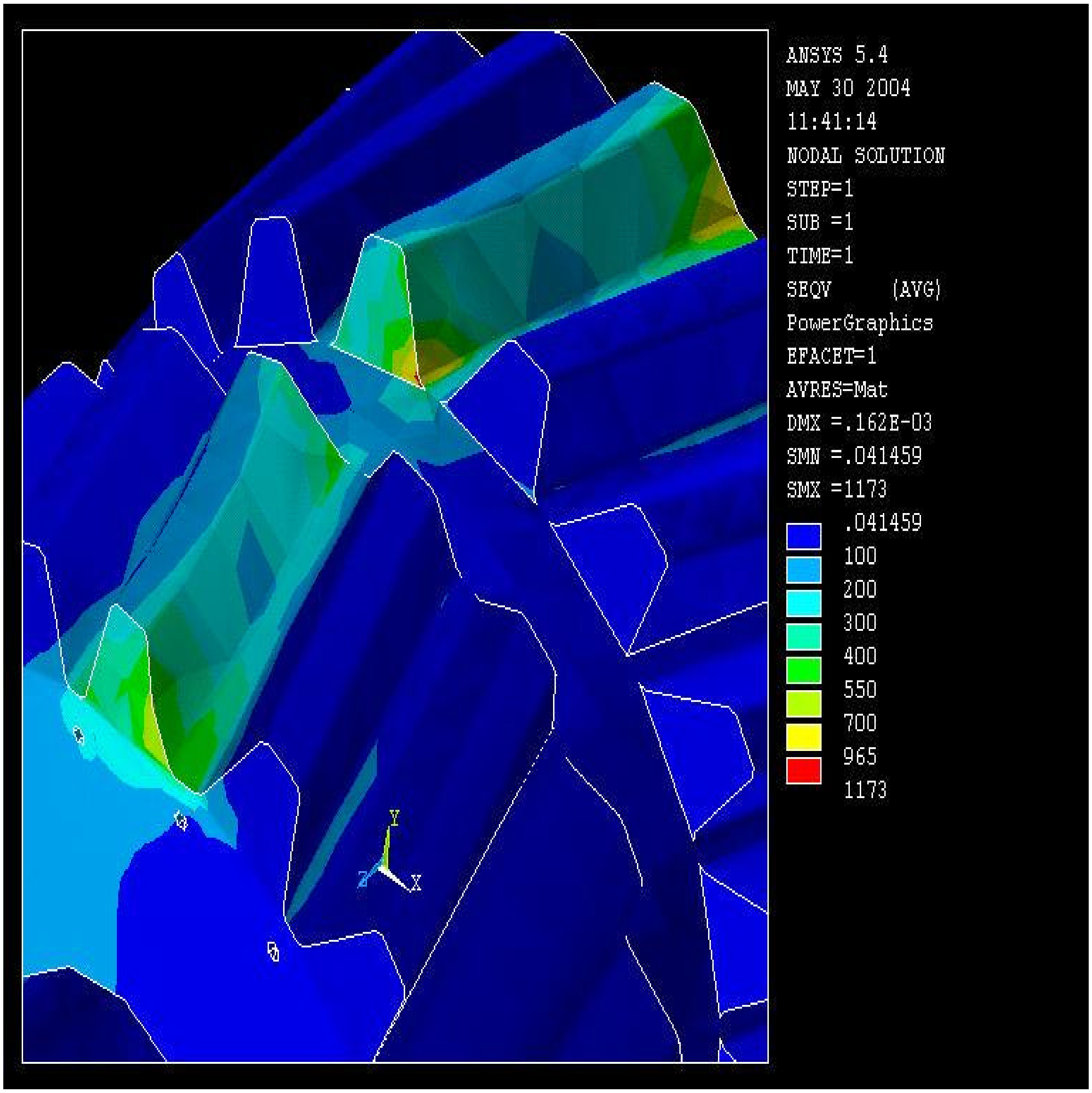


Figure 3.33 Stress analysis of modified double helical gear of diameter 234mm (Hole at the roots of the gear teeth)

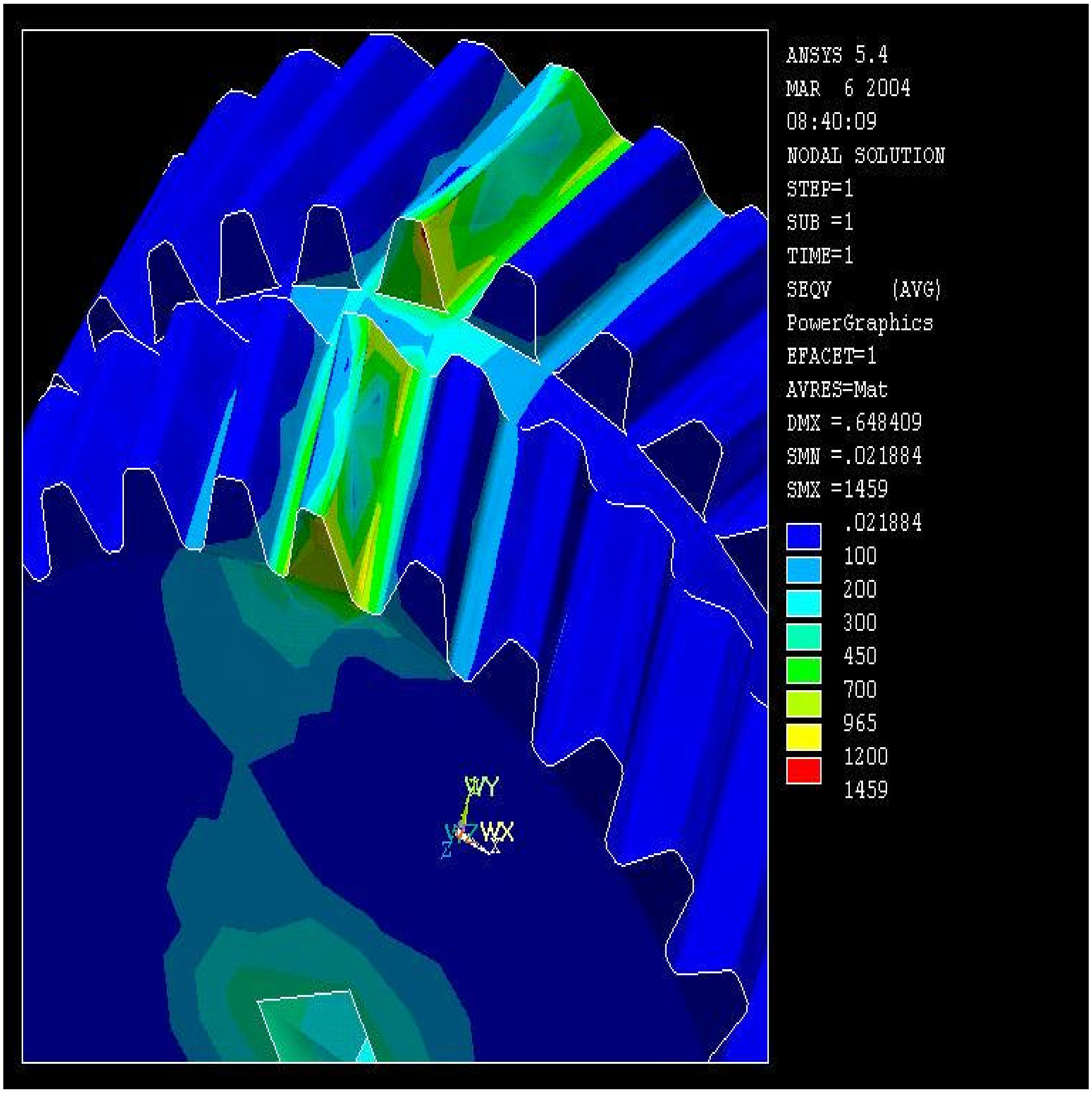


Figure 3.34 Stress analysis of modified double helical gear of diameter 446mm (Taper on the edges of the gear teeth & groove in the gear wheel)

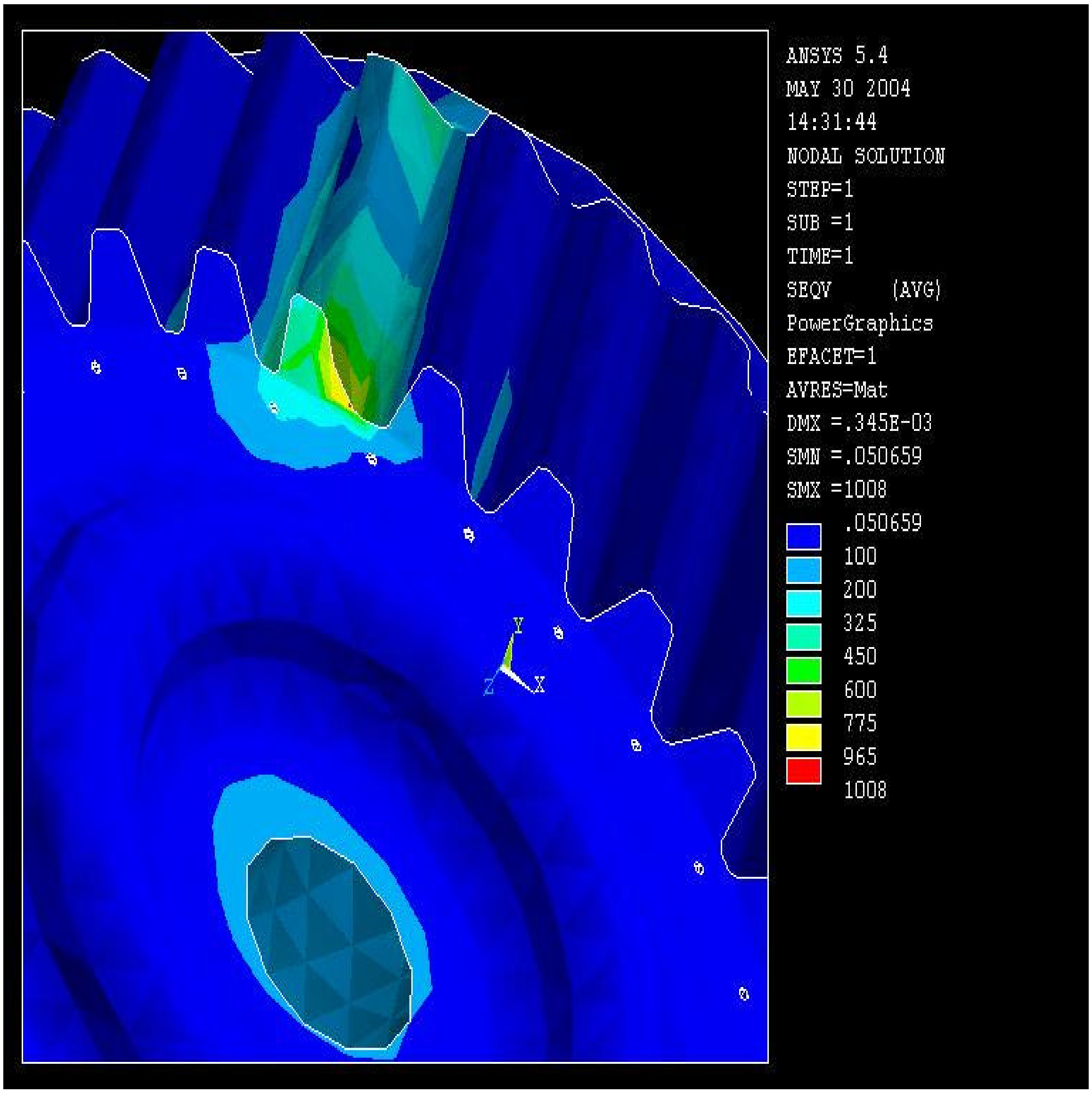


Figure 3.35 Stress analysis of modified double helical gear of diameter 446mm (Hole at the roots of the gear teeth)

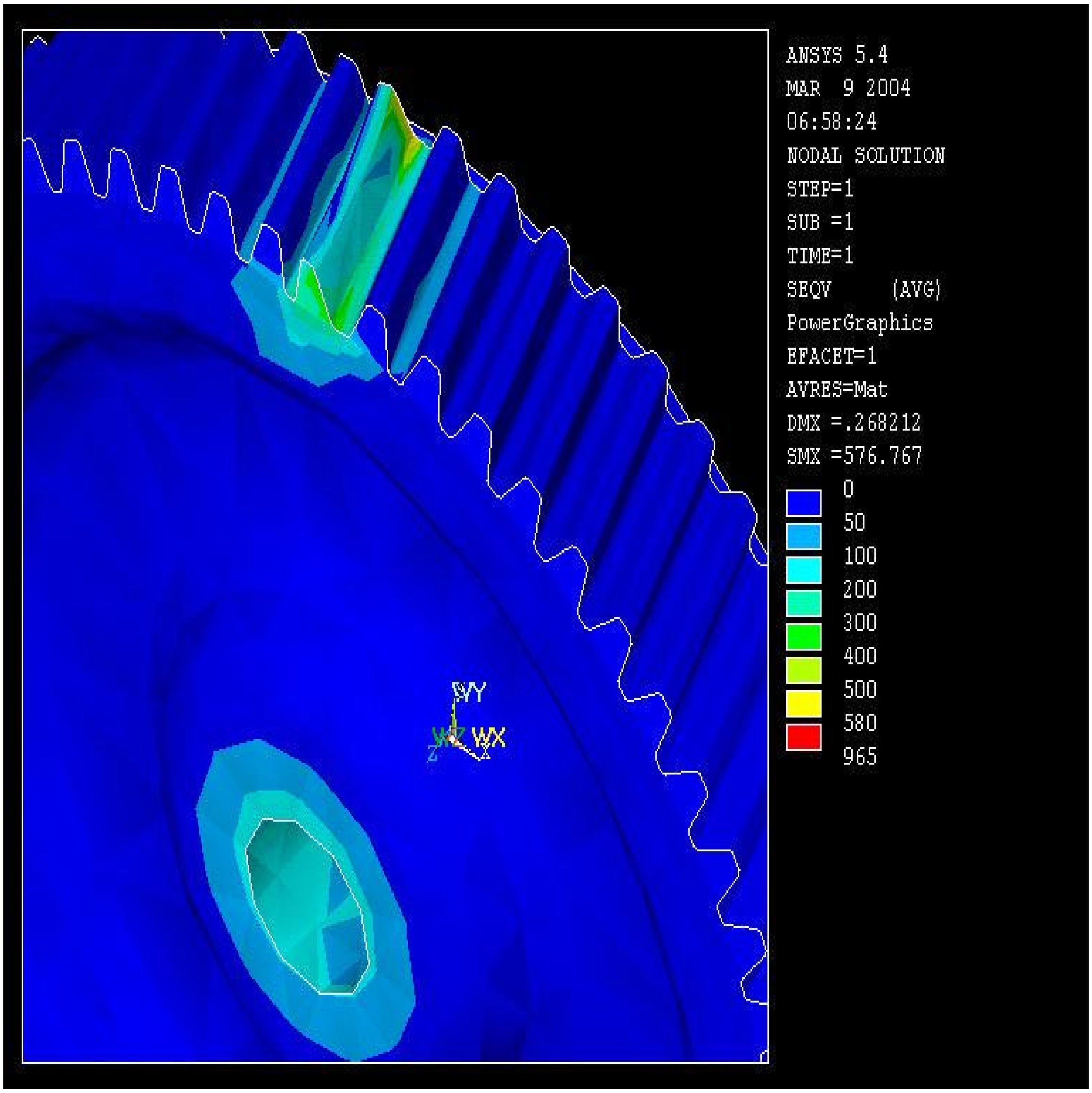


Figure 3.36 Stress analysis of modified double helical gear of diameter 636mm (Taper on the edges of the gear teeth & groove in the gear wheel)

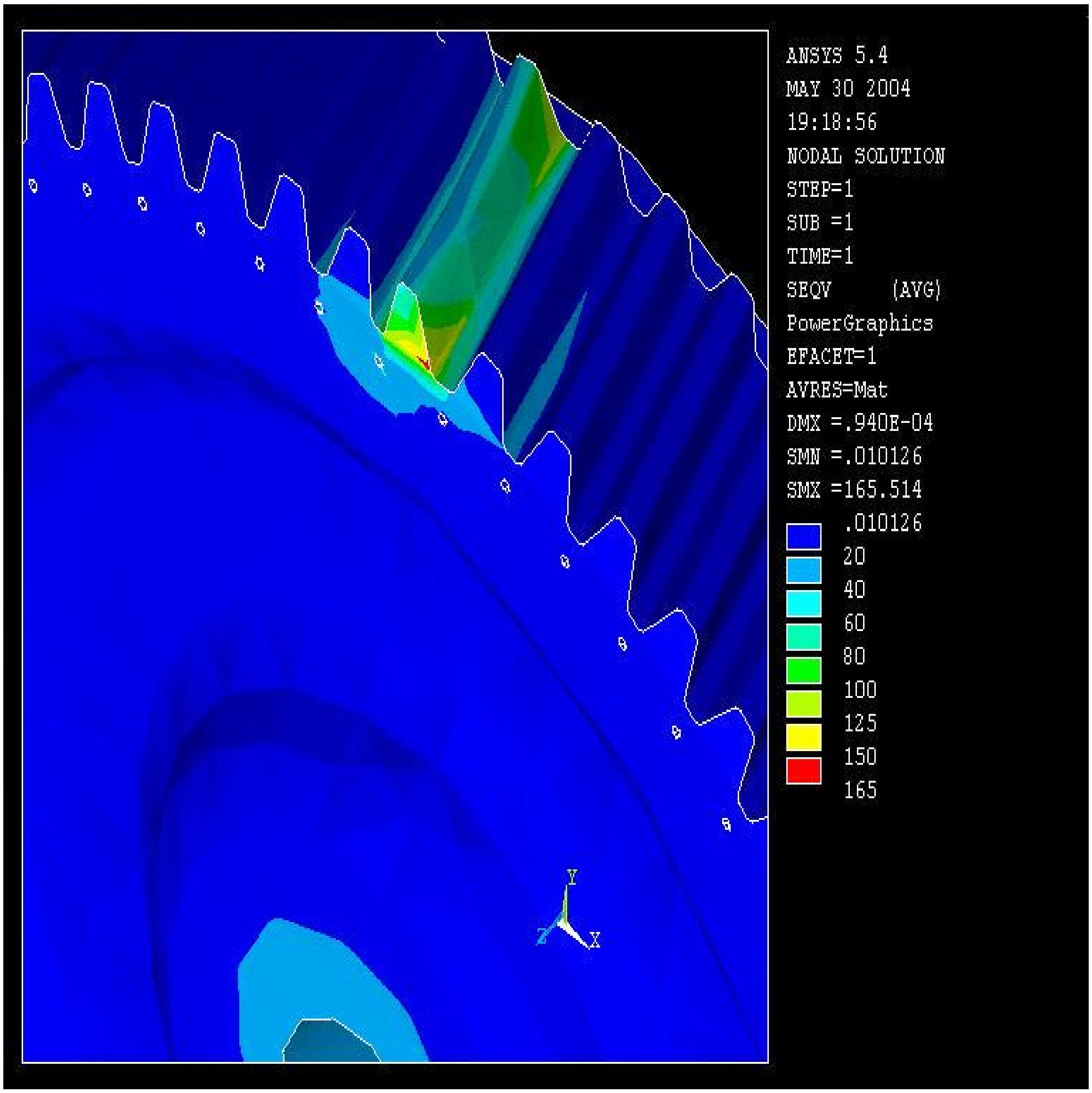


Figure 3.37 Stress analysis of modified double helical gear of diameter 636mm (Hole at the roots of the gear teeth)

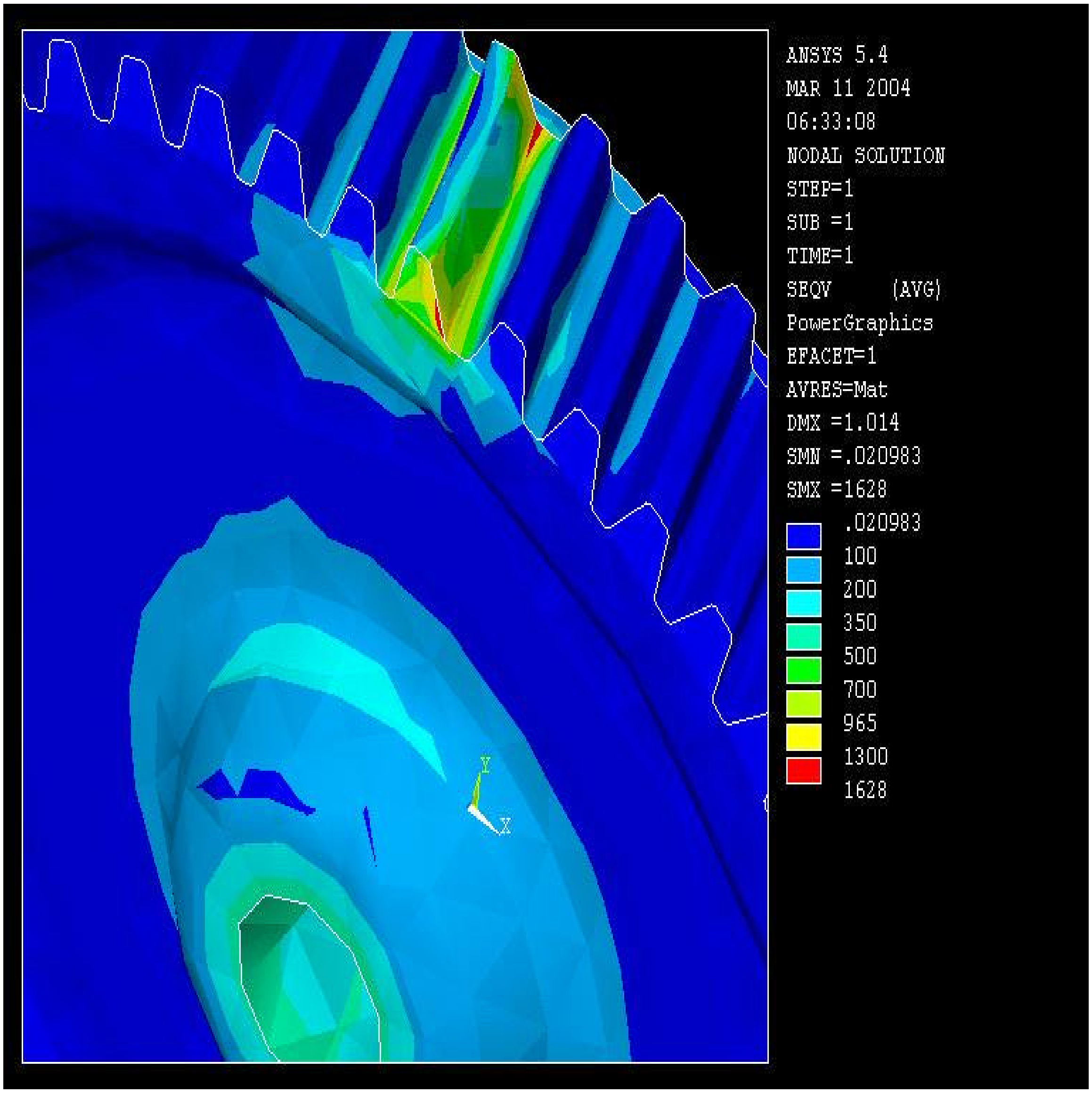


Figure 3.38 Stress analysis of modified double helical gear of diameter 675mm (Taper on the edges of the gear teeth & groove in the gear wheel)

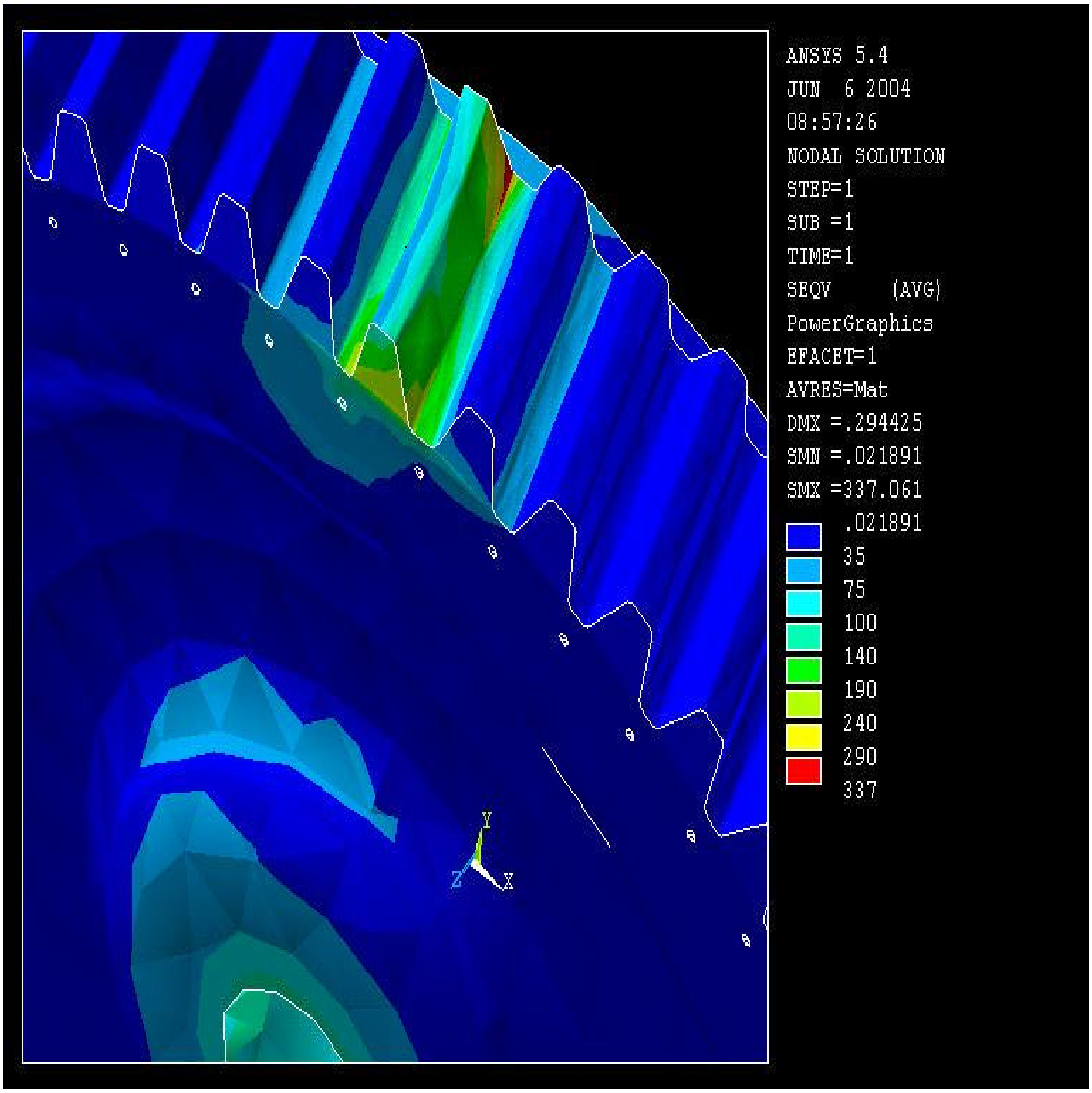


Figure 3.39 Stress analysis of modified double helical gear of diameter 675mm (Hole at the roots of the gear teeth)

CHAPTER 4
CONCLUSION

4.1 Conclusion

The stress analysis of the gearbox was carried out and it was observed that the stresses induced on the gear tooth were higher than the permissible/safe limit.

After modifying the design of the existing gearbox, again the stress analysis was carried out and the results were found to be well within allowable/safe limit.

It was further observed that the stresses induced on the gear tooth were reduced considerably by making hole at the root of the gear tooth.

4.2 Scope of Further Work

- For analyzing stresses induced in the gear teeth using finite element analysis only condition of static loading was applied. But actually the gears are subjected to dynamic loading condition, so there is an ample scope of further work if dynamic loading can also be applied for the analysis.

- As the hole at the root of the gear tooth acts as a stress reliever/reducer, hence its location and size can be optimized further. The number of holes to be made at the root of the gear tooth can also be optimized later on.

- Here only three modifications were used; some other design modifications can be incorporated to minimize the induced stresses on the gear tooth.

APPENDIX

Material Composition & Properties of Forged Steel (EN24)

The gears were made of forged steel of specification EN24 (Black Alloy Steel) of composition as given under :-

	C	Mn	Si	S	P	Cr	Mo	Ni
Min.	0.36	0.45	0.10	-	-	1.00	0.20	1.30
Max.	0.44	0.70	0.40	0.040	0.035	1.40	0.35	1.70

The material properties of EN24 are as under :-

Yield Strength (N/m^2)	Ultimate Strength (N/m^2)	Young's Modulus of Elasticity (N/m^2)	Poission Ratio	Density (kg/m^3)
$940 * 10^6$	$1100 * 10^6$	$205 * 10^9$	0.29	7850

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