SUSTAINABLE & ECONOMIC ADDITIVE MANUFACTURING OF GEARS USING TOPOLOGY OPTIMISATION AND GENERATIVE DESIGN

Report submitted to the SASTRA Deemed to be University
as the requirement for the course

MEC400 PROJECT WORK

Submitted by

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SCHOOL OF MECHANICAL ENGINEERING

THANJAVUR, TAMIL NADU, INDIA – 613 401

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B. Tech. Mechanical Engineering

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BONAFIDE CERTIFICATE

This is to certify that the thesis titled "**Sustainable & Economic Additive Manufacturing of Gears using Topology Optimisation and Generative Design**" submitted in partial fulfillment of the requirements for the award of the degree of B. Tech. Mechanical Engineering to the SASTRA Deemed to be University, is a bonafide record of the work done by **Mr. Jamalapuram Praharshith Kashyap** (Reg. No. **124009054) Mr. Sanjay Baskar** (Reg. No. **124009199**) during the final semester of the academic year 2023-24, in the **School of Mechanical Engineering**, under my supervision. This thesis has not formed the basis for the award of any degree, diploma, associateship, fellowship or other similar title to any candidate of any University.

Signature of Project Supervisor   :

Name with Affiliation   : **Shri K. Palaksha Reddy, Assistant Professor at SASTRA**

Date   :

Project Viva-voce held on _____

Examiner 1   **Examiner 2**

SCHOOL OF MECHANICAL ENGINEERING
THANJAVUR – 613 401

Declaration

We declare that the thesis titled "**Sustainable & Economic Additive Manufacturing of Gears using Topology Optimisation and Generative Design**" submitted by us is an original work done by us under the guidance of **Shri K Palaksha Reddy, Assistant Professor, School of Mechanical Engineering, SASTRA Deemed to be University** during the final semester of the academic year 2023-24, in the **School of Mechanical Engineering**. The work is original and wherever We have used materials from other sources, We have given due credit and cited them in the text of the thesis. This thesis has not formed the basis for the award of any degree, diploma, associate-ship, fellowship or other similar title to any candidate of any University.

Signature of the candidate(s)   :

Name of the candidate(s)   : Jamalapuram Praharshith Kashyap (124009054) & Sanjay Baskar (124009199)

Date   : 01-06-2024

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ABSTRACT

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Gears have been a crucial part of the Automobile Industry for transmitting power and motion from the source of power to the driven elements. An automobile's gearbox life is directly proportional to the design strength and optimisation of the gear for the desired application in the automobile, whilst these two are major safety factors it is also desirable for the manufacturers to keep the production costs feasible. Two of the most effective methods of optimizing the gear strength while reducing the weights of the gears are, Topology Optimisation & Generative Design, both of which are heavily applied into Additive Manufacturing processes & Aerospace Part Manufacturing Industries for better design & cost optimisation. This study focuses on applying Topology Optimisation & Generative Design study on a 4-wheeler vehicle inspired gear model, and comparing the safety factors, strength retention & ideal weight reduction factors and propose a range of the above mentioned factors to achieve a financially sustainable & Metal Additive Manufacturable optimisation process of gear design.
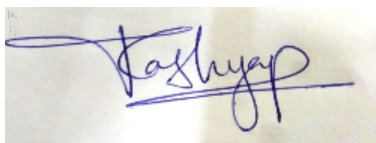
SPECIFIC CONTRIBUTIONS:
-   Solidworks CAD Modelling
-   ANSYS Static Stress Simulation Study
-   Autodesk Fusion360 Topology Optimization & Generative Design Studies

Specific Learning
-   Acquired Proficiency in CAD Modelling using Solidworks.
-   Learned the differences in Structural Optimization processes in ANSYS & Fusion360.
-   Better grasp at thesis formatting.

Keywords: Spur Gears, Metal Additive Manufacturing, Topology Optimization, Generative Design, Comparative Study.

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ABSTRACT

(124009199)

With the increasing awareness and development of Additive Manufacturing (AM), significant efforts are being made to optimize production processes. This study focuses on the evaluation and optimization of gear design through advanced AM techniques, generative design (GD), and topology optimization (TO). TO and GD have been introduced in the industry to build and refine high-grade, low-weight aerospace components, playing a crucial role in maximizing strength and optimizing material consumption. The project addresses a specific application-cum-research gap in mesh resolution and strength retention in metal 3D-printed gears. Initially, target motor specifications and appropriate gear types are identified based on standard reference values. The selection of ideal materials is conducted with consideration of weight, strength, and cost factors, both for AM processing and production. Automated GD and TO processes determine optimal design parameters, ensuring the safety factor and material strength are maintained. Utilizing software tools such as ANSYS Workbench, Solidworks, SIEMENS Solid Edge, MakerBot Print, and Creo, gear models are developed and optimized to achieve the perfect balance between strength retention and mesh resolution. A comparative analysis is performed between simulation results and theoretical design calculations, graphing the variations in simulated versus calculated stress results and estimating material costs. This study aims to provide insights into the most effective and cost-efficient gear design parameters, thereby contributing to the optimization of AM processes.

SPECIFIC CONTRIBUTION
- Assisted in the topology optimization process.
- Experimented with new iterations to refine and enhance design parameters of metal 3D-printed - gears.
- Focused on optimizing the balance between strength retention and mesh resolution.
- Addressed specific application-cum-research gaps in mesh resolution and strength retention.

Specific Learning
- Learned how to experiment with and iterate new design parameters.
- Acquired proficiency in using software tools such as ANSYS Workbench, Solidworks, SIEMENS Solid Edge, MakerBot Print, and Creo.
- Developed skills in optimizing the balance between strength retention and mesh resolution in metal 3D-printed gears.
- Enhanced understanding of addressing application-cum-research gaps in mesh resolution and strength retention.

Keywords: Additive Manufacturing (AM), Production Processes, Gear Design, Advanced AM Techniques, Generative Design (GD), Topology Optimization (TO).

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CHAPTER 1

INTRODUCTION

1.1 SPUR GEAR

Gears are fundamental components in mechanical systems, playing a crucial role in transmitting power and motion between machine parts. They come in various shapes and sizes, each designed for specific applications and performance requirements. The primary types of gears include spur gears, helical gears, bevel gears, worm gears, and planetary gears, each with unique characteristics and advantages.

Gears with straight teeth parallel to the axis of rotation, spur gears are the most prevalent type and are suitable for transferring motion and power between shafts that are parallel. They are widely employed in various machinery like automobiles, and conveyor systems due to their reputation for efficiency and simplicity. Although they are cost-effective and easier to manufacture compared to other gear types, they can produce more noise at high speeds. The usual manufacturing methods for spur gears include milling, hobbing, and gear shaping, which enable the precise and efficient production of these gears. Their simple design and dependable performance make them essential components in mechanical engineering.

1.2 METAL ADDITIVE MANUFACTURING

The rise of Metal Additive Manufacturing (AM), also known as 3D printing, has completely changed how things are made, especially in manufacturing. It allows for more freedom in design and better production abilities. When it comes to making gears, this new technology is a big change from the old ways of taking things away to add things. Gears are important in lots of machines and systems, so they need to be precise, strong, and often have complex designs.

Current MAM technology has a few rough edges with the surface finish and dimensional accuracy. However, Using MAM also comes with benefits such as ease of manufacturing with complex geometries, reduction of material wastage, automation, and inventory reduction. Optimizing the designs using Topology Optimization & Generative Design provides more freedom for engineers to utilize complex geometries without worrying about

the machinability of the gear using traditional manufacturing methods. This also promotes reduction of time in post processing because of the improved designs carrying better dimensional accuracy and surface finishes. Thereby also proving to be cost effective & time efficient.

1.3 TOPOLOGY OPTIMIZATION

Topology optimization is emerging as a powerful design strategy in the field of gear manufacturing, particularly when combined with Metal Additive Manufacturing (AM). This advanced computational technique allows engineers to create highly efficient gear designs by optimizing material distribution within a given design space, subject to specified performance criteria and constraints. The integration of topology optimization with Metal AM enables the production of gears with complex geometries, reduced weight, and enhanced performance characteristics that are unattainable with traditional manufacturing methods.

1.4 GENERATIVE DESIGN

Generative design is transforming the landscape of gear manufacturing by leveraging advanced algorithms and computational power to create optimized, high-performance gear designs. Unlike traditional design methods, generative design explores a vast design space to autonomously generate multiple feasible solutions based on specified constraints and performance criteria. When paired with Metal Additive Manufacturing (AM), generative design facilitates the production of gears with intricate geometries, improved efficiency, and enhanced material properties.

1.5 MATERIALS & THEIR PROPERTIES

Table 1.1 Mechanical properties of various gear materials

SR. No.	Material	Purpose (Simulation or Design)	Density (kg/m^3)	Young's Modulus (GPa)	Modulus of Rigidity (GPa)	Poisson's Ratio
1	C45	Design	7850	210	80	0.29
2	AISI 1045 Steel	Simulation	7850	205	80	0.29
3	AlSi10Mg	Simulation	2670	70	26	0.33
4	AlSi304	Simulation	2700	74	28	0.33
5	Aluminum 6061 T6	Simulation	2700	69	26	0.33

- **C45 and AISI 1045 Steel:** Both of these materials are medium carbon steels with comparable properties, often regarded as equivalent in terms of mechanical characteristics.

- **AlSi10Mg and AlSi304:** These alloys, composed of aluminum and silicon, are frequently utilized in additive manufacturing. AlSi10Mg is well-known and extensively documented for AM applications, while the properties of AlSi304 are less standardized but are assumed to be similar due to the analogous alloy compositions.

- **Aluminum 6061 T6:** This alloy is precipitation-hardened and is recognized for its excellent mechanical properties and weldability.

Table 1.2 Key benefits & applicabilities of various gear materials

Material	Key Properties & Benefits for MAM of Spur Gears	General Benefits for MAM of Spur Gears
C45 and AISI 1045 Steel	- Strong and tough, ideal for high loads. - Durable with good wear resistance. - Easy to machine and finish accurately. - Custom gears tailored to specific needs. - Enables just-in-time manufacturing, reducing inventory.	- Allows for complex gear designs. - Reduces material waste compared to traditional methods. - Speeds up design and testing with rapid prototyping.
AlSi10Mg	- Lightweight, lowering gear assembly weight. - Strong for its weight. - Resists corrosion well. - Good at dissipating heat. - Easy to weld for assembly and repair.	- Allows for complex gear designs. - Reduces material waste compared to traditional methods. - Speeds up design and testing with rapid prototyping. - Custom gears tailored to specific needs. - Enables just-in-time manufacturing, reducing inventory.
AlSi304	- Lightweight and strong, similar to AlSi10Mg. - Versatile use despite less standardization. - Resists corrosion and heat well. - Custom gears tailored to specific needs. - Enables just-in-time manufacturing, reducing inventory.	- Allows for complex gear designs. - Reduces material waste compared to traditional methods. - Speeds up design and testing with rapid prototyping.
Aluminum 6061 T6	- Excellent strength and toughness. - Easy to machine accurately. - Resists corrosion, making it durable. - Effective at heat dissipation. - Easy to weld for integration and repair.	- Allows for complex gear designs. - Reduces material waste compared to traditional methods. - Speeds up design and testing with rapid prototyping. - Custom gears tailored to specific needs. - Enables just-in-time manufacturing, reducing inventory.

1.6 MOTIVATION

The motivation behind this research is driven by the crucial role gears play in the mechanical engineering world as the most common means of transmitting power. Gears are integral components in a wide array of applications. Their importance is evident in essential machines such as automobiles, where they are fundamental in changing speed and power ratios, as well as altering the direction between input and output.

Despite their widespread use and significance, there is still considerable scope for enhancing the performance and efficiency of gears. Advanced techniques like Topology Optimization (TO) and Generative Design (GD) present promising approaches to achieve these improvements. TO optimizes material layout within a given design space for specific loads, boundary conditions, and constraints, thereby maximizing system performance. Similarly, GD uses advanced algorithms to explore a vast design space and generate optimal solutions based on specified constraints and performance criteria, enabling the creation of innovative and efficient designs.

Implementing TO and GD in gear design can lead to several significant benefits:

1. Performance Enhancement: By optimizing gear geometry using TO and GD, it is possible to achieve superior performance characteristics without compromising strength. This addresses the ongoing need for high-performance gear systems in modern machinery.

2. Weight Reduction: Optimizing material use through TO and GD can result in a significant reduction in gear weight. A lower weight not only enhances the strength-to-weight ratio but also reduces the likelihood of mechanical failure, leading to more reliable and efficient systems.

3. Improved Mechanical Properties: Weight reduction achieved through TO and GD can lead to improved mechanical properties, such as better strength-to-weight ratio and adequate hardness. These improvements contribute to the overall durability and reliability of gear systems.

4. Efficient Analysis and Design: Utilizing Finite Element Analysis (FEA) for design

optimization allows for a more efficient approach compared to solving complex partial differential equations. FEA can quickly identify stress and deformation in gear geometry, facilitating faster and more accurate design iterations.

5. Innovative and Complex Geometries: GD enables the creation of complex and innovative gear geometries that traditional design methods cannot achieve. This can lead to more efficient and customized solutions that better meet specific performance requirements.

6. Enhanced Transmission System Performance: By removing material from low-stress regions in the gear, TO and GD can result in an optimized design that not only enhances the performance of the transmission system but also extends the life of bearings and shafts.

7. Sustainability and Material Efficiency: The application of TO and GD promotes sustainability by reducing material waste and improving material efficiency. This aligns with the growing emphasis on environmentally friendly manufacturing practices.

CHAPTER 2
OBJECTIVES

The primary objective of this research is to optimize the geometry of gears using topology optimization techniques in conjunction with finite element analysis to achieve significant weight reduction and improved performance while maintaining the required strength and durability.

2.1 LITERATURE REVIEW & RESEARCH GAP

The Literature Study was conducted through various established journals & authors, till a suitable correlation paper stating the applicative extent between Additive Manufacturing & Topology Optimisation was identified.[1] Then it was further extended into a more specific context of Additive Manufacturing, Topology Optimisation, Finite Element Analysis & Gears, where a TO/FEA study paper on 2-wheeler scooty gears was taken for reference.[2] There was also an extensive study done to gain understanding on the working of Topology Optimisation & Generative Design in order to polish the problem statement.

Research Gap was identified through the initial study paper [1], where it was noted that *"[The] topologically optimized designs may require [a] significant amount of support structures before they can be additively manufactured, resulting in increased fabrication and clean-up costs."* which was taken up as the study focus for this paper. Through further study it was also noted that the Generative Design process simplifies the need of support structures while applied to AM systems. This was further expanded into a combined application of Topology Optimization & Generative Design using Autodesk Fusion360 & SIEMENS Solid Edge respectively to see if there would be further improvement with support structures and strength retention.

2.2 TOPOLOGY OPTIMIZATION FOR MATERIAL REDUCTION
  - Objective: To use topology optimization methods to identify and remove material from low-stress regions of the gear.
  - Rationale: Reducing material in low-stress regions can lead to a lighter gear without compromising structural integrity.
 - Approach:
  - Use FEA to map stress distribution across the gear.

- Apply topology optimization algorithms to suggest optimal material removal areas.
- Validate the optimized design through simulations and physical testing.

2.3 GEOMETRIC DESIGN ENHANCEMENTS

- Objective: To refine the geometric design of the gear to improve the strength-to-weight ratio and enhance mechanical properties.
- Rationale: Improved geometric design can lead to better load distribution and higher efficiency.
- Approach:
- Analyze current gear geometry and identify areas for potential geometric improvements.
- Integrate findings from topology optimization into the geometric design process.
- Use parametric design techniques to iterate and refine gear geometry.

2.4 FINITE ELEMENT ANALYSIS FOR STRESS AND DEFORMATION

- Objective: To employ FEA for detailed stress and deformation analysis of the optimized gear design.
- Rationale: FEA provides a comprehensive method for evaluating the mechanical performance of the gear under various loading conditions.
- Approach:
- Develop FEA models of the original and optimized gear designs.
- Simulate real-world loading conditions to assess stress distribution and deformation.
- Compare results to ensure the optimized design meets or exceeds performance criteria.

2.5 WEIGHT REDUCTION IMPACT ASSESSMENT

- Objective: To quantify the impact of weight reduction on gear performance and overall transmission system efficiency.
- Rationale: Understanding the benefits of weight reduction can justify the optimization efforts and guide future designs.
- Approach:
  - Measure the weight of the original and optimized gears.
  - Analyze the impact of reduced weight on performance metrics such as efficiency, fuel consumption (in automotive applications), and wear rates.
  - Conduct lifecycle analysis to evaluate long-term benefits and potential trade-offs.

2.6 INTEGRATION AND VALIDATION

- Objective: To integrate the optimized gear design into a complete transmission system and validate its performance through experimental and real-world testing.
- Rationale: Real-world validation is essential to confirm the theoretical and simulation-based findings.
- Approach:
  - Prototype the optimized gear design.
  - Integrate the prototype into a transmission system.
  - Perform rigorous testing under various operational conditions to validate performance improvements.

2.7 EXPECTED OUTCOMES

- Performance Improvement: Enhanced gear performance due to optimized weight and stress distribution.
- Weight Reduction: Significant reduction in gear weight leading to better efficiency and mechanical properties.
- Durability: Maintained or improved strength and durability of the gear, resulting in longer service life and reduced failure rates.
- System Efficiency: Overall improvement in transmission system efficiency, leading to potential cost savings and better operational performance.

2.8 CONCLUSION OF STUDY

The proposed research aims to leverage advanced optimization techniques to push the boundaries of traditional gear design. By focusing on topology optimization and detailed geometric design, we expect to achieve a lightweight, high-performance gear that meets the stringent demands of modern mechanical systems.

CHAPTER 3

METHODOLOGY

3.1 DESIGNING THE SPUR GEAR

3.1.1 Acquiring input information from a standard automobile:

For designing any gear, the three basic input parameters are Power Transmitted from the driver to driven shaft (P), number of rotations per minute (n), & the gear ratio (i). These values were taken/rounded off from the Hyundai Verna 1.5L turbo GDi petrol engine.[7]

Table 3.1 Extra Standardized Results for Power Output Range

SR. No.	Extract	Standardized Result
1	"Within the power range required to drive an automobile (about 20-200 kW for passenger vehicles and 20-300 kW for commercial vehicles)."[4]	20-200 kW
2	"The most powerful production car on the market is the McLaren F1 6.1, which develops an excess of 627 hp. "[5]	468 kW

Table 3.2. Extra Standardized Guideline for RPM Range

SR. No.	Observation	Standardized Observation
1	"The ideal RPM range for a car can vary depending on the vehicle's make, model, and engine specifications. However, as a general guideline, most cars operate efficiently between 1,500 and 3,000 RPM during normal driving conditions. This range ensures a balance between fuel economy and power delivery."[6]	1500-3000 rpm

As of the Gear Ratio, A Direct Drive (1:1) was opted for the sake of ease in dimension calculations. For the ease of performing stress and load analysis, and the ease of comparison and designing, the assumed values for the design of Spur gear are as follows:

- P = **Power Transmitted** = $110\ kW$
- n = **Rotations Per Minute** = $3000\ rpm$

- i = **Gear Ratio** = $1:1$

3.1.2 References for Designing the Spur Gear:

Using Design Data Book Formula [8] calculations were done utilizing the formulae provided in the *Chapter 8.*

Table 3.3. Standard Material Properties

SR. No.	Material	Properties
1	C45	E = Young's Modulus = $2.15 \times 10^6 \, kgf/cm^2$ SH = Surface Hardness HB = $200 \, kg/mm^2$ $[\sigma_c]$ = Design Surface Stress = $5000 \, kgf/cm^2$ $[\sigma_b]$ = Design Bending Stress = $1400 \, kgf/cm^2$ σ_u = Ultimate Tensile Strength $\geq 63 \, kgf/mm^2$

Table 3.4 Initial Assumptions

SR. No.	Gear Type	Assumptions
1	Spur	$\Psi_m = \dfrac{b}{m} = 10$ $\Psi = \dfrac{b}{a} = 0.3$ Z = Number of teeth = 30 α = Pressure Angle = 20^0 k = Load Concentration Factor = 1 k_d = Dynamic Load Factor = 1.4 y = Form factor (@ $Z = 30 \, \& \, X = 0$) = 0.440

3.2 DIMENSIONS & PARAMETERS OF THE SPUR GEAR

Table 3.5 Final Calculated Dimensions

[Calculations provided in Appendix A.]

SR. No.	Gear Type	Dimensions
1	Spur	a = center distance = $200\ mm$ = PCD n = RPM = $3000\ rpm$ Z = Number of teeth = $50\ teeth$ i = Gear Ratio = $1:1$ b = Face Width = $60\ mm$ $[M_t]$ = $4750.8\ kgf - cm$ P = $110\ kW$ Surface Stress = $\sigma_c \simeq 4328\ kgf/cm^2$ Bending Stress = $\sigma_b \simeq 415\ kgf/cm^2$ m = Module = $4\ mm$

Since the Gear Ratio is 1:1, Both the Pinion and Gear (Driven & Driver gear) are of the same dimensions.

3.3 STRESS ANALYSIS OF SPUR GEAR (VON MISES STRESS/EQUIVALENT STRESS)

Stress is a fundamental concept in materials science that describes the internal forces present in a material, which resist deformation and determine its mechanical behavior. When an external load is applied to a structure, such as a gear or the gear tooth, the stress within the structure changes, and understanding this distribution of stress is critical to ensure the safety of the structure, as well as, optimizing the material and design of the structure.

Stress is typically measured in units of force per unit area, and in a gear, the stresses are applied across the radial face of the gear and to the gear teeth. These forces can cause stress concentrations in certain areas of the gear, which can lead to failures such as cracks, deformation, or fractures.

In ANSYS, Stress (or) von Mises Stress (or) Equivalent Stress (σ_v) is calculated through a matrix approach of stress applied in 9 different components with respect to the 3 axes (XYZ-axes). The system follows the following formula:

$$\sigma_v = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$

(*or*)

$$\sigma_v = \sqrt{\frac{(\sigma_{xx}-\sigma_{yy})^2+(\sigma_{yy}-\sigma_{zz})^2+(\sigma_{zz}-\sigma_{xx})^2+6(\sigma_{xy}^2+\sigma_{yz}^2+\sigma_{xz}^2)}{2}} \qquad (3.1)$$

where, σ_v (sigma) is von Mises stress (or) Equivalent Stress induced by the applied load (in *MPa*, MegaPascals).

3.4 GENERATIVE DESIGN STUDY OF SPUR GEAR

In Generative Design study, Designer provides a set of constraints, loads, performance criteria, materials, and cost constraints to the software. Using a top-down approach, the system utilizes a set of logarithms that perform iterative refinement & optimization to find the potential solutions for the design, which meets the target goals. This is the general approach while designing and engineering processes where the end goals are well-defined from the start.

For this purpose, Autodesk Fusion360 provides an industry standard GD simulation study platform. The initial inputs are given through the Solidworks CAD model of the spur gear. Surface Constraints, Load Values, Materials, Safety Factor & MAM Machine information are provided by the designer for the algorithm to start the iterative refinement & optimisation. The software generates output by generating various design variations while altering the provided parameters.

3.5 TOPOLOGY OPTIMISATION STUDY OF SPUR GEAR

Whilst following a similar trend of top-down approach like Generative Design Study, Topology Optimisation heavily focuses on evaluating and refining the provided input design of the spur gear, rather than generating multiple design outputs for the provided parameters. In the TO Study, Designer provides the software (Fusion360) with factors that are to be retained, such as safety factor, overall strength on the load applied regions, and load constraints while optimizing the material distribution around the spur gear design.

Topology Optimisation follows Finite Element Analysis, where the CAD file is meshed into fine triangular components, and material characteristics under load are studied. After which, the software, Fusion360 & ANSYS in this case, optimize material distribution through the unnecessary parts of the spur gear design. The output is a lighter weight spur gear component, which carries the same strength and safety factor as the original design.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 SOLIDWORKS DESIGNING

4.1.1 Introduction to Solidworks

      SolidWorks is a computer-aided design (CAD) and computer-aided engineering (CAE) software suite developed by Dassault Systèmes. It is utilized in various industries for designing and engineering products. Due to its core features and compatibility with other softwares in this project, it was chosen as the primary CAD system.

4.1.2 Core Features Used in Solidworks

4.1.2.1 Parametric Modeling

SolidWorks employs a parametric approach, allowing users to define models using parameters such as dimensions, constraints, and relationships. This enables easy modifications and updates, as changes in parameters automatically adjust the model accordingly.

4.1.2.2 Sketching

Users can create 2D sketches that serve as the foundation for 3D models. Sketches are defined using geometric entities like lines, arcs, and splines, and can be constrained to control shape and size precisely.

4.1.2.3 3D Modeling

SolidWorks offers a wide range of tools for creating 3D parts, including extrusion, lofting, sweeping, and revolutions. Users can add features like fillets, chamfers, holes, and patterns to enhance the model's complexity and functionality.

4.1.2.4 Assembly

Complex assemblies can be created by combining individual parts. SolidWorks provides mating conditions to define how components interact and move relative to each other. This is crucial for simulating mechanical operations and ensuring proper fit and function.

4.1.2.5 Drawing & Documentation

SolidWorks enables the creation of detailed 2D drawings from 3D models, complete with annotations, dimensions, and tolerances. This is essential for communicating design intent and specifications to manufacturers.

4.1.3 Spur Gear Designing

The Base Model was designed on Solidworks utilizing the dimensions & parameters mentioned in Table 3.2.1. As the project progressed, later iterations were designed into the Base Model. The base model and the consequent iterations are shown below:
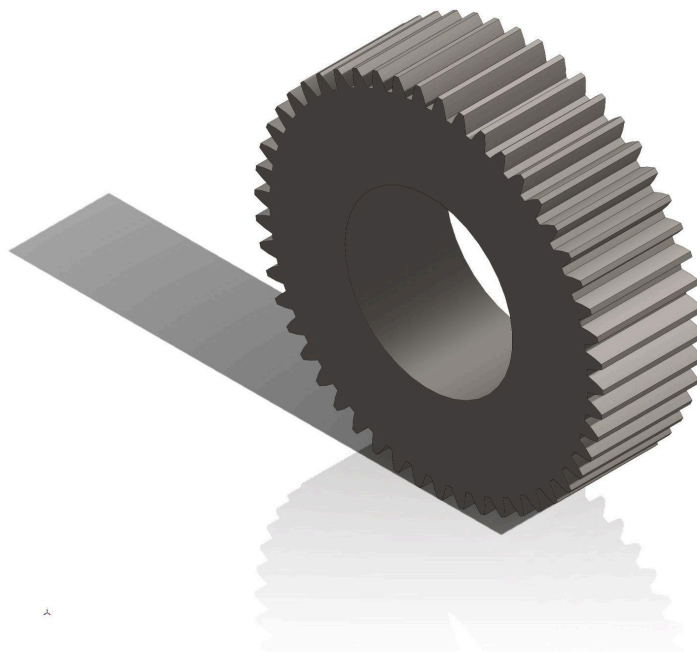
Fig.4.1 Normal Design (No Topology Optimisation & Generative Design applied)
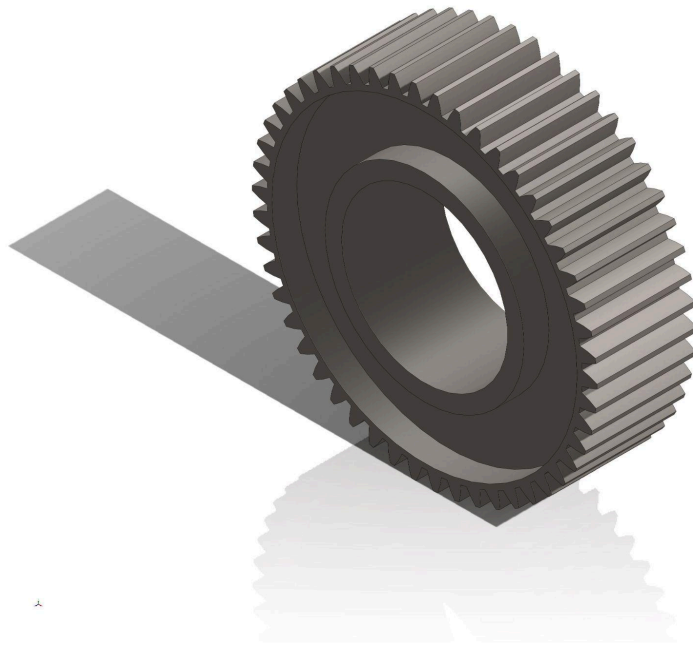
Fig.4.2 Only Generative Design Optimised Design
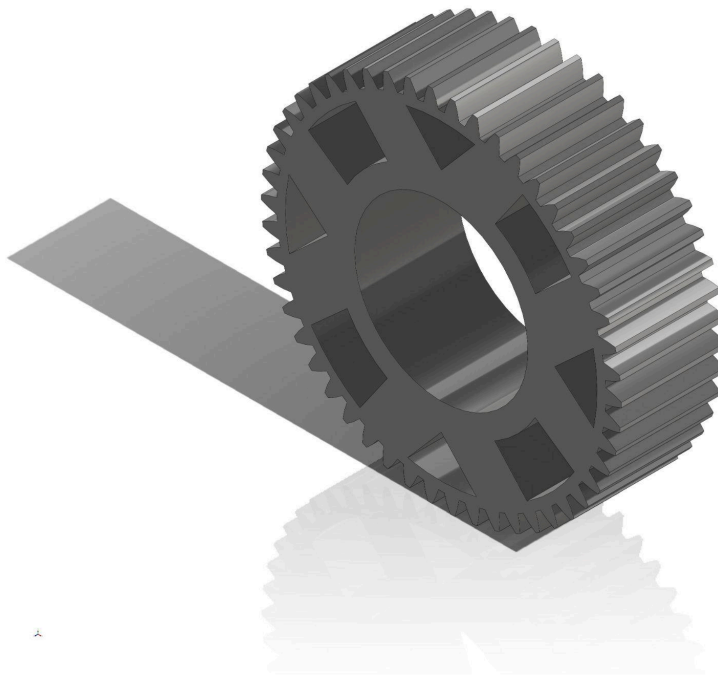
Fig.4.3 Only Topology Optimised Design
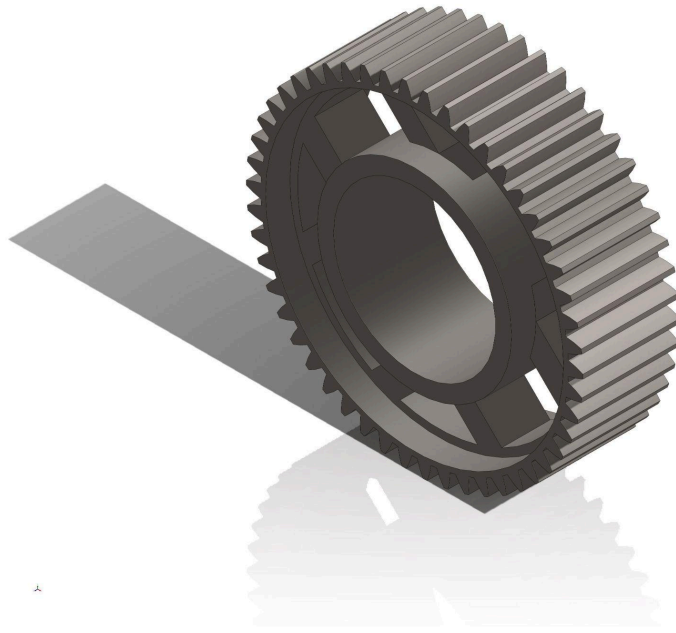
Fig.4.4 Final Design (Both Topology Optimisation & Generative Design applied)

Table 4.1 Design-wise Physical Properties

Spur Gear Design Type	Mass (in grams)	Volume (in cubic millimeters)	Surface Area (in square millimeters)
Base Model	21841.22	2782321.17	281639.15
GD Model	14644.01	1865478.77	338941.8
TO Model	6864.52	874460.73	191523.05
GD + TO Model	5293.96	674389.46	186210.97

4.2 ANSYS Static Stress Analysis

4.2.1 Introduction to ANSYS

ANSYS is an engineering simulation software suite developed by ANSYS, Inc. It is used for performing comprehensive multiphysics simulations, enabling engineers to predict and optimize product performance across a range of industries. The software offers capabilities in finite element analysis (FEA), computational fluid dynamics (CFD), and electromagnetic field analysis, among others.

4.2.2 Introduction to ANSYS Mechanical

ANSYS Mechanical is a specialized suite within the extensive ANSYS software range, focused on structural analysis. It is tailored for finite element analysis (FEA) and is extensively utilized by engineers to simulate the physical behavior of structures under different conditions. ANSYS Mechanical offers a wide array of tools for both linear and nonlinear analysis, dynamic studies, and sophisticated material modeling, facilitating detailed and precise simulations.

Majority of the theoretical design validation of this project was performed on ANSYS Mechanical suite in order to achieve higher simulation precision and detailed results. Spur Gears are a mechanical component which actively undergo mechanical loads, wear & tear and other Structural Stresses.

4.2.2.1 ANSYS Mechanical: Static Structural Study

A Static Structural Study in ANSYS Mechanical focuses on analyzing the response of structures under steady-state loading conditions. This type of analysis assumes that loads are applied slowly and gradually until they reach their full magnitude, ensuring that inertial and damping effects can be neglected.

Two main simulation results that were taken from this study were Stress (von Mises; Maximum & Average; in MPa) & Total Deformation (in mm). These two factors signify the material strength and design strength & the design efficiency.

4.2.2.2 ANSYS Mechanical - Static Structural Study: Parameters & Setup
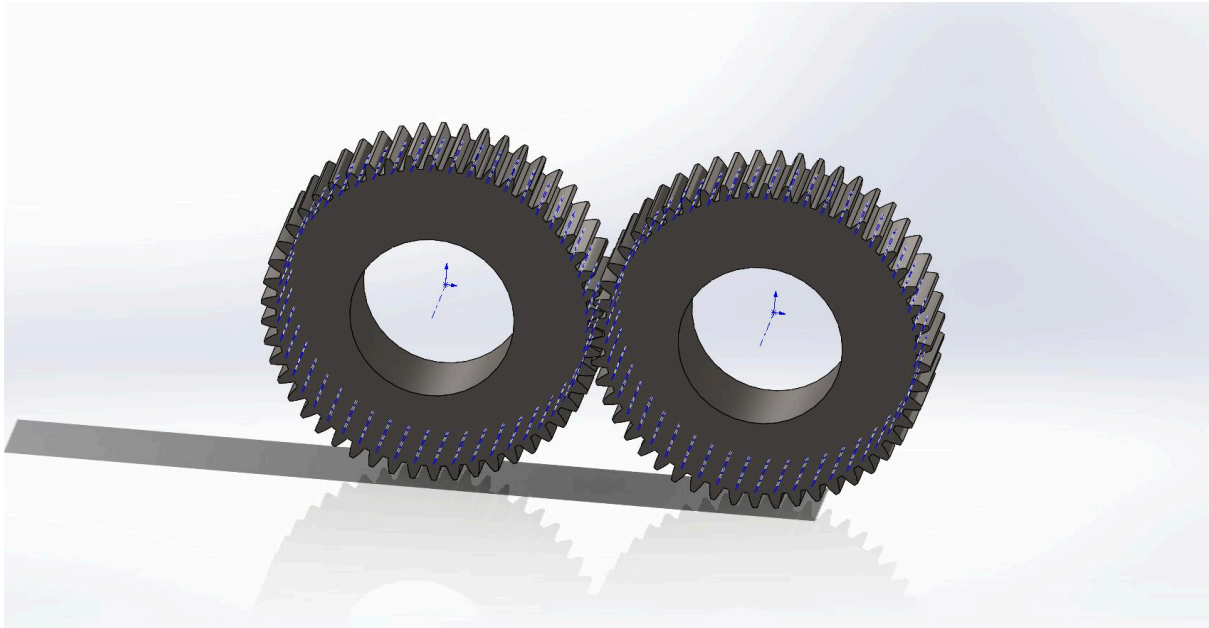
Fig.4.5 Spur Gear Assembly on Solidworks

In a spur gear majority of the stresses and deformation are observed in between the meshed gear teeth. Therefore, given the gear ratio is 1, two base model spur gears were meshed in Solidworks and then exported in *.step* file into ANSYS for conducting Static Structural study.
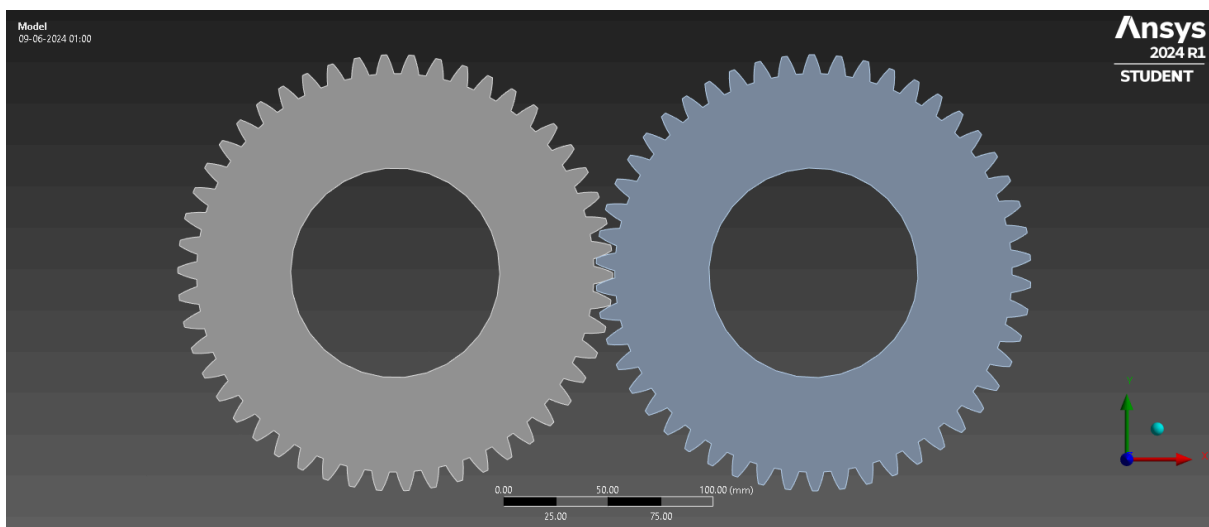
Fig.4.6 Spur Gear Assembly on ANSYS

Upon importing the gear assembly into ANSYS Mechanical Suite, a set of parameters & constraints were attached in order to perform the Static Structural study. It is important to signify which gear is the driven gear and which one is the driving gear for achieving accurate results. Hereon, the left gear is referred to as driven gear (G1) & the right gear is the driving gear (G2).

Table.4.2 Parameters & Constraints applied to the Spur Gear Assembly

Constraint/Parameter	Applied to	Value/Significance
Remote Displacement	G1	Locked 5 degrees of freedom & allowed only rotation about Z-axis.
Frictionless Support	G1 & G2	For simulating a shaft's support for both gears.
Moment	G2	110 kW or 110,000,000 N-mm in counterclockwise direction, in order to simulate the design parameters taken in Chapter 3.1.
Mesh Sizing	G1 & G2	Minimum edge length was given about 1.3138 mm

4.2.2.3 ANSYS Mechanical - Static Structural Study: Simulations
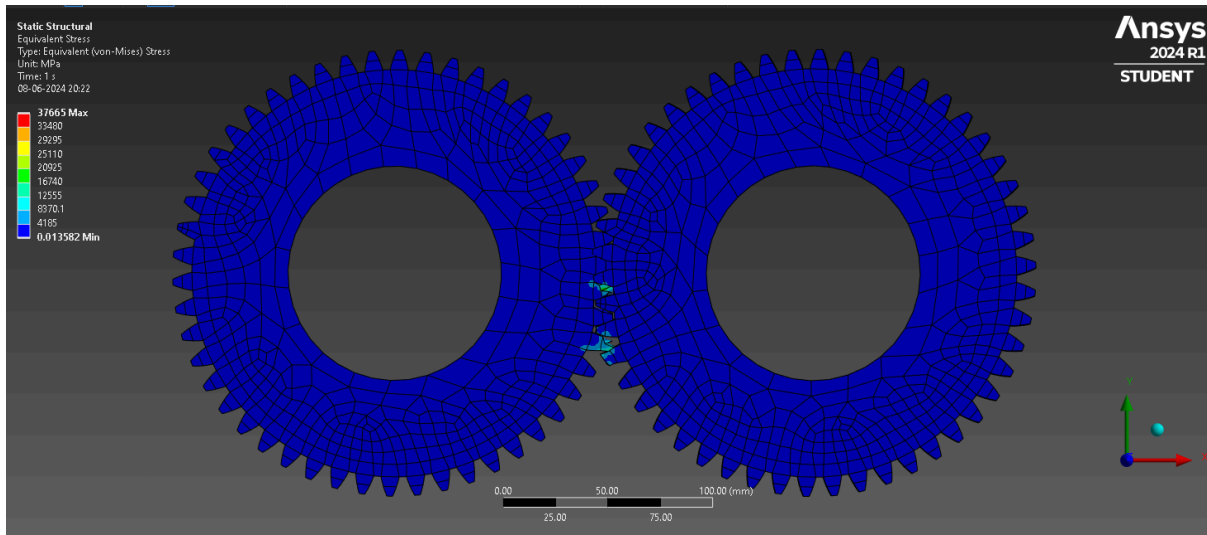
Fig.4.7 Base Model: Equivalent (von Mises) Stress
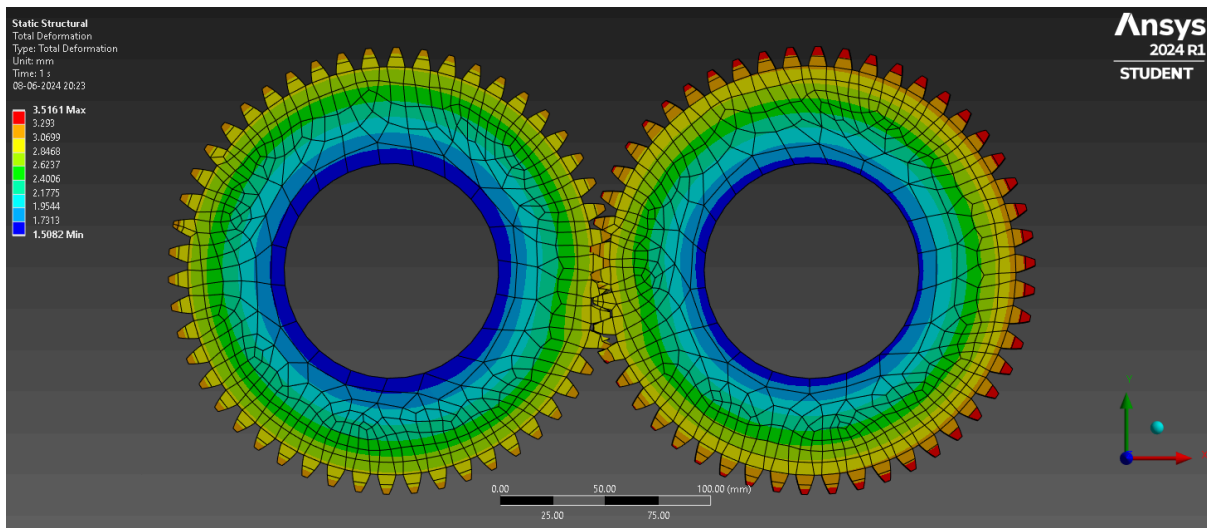
Fig.4.8 Base Model: Total Deformation
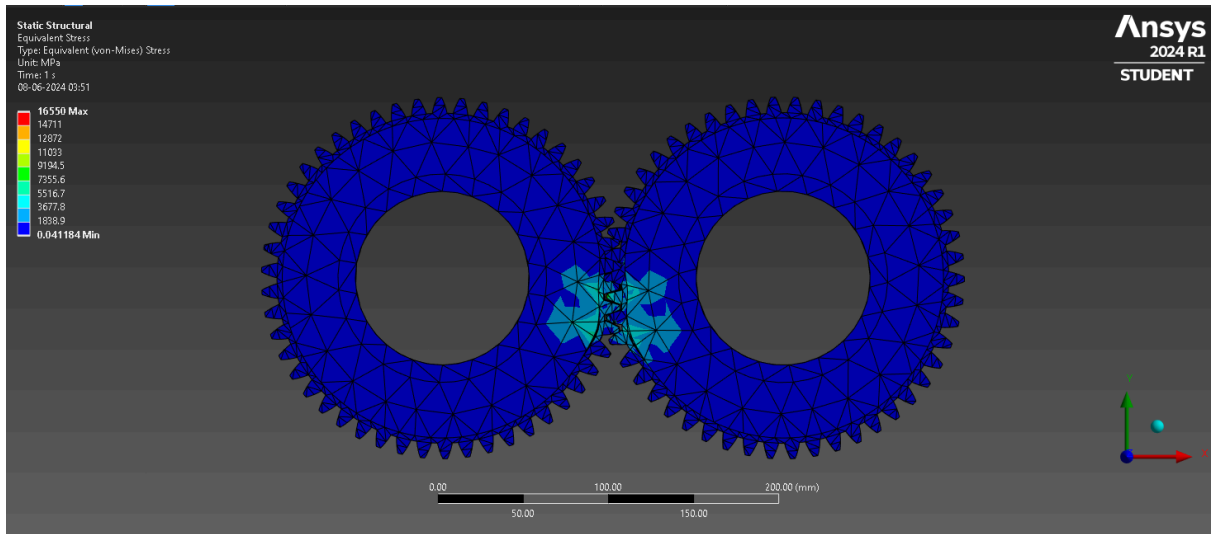
Fig.4.9 GD Model: Equivalent (von Mises) Stress
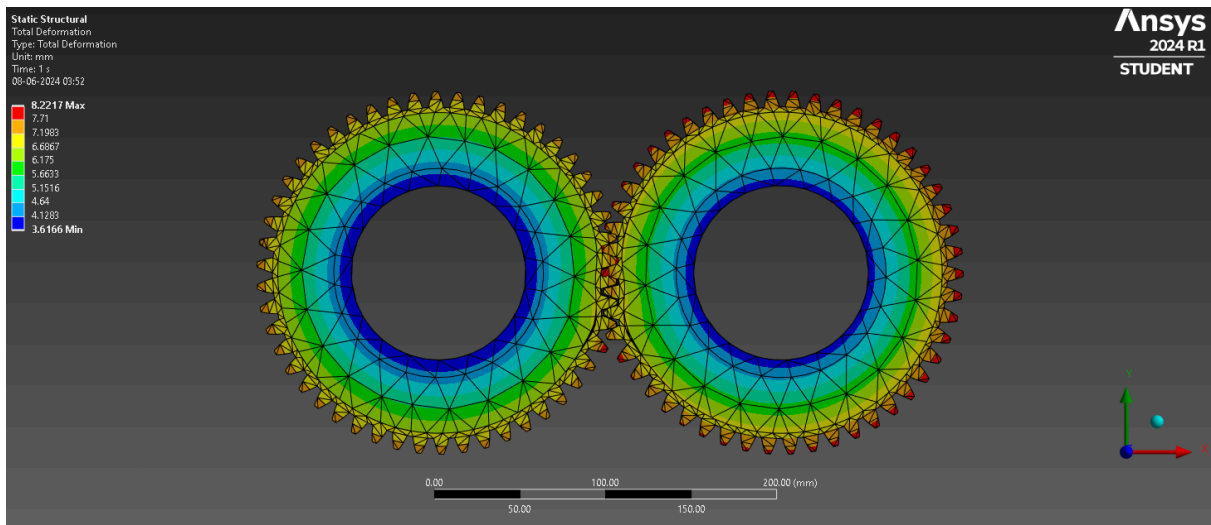
Fig.4.10 GD Model: Total Deformation
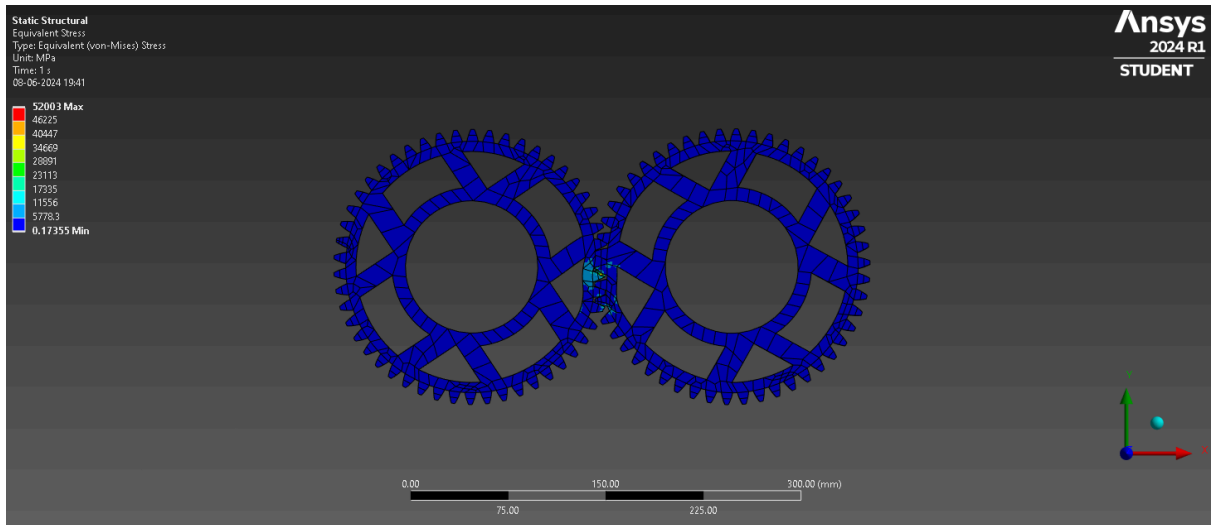
Fig.4.11 TO Model: Equivalent (von Mises) Stress
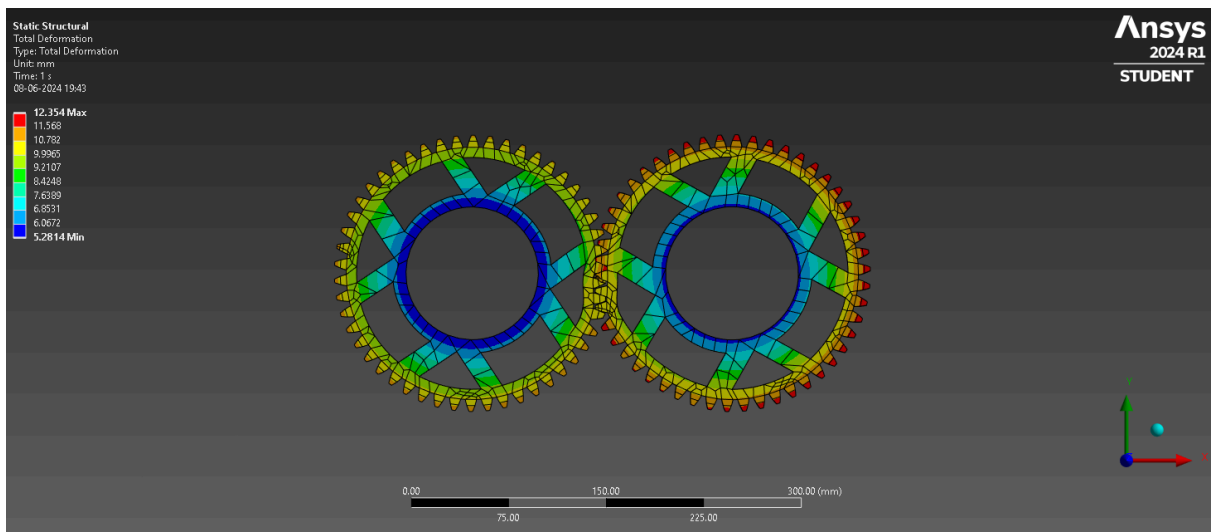
Fig.4.12 TO Model: Total Deformation
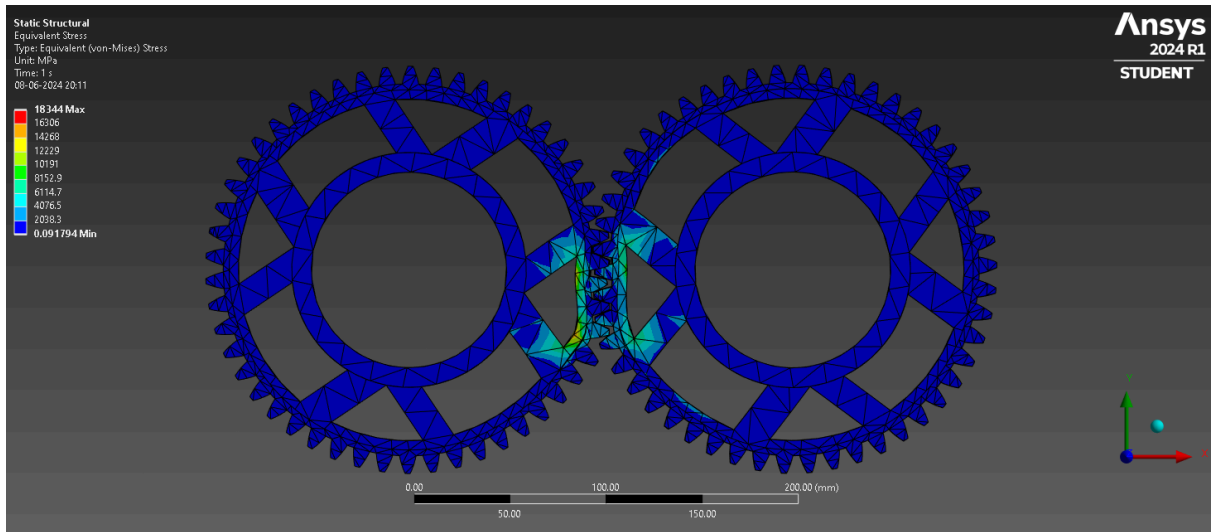
Fig.4.13 GD & TO Model: Equivalent (von Mises) Stress
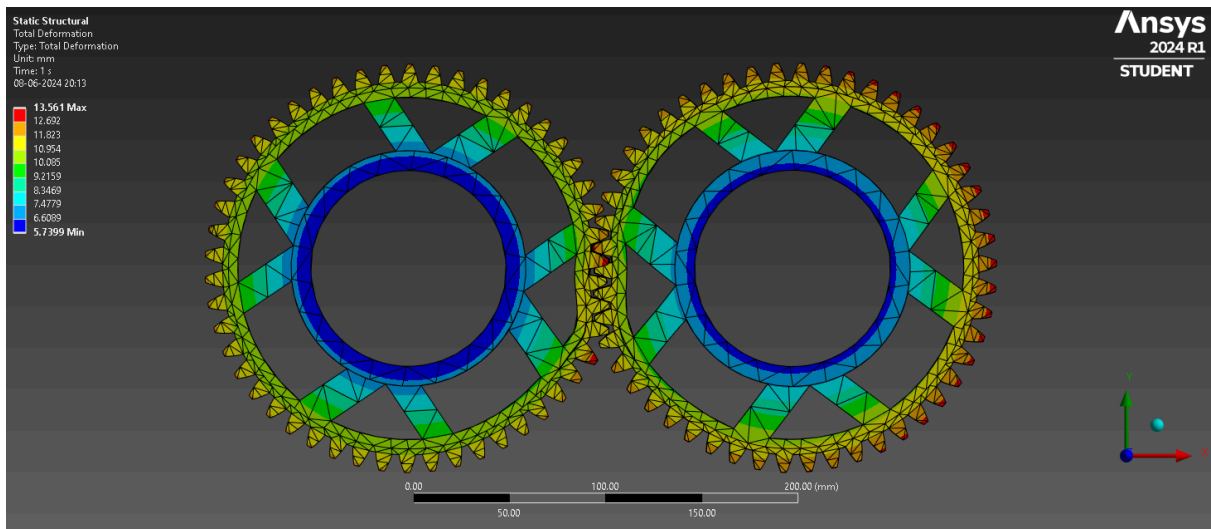
Fig.4.14 GD & TO Model: Total Deformation

4.2.3 ANSYS Mechanical: Static Structural Study - Results

A generalized trend observed through the iterations were such that the highest values of Equivalent (von Mises) Stress were observed in the TO Model, the lowest values were observed in the Base Model. Essentially signifying Topology Optimized design had greater design strength and stress tolerance than conventional design. However, it was also recorded that the GD + TO Model carried the second highest stress values as well as a well distributed Average Stress values, signifying the stress was much more efficiently distributed with the GD+TO Model when compared to the other models.

Table 4.3 Equivalent Stress Results

Gear Design Type	Equivalent (von Mises) Stress (in MPa)		
	Minimum	Maximum	Average
Base Model	1.36E-02	37665	251.66
GD Model	4.12E-02	16550	368.91
TO Model	0.17355	52003	637.68
GD + TO Model	9.18E-02	18344	566.05

The trend observed in Total Deformation is the more the mass is optimized. the more is the deformation.

Table 4.4 Total Deformation Results

Gear Design Type	Total Deformation (in mm)	
	Minimum	Maximum
Base Model	1.51	3.5161
GD Model	3.62	8.2217
TO Model	5.2814	12.354
GD + TO Model	5.74	13.561

4.3 Autodesk Fusion360 Studies

Autodesk Fusion 360 is a cloud-based CAD/CAM software suite that combines design, engineering, and manufacturing capabilities in a single platform. It offers a range of tools for 3D modeling, simulation, rendering, and collaboration. Autodesk offers this software for free under student's license, making it a suitable and competent candidate for conducting Generative Design & Topology Optimization studies for this project.

Similar to ANSYS Static Stress Study, a set of parameters, constraints & load factors were added to the study in order to achieve accurate results. However the key difference lies in what it is applied to for the study. During the GD & TO Studies, a singular spur gear base model is utilized instead of an assembly, as design optimization algorithm works efficiently on a singular object, a singular spur gear.

4.3.1. Generative Design Study

Table.4.5 Parameters, Load & Constraints applied to the Spur Gear (Base Model)

Constraint/Parameter/Load	Applied To	Value/Significance
Preserve Geometry	Centre & Gear teeth geometry	These geometries shall be preserved
Gravity	Full Body	$9.80665 \ ms^{-2}$
Target Mass	Full Body excluding Preserved Geometry	The final target mass in relative scale to the original mass: ~60%
Limits	Safety Factor	Should not go below 2.00
Load Case (Pressure)	All Gear teeth	4.63 MPa/per tooth
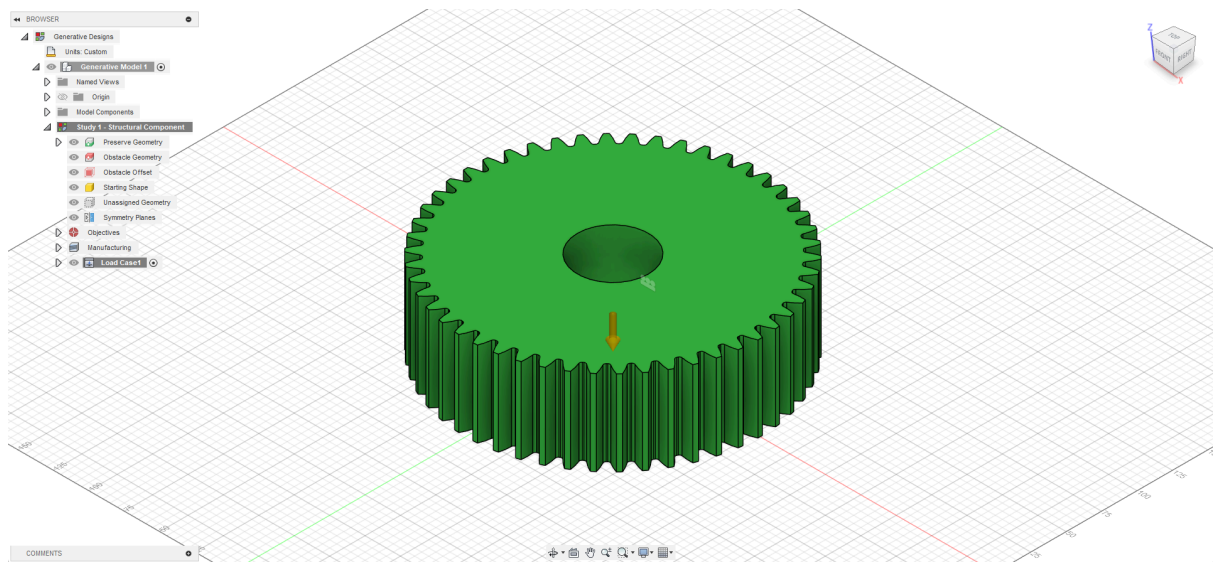
Fig.4.15 Autodesk Fusion360 Workspace
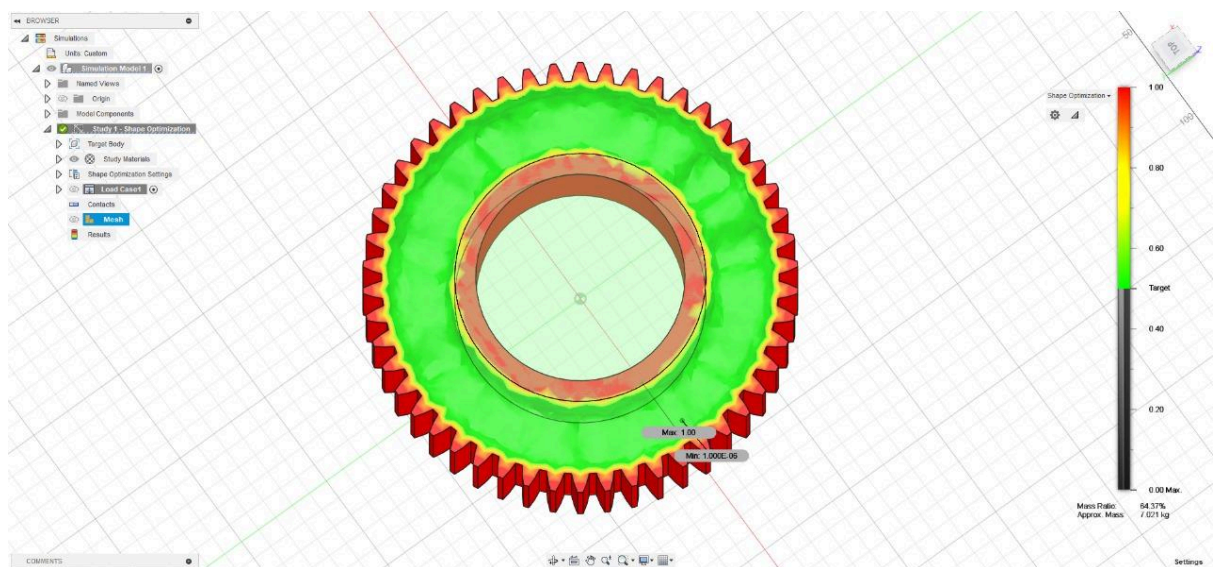
Fig.4.16 GD suggested design after multiple iterations
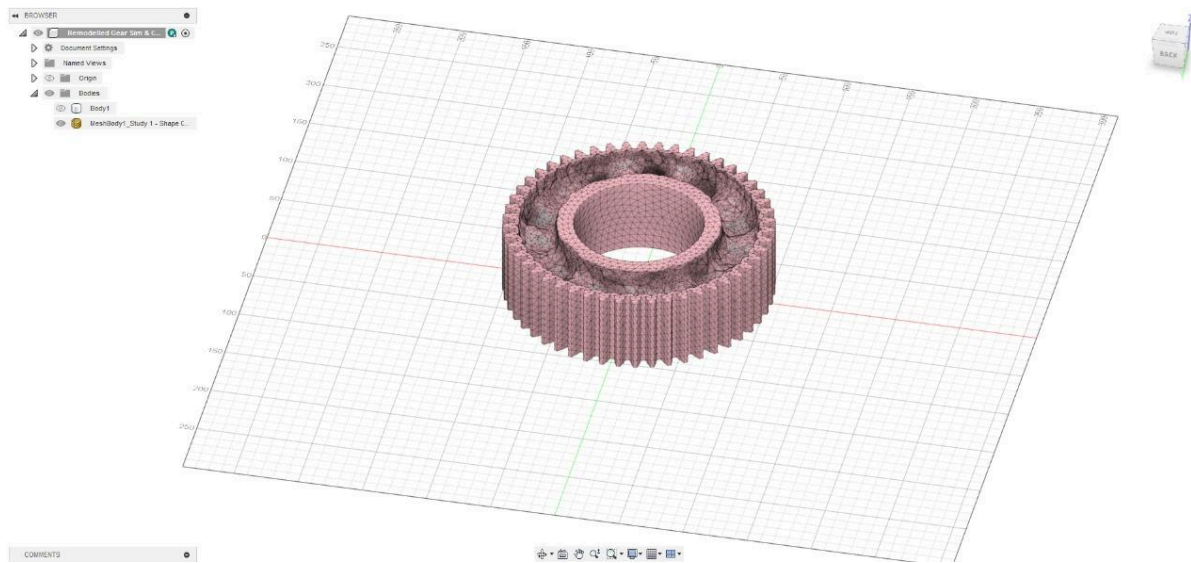
Fig.4.17 Final Rough Mesh of GD Output

4.3.2. Topology Optimization Study

During the TO process, the spur gear is divided into 4 quarters with respect to the front and right plane. The design is also simplified into a flat faced cylindrical ring. Unlike GD, where the entire design elements are required for the algorithms to iterate different forms, TO utilizes the stress distribution within the body to optimize the design.

Table.4.6 Parameters, Load & Constraints applied to the Spur Gear (Base Model)

Constraint/Parameter/Load	Applied To	Value/Significance
Preserve Geometry	Centre & Outer Cylindrical face	These geometries shall be preserved
Target Mass	Full Body excluding Preserved Geometry	The final target mass in relative scale to the original mass: ~60% & ~45%
Limits	Safety Factor	Should not go below 2.00
Load Case (Moment)	Outer Cylindrical Face	110 kW or 110,000,000 N-mm
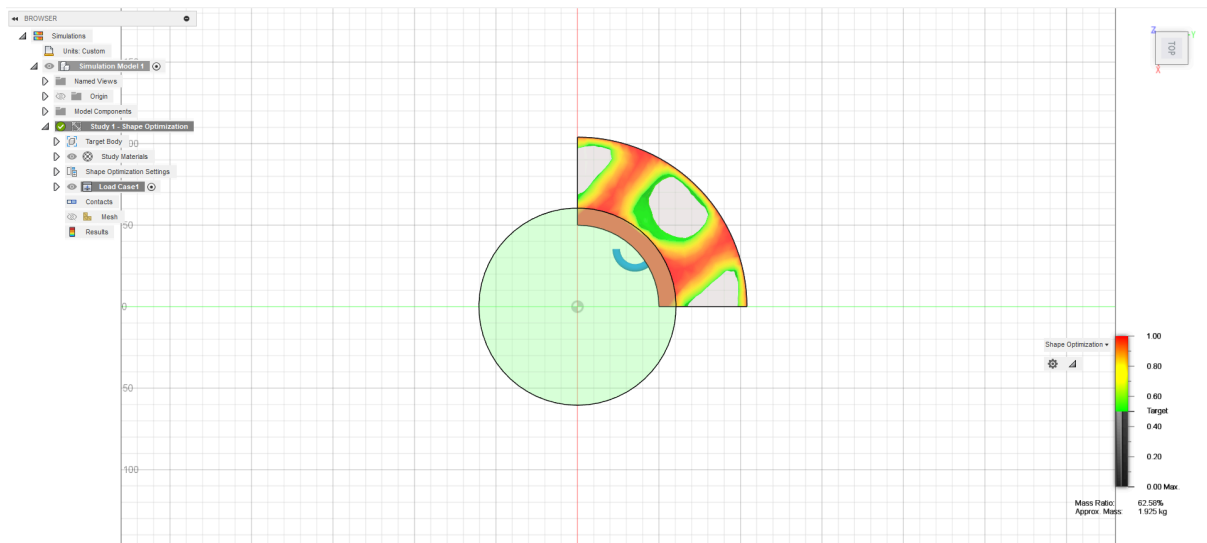
Fig.4.18 TO Output for target mass ~63%
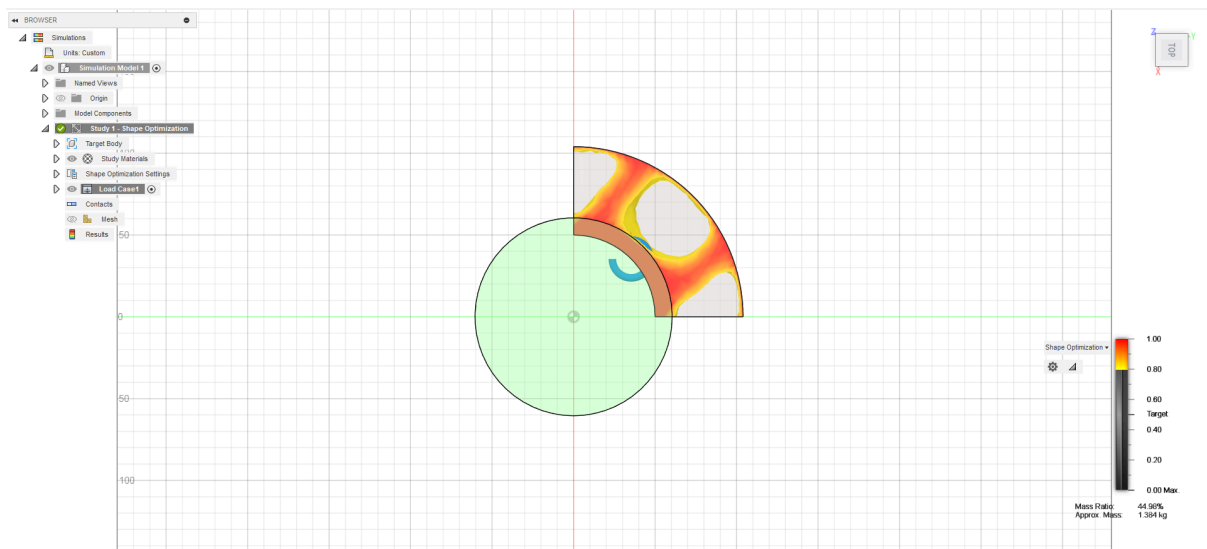
Fig.4.19 TO Output for target mass ~45%

As the ~45% mass target had a safety factor < 1.00, it was discarded from further study and ~63% was finalized for further ANSYS stress study.

4.4 METAL AM ESTIMATION

For simulating Metal AM material consumption and cost estimation for each model, EOS M 290.

4.4.1 About EOS M 290

The EOS M 290 is a robust and versatile metal 3D printing machine that offers high precision, a wide range of material compatibility, and advanced monitoring capabilities. It is suitable for producing high-quality, functional parts across multiple industries. Its combination of intuitive software, rigorous quality assurance, and adaptability makes it a valuable tool for advanced manufacturing applications. It offers a scanning speed of up to 7 m/s, layer thickness adjustable between 20 - 60 microns. The precision on this machine can get as low as 100 microns at 20 micron layer thickness.

The EOS M 290 supports a wide range of metal powders, including but not limited to:
- Aluminum alloys (e.g., AlSi10Mg)
- Titanium alloys (e.g., Ti64)
- Stainless steels (e.g., 316L)

The Build Volume of EOS M 290 is as follows:
- $250 \times 250 \times 325 \ mm \ (9.85 \ x \ 9.85 \ x \ 12.8 \ in)$

The Laser utilized in EOS M 290:
- Type: Fiber laser
- Power: 400 W
- Wavelength: 1060-1100 nm

Metal Additive Manufacturing technology used: Direct Metal Laser Sintering (DMLS).

4.4.2 About DMLS

Direct Metal Laser Sintering (DMLS) is an additive manufacturing (AM) technology that produces high-precision, high-strength metal parts directly from digital 3D models. This technology is widely used in industries such as aerospace, automotive, medical, and engineering for creating complex geometries and functional prototypes.

The Build Process is as follows:
- **Powder Bed**: A thin layer of metal powder is spread across the build platform.
- **Laser Sintering**: A high-powered fiber laser selectively sinters (melts and fuses) the powder particles together according to the cross-sectional geometry of the sliced 3D model layer by layer.
- **Layering**: The build platform lowers slightly, and a new layer of powder is spread over the previous layer. The process repeats, building the part layer by layer from the bottom up.

4.4.3 AM Estimates: Time Estimate

Table 4.7 Build Time Estimate

Gear Model	Volume (mm^3)	Build Time ($hours$)		
		@10 $cm^3/hour$	@15 $cm^3/hour$	@20 $cm^3/hour$
Base Model	2782321.17	278.23	185.49	139.12
GD Model	1865478.77	186.55	124.37	93.27
TO Model	874460.73	87.54	58.3	43.72
GD+TO Model	674389.46	67.44	44.96	33.72

4.4.4 AM Estimates: Cost Estimate

Table 4.8 Cost Estimate (@10 $cm^3/hour$)

Gear Model	Volume (mm^3)	Build Rate ($cm^3/hour$)	Print Time ($hours$)	Mass ($grams$)	Material Cost ($)	Machine Cost ($)
Base Model	2782321.17	10	278.23	21841.22	2184.12	~20000
GD Model	1865478.77	10	186.55	14644.01	1464.4	~13000
TO Model	874460.73	10	87.54	6864.52	686.45	~6000
GD+TO Model	674389.46	10	67.44	5293.96	529.4	~4500

Table 4.9 Cost Estimate (@15 $cm^3/hour$)

Gear Model	Volume (mm^3)	Build Rate ($cm^3/hour$)	Print Time ($hours$)	Mass ($grams$)	Material Cost ($)	Machine Cost ($)
Base Model	2782321.17	15	185.49	21841.22	2184.12	~14000
GD Model	1865478.77	15	124.37	14644.01	1464.4	~9000
TO Model	874460.73	15	58.3	6864.52	686.45	~4500
GD+TO Model	674389.46	15	44.96	5293.96	529.4	~3500

Table 4.10 Cost Estimate (@20 $cm^3/hour$)

Gear Model	Volume (mm^3)	Build Rate ($cm^3/hour$)	Print Time ($hours$)	Mass ($grams$)	Material Cost ($)	Machine Cost ($)
Base Model	2782321.17	20	139.12	21841.22	2184.12	~11000
GD Model	1865478.77	20	93.27	14644.01	1464.4	~7000
TO Model	874460.73	20	43.72	6864.52	686.45	~3500
GD+TO Model	674389.46	20	33.72	5293.96	529.4	~2500

CHAPTER 5

CONCLUSION

5.1 Conclusion

Through the observations & results, it can be concluded that utilizing Generative Design and Topology Optimization in conjunction with each other produces both economically feasible & materially strong gears that could be applied from prototyping to improving an engine's life, as well as, reducing maintenance costs. Gears have been a crucial part of today's technology, ranging from automobiles to power plants. Optimizing them for specific target applications improves their efficiency and life span, however these optimizing processes can only be manufactured through additive manufacturing processes. Therefore, it was this paper's objective to determine the optimal design optimisation process for a mechanical component while maintaining the manufacturing costs to the feasible range.

The major drawback for these processes is over optimization and mesh resolution, due to which a certain range of values are required. Through the results, it can be concluded that:

Optimal Range of Mass Optimization for better strength retention: 50% - 70%
Optimal minimum mesh edge for a mesh resolution without material loss: 2 mm - 1.3138 mm.

These range of values have shown greater strength retention & economic feasibility within a Spur Gear, designed for 4 wheeler automobiles.

5.2 Future Work

All current technologies and softwares that are based around Topology Optimisation & Generative Design are independent and disconnected from one another. Through this project it has been shown clearly that combining these very powerful technologies would greatly amplify the Additive Manufacturing technology and make it feasible & accessible to everyone and every industry. Thus making Additive Manufacturing more than just a prototyping element and pushing the boundaries of what is possible to manufacture, a total creative freedom.

Therefore, any future work can be focused on integrating Topology Optimization & Generative Design into a singular process, such that a design's topology optimisation can be iterated through many means offering greater flexibility and choices for engineers to choose a design from.

REFERENCES

1. Amir M. Mirzendehdel, Krishnan Suresh (2016). *Support structure constrained topology optimization for additive manufacturing.*

2. Mit Patel, Vinay Khatod (2019). *Topology Optimization of Automotive Gear using FEA.*

3. R. S. Khurmi, J. K. Gupta, *A Textbook of Machine Design* (Eurasia Publishing House, New Delhi: Ramnagar, 2005).

4. *Automobile Technology.* Second Edition. San Diego: Harcourt Brace Jovanovich, 1992: 432.

5. *"Most Powerful Car."* Guinness Book of Records 2001. New York: Guinness, 2001: 135.

6. *What is RPM in Car & Bike: RPM Full Form, Meaning & Formula Explained.* Bengaluru: ACKO Insurance, 2024.

7. *Hyundai Verna Performance - Mileage, Speed & Transmission.* Delhi: Hyundai Motor India, 2024.

8. *Design Data: Data Book of Engineers,* by PSG College-Kalaikathir Achchagam - Coimbatore: November, 2020.

9. *Topology Optimisation: Theory, Methods & Applications.* by M.P. Bendsoe & O.Sigmund: ISBN 3-540-42992-iSpringer-Verlag Berlin Heidelberg: New York.

10. Yassine Saadlaoui, Jean-Louis Milan, Jean-Marie Rossi, Patrick Chabrand (2017). *Topology optimization and additive manufacturing: Comparison of conception methods using industrial codes*

11. D. Brackett, I. Ashcroft, R. Hague (2011). *TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING.*

12. Dan Walton, Hadi Moztarzadeh (2017). *Design and development of an additive manufactured component by topology optimisation*

13. Jikai Liu & Andrew T. Gaynor & Shikui Chen & Zhan Kang & Krishnan Suresh & Akihiro Takezawa & Lei Li & Junji Kato & Jinyuan Tang & Charlie C. L. Wang & Lin Cheng & Xuan Liang & Albert. C. To (2018). *Current and future trends in topology optimization for additive manufacturing.*

14. *Autodesk Generative Design for Manufacturing Specialization.* (Autodesk) - Coursera

15. *Generative Design for Additive Manufacturing.* (Autodesk) - Coursera

APPENDIX

A. SPUR GEAR DIMENSION CALCULATIONS

A.1. *Minimum Centre Distance* (a)

The formula for determining 'a' during design process is as follows -

$$a \geq (i + 1)\sqrt[3]{\left(\frac{0.74}{[\sigma_c]}\right)^2 * \frac{E\,[T]}{i\,\Psi}} \quad \rightarrow (A.1)$$

We know that,

$$\Rightarrow [T] = T * k.k_d$$

$$= 97420 * \frac{110}{3000} * 1.4 \qquad \qquad \textit{[From Given]}$$

$$= 5000.893\ kgf - cm$$

Substituting the determined values into (1)

$$\Rightarrow a \geq (1 + 1)\sqrt[3]{\left(\frac{0.74}{5000}\right)^2 * \frac{2.15*10^6*5000.893}{1*0.3}}$$

$$\geq (2) * ((2.1904 * 10^{-8}) * (35833.3 * 10^6))^{\frac{1}{3}}$$

$$\geq 2 * (784.8932)^{\frac{1}{3}}$$

$$\geq 184.5\ mm$$

$$\boxed{\Rightarrow a \geq 184.5\ mm}$$

- ### A.2. *Minimum Module* (m)

The formula for determining 'm' during design process is as follows -

$$m \geq 1.26\sqrt[3]{\frac{[M_t]}{y[\sigma_b]\Psi_m Z}} \quad \rightarrow (A.2)$$

By substituting the values from Given in (2) the following equation will be derived -

$$\Rightarrow m \geq 1.26 * \left(\frac{5000.893}{0.440*1400*10*30}\right)^{\frac{1}{3}}$$

$$\geq 1.26 * (0.02706)^{\frac{1}{3}}$$

$$\geq 0.378$$

$$\simeq 0.4\ cm$$

Standard Module
$\Rightarrow m \simeq 4\,mm$

- *Correction of Number of Teeth in the gear*

$$\Rightarrow Z = \frac{2a}{m(i+1)} \quad \rightarrow (A.3)$$

Upon substitution of the acquired values -

$$\Rightarrow Z = \frac{2*185}{4*2}$$

Corrected number of teeth on the Spur gear
$\Rightarrow Z = 50$

- **A.3. *Pitch Circle Diameter*** (PCD)

PCD can be determined using the formula -

$$PCD = d = mZ \quad \rightarrow (A.4)$$

Upon Substitution of values, we get -

Pitch Circle Diameter
$\Rightarrow PCD = 200\,mm$

- **A.4. *Correction of Centre Distance***

Since the Gear Ratio $(i) = 1$

Corrected Center Distance
$\Rightarrow a = PCD = 200\,mm$

Design criteria wise,

$$\Rightarrow a_{min} = 184\,mm$$

$a > a_{min}$
Design is Safe.

- **A.5. *Face Width*** (b)

Face Width can be determined through this formula -

$$\Psi = \frac{b}{a} \quad \rightarrow (A.5)$$

For which, we have assumed $\Psi = 0.3$ and we know $a = 200\,mm$

Therefore, substituting the values provides us with

$$\boxed{\begin{array}{c} \text{Face Width} \\ \Rightarrow b = 60\ mm \end{array}}$$

Through which we can also determine the corrected value of $'k'$

$$\Rightarrow k = \frac{b}{d} = \frac{60}{200} = 0.3$$

Through standard values for $'k'$, We can correct it to $k = 1$.

- **A.6. *Pitch Line Velocity***

Pitch Line Velocity can be determined using -

$$v = \frac{\pi d n}{60*1000} \rightarrow (A.6)$$

Upon substituting the values we get -

$$\boxed{\begin{array}{c} \text{Pitch Line Velocity} \\ \Rightarrow v = 31.41\ m/sec \end{array}}$$

Using this value we can determine the corrected value of $'k_d'$ using the formula -

$$k_d = \frac{v \times (SH)^{0.75}}{1000} \rightarrow (A.7)$$

Upon substituting the values, we arrive at -

$$\Rightarrow k_d = \frac{31.41*(200)^{0.75}}{1000} = 1.33$$

This is for IS Grade 8 or Grade 10 $C45$ steel with $SH = 200\ kg/mm^2$

- **A.7. *Correction of* $[T]$**

$$\Rightarrow [T] = T \times k.k_d \rightarrow (A.7)$$

Upon substituting the related values, we get -

$$\Rightarrow [T] = 97420 * \frac{110}{3000} * 1.33$$

$$\boxed{\begin{array}{c} \text{Corrected } [T] \\ \Rightarrow [T] = 4750.8\ kgf - cm \end{array}}$$

-

- **A.8.** *Verification of Design Parameters*

  - **A.8.1.** *Verifying Surface Stress* $\left(\sigma_c\right)$

To verify Surface Stress, we can use the formula -

$$\sigma_c = 0.74 \times \frac{i+1}{a}\sqrt{\frac{i+1}{ib} * E[T]} \rightarrow (A.8)$$

Upon substituting the acquired values, we get -

$$\Rightarrow \sigma_c = 0.74 * \frac{2}{20} * \sqrt{\frac{2}{6} * 2.16 \times 10^6 * 4750.8}$$

$$= 0.074 * \left(\frac{1}{3} * 2.16 * 4750.8\right)^{\frac{1}{2}} * 10^3$$

$$= 0.074 * (3420.576)^{\frac{1}{2}} * 10^3$$
$$= 0.074 * 58.485 * 1000$$
$$= 4327.9$$

Therefore, the Surface Stress; $\sigma_c \simeq 4328 \, kgf/cm^2$
Which, Design Criteria wise,

$$\boxed{\begin{array}{c} \left[\sigma_c\right] > \sigma_c \\ \textbf{Design is Safe.} \end{array}}$$

  - **A.8.2.** *Verifying Bending Stress* $\left(\sigma_b\right)$

To verify Bending Stress, we can use the formula -

$$\sigma_b = \frac{i+1}{a*m*b*y} \times [T] \rightarrow (A.9)$$

Upon substituting the acquired values, we get -

$$\Rightarrow \sigma_b = \frac{2*4750.8}{20*0.4*6*0.477}$$

$$= 414.98$$

Therefore, the Bending Stress; $\sigma_b \simeq 415 \, kgf/cm^2$
Which, Design Criteria wise,

$$\boxed{\begin{array}{c} \left[\sigma_b\right] > \sigma_b \\ \textbf{Design is Safe.} \end{array}}$$

- **A.9. *Other Design Parameters***

  - **A.9.1. *Addendum $\left(h_a\right)$ & Dedendum $\left(h_f\right)$***

    - $\left(h_a\right) = 1 * m = 4\,mm$
    - $\left(h_f\right) = 1.25 * m = 5\,mm$

  - **A.9.2. *Tip & Root Circle Diameter $\left(d_t \,\&\, d_r\right)$***

    - $\left(d_t\right) = d + 2h_a = 200 + 2(4) = 208\,mm$
    - $\left(d_r\right) = d - 2h_f = 200 - 2(5) = 190\,mm$

  - **A.9.3. *Tooth Height $\left(h_t\right)$***

    - $h = h_a + h_f = 4 + 5 = 9\,mm$

B. PRESSURE GENERATED ON EACH TOOTH CALCULATIONS

Input parameters are taken from **Table 3.2.1.**

B.1 Tangential Force (F_t)

The formula for tangential force is as follows:

$$\Rightarrow F_t = \frac{T}{r} \rightarrow (B.1)$$

Where,

$$\text{Torque } (T) = \frac{P}{\omega} = \frac{110000\ kW}{\frac{3000*2\pi}{60}\ rad/s} \simeq 350.19\ Nm$$

$$\text{Pitch Radius } (r) = \frac{PCD}{2} = \frac{200}{2} = 0.1\ m$$

Therefore,

$$\Rightarrow F_t = \frac{T}{r} = \frac{350.19}{0.1} = 3501.9\ N$$

B.2 Contact Ratio (C_p)

Since the given Gear Ratio $(i) = 1$;

through standard C_p values that range from 1.2 to 1.6.

For simplicity, we can assume Cp = 1.4

$$\Rightarrow C_p = 1.4$$

B.3 Contact Force (F_c)

The formula for contact force is as follows:

$$\Rightarrow F_c = \frac{F_t}{C_p} = \frac{3501.9}{1.4} \rightarrow (B.2)$$

Therefore,

$$\Rightarrow F_c \simeq 2501.36\ N$$

B.4 Contact Area (A)

The formula for Contact Area is as follows:

$$\Rightarrow A = tooth\ height\ *\ tooth\ face\ width$$

$$\Rightarrow A = 9 * 60 = 540\ mm^2 = 0.00054\ m^2$$

B.5 Tooth Pressure (P)

The formula for Tooth Pressure is as follows:

$$\Rightarrow P = \frac{F_c}{A} \rightarrow (B.3)$$

Therefore,

$$\Rightarrow P = \frac{F_c}{A} = \frac{2501.36}{0.00054}$$

$$\Rightarrow P \simeq 4634.67\ N/m^2 = 4.63\ MPa$$

C. AM Estimate Calculations

C.1 Time Estimate

It's a known fact that regardless of the layer thickness, the time consumed relies on the volume of the model and the build rate of the machine. Therefore, we shall be considering 3 build rates:

- $10 \ cm^3/hour$ ($10000 \ mm^3/hour$)
- $15 \ cm^3/hour$ ($15000 \ mm^3/hour$)
- $20 \ cm^3/hour$ ($20000 \ mm^3/hour$)

These values are available on the EOS M 290 AM Machine.

For each model, this formula can be applied to determine the Print Time (in hours), Volume of each model is provided in **Table 4.1.3.1**:

$$\Rightarrow \ Print \ Time \ (hours) = \frac{Volume \ (mm^3)}{Build \ Rate \ (mm^3/hour)} \ \rightarrow (C.1)$$

This provides us with the following tabulated results:

Table C.1.1. Build Time Estimate

Gear Model	Volume (mm^3)	Build Time $(hours)$		
		$@10 \ cm^3/hour$	$@15 \ cm^3/hour$	$@20 \ cm^3/hour$
Base Model	2782321.17	278.23	185.49	139.12
GD Model	1865478.77	186.55	124.37	93.27
TO Model	874460.73	87.54	58.3	43.72
GD+TO Model	674389.46	67.44	44.96	33.72

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C.2 Cost Estimate

Two factors that are paid for during this procedure are the material (AlSi10Mg) and the machine operation cost (\$/hour). Both of these rates are standardized american rates, they are as follows:

- Cost of AlSi10Mg: \$0.10 per gram
- Cost of Machine Operation: \$50 per hour

With this we can calculate the Material Cost, Machine Cost & Total Cost, using the following relations:

$\Rightarrow Material\ Cost\ =\ Mass\ (grams)\ x\ Cost\ per\ gram$

$\Rightarrow Machine\ Cost\ =\ Print\ time\ (hours)\ x\ Cost\ of\ machine\ operation$

$\Rightarrow Total\ Cost\ =\ Material\ Cost\ +\ Machine\ Cost$

Which provides us with the following tabulated results:

Table C.2.1 Cost Estimate $(@10\ cm^3/hour)$

Gear Model	Volume (mm^3)	Build Rate $(cm^3/hour)$	Print Time $(hours)$	Mass $(grams)$	Material Cost (\$)	Machine Cost (\$)
Base Model	2782321.17	10	278.23	21841.22	2184.12	~20000
GD Model	1865478.77	10	186.55	14644.01	1464.4	~13000
TO Model	874460.73	10	87.54	6864.52	686.45	~6000
GD+TO Model	674389.46	10	67.44	5293.96	529.4	~4500

Table C.2.2 Cost Estimate $(@15\ cm^3/hour)$

Gear Model	Volume (mm^3)	Build Rate $(cm^3/hour)$	Print Time $(hours)$	Mass $(grams)$	Material Cost (\$)	Machine Cost (\$)
Base Model	2782321.17	15	185.49	21841.22	2184.12	~14000
GD Model	1865478.77	15	124.37	14644.01	1464.4	~9000
TO Model	874460.73	15	58.3	6864.52	686.45	~4500
GD+TO Model	674389.46	15	44.96	5293.96	529.4	~3500

Table C.2.3 Cost Estimate (@20 $cm^3/hour$)

Gear Model	Volume (mm^3)	Build Rate ($cm^3/hour$)	Print Time (*hours*)	Mass (*grams*)	Material Cost ($)	Machine Cost ($)
Base Model	2782321.17	20	139.12	21841.22	2184.12	~11000
GD Model	1865478.77	20	93.27	14644.01	1464.4	~7000
TO Model	874460.73	20	43.72	6864.52	686.45	~3500
GD+TO Model	674389.46	20	33.72	5293.96	529.4	~2500

D. Peer Evaluation Form for Group Work (9054)

Name: **JAMALAPURAM PRAHARSHITH KASHYAP (124009054)**

Write the name of each of your group members in a separate column. For each person, indicate the extent to which you agree with the statement on the left, using a scale of 1-4 (1 = Strongly Disagree; 2 = Disagree; 3 = Agree; 4 = Strongly Agree). Total the numbers in each column.

Evaluation Criteria	Group member: SANJAY BASKAR
Attends group meetings regularly and arrives on time.	4
Contributes meaningfully to group discussions.	3
Completes group assignments on time.	2
Prepares work in a quality manner.	2
Demonstrates a cooperative and supportive attitude.	4
Contributes significantly to the success of the project.	2
TOTALS	17

Feedback on team dynamics:

1. How effectively did your group work?
   - Moderately effective. There was a disparity between how much work was done by an individual and the other team member.

2. Were the behaviors of any of your team members particularly valuable or detrimental to the team? Explain.
   - Initially there was a lack of effort towards the project from my teammate, but after it was addressed through our guide, it was very slightly improved.

3. What did you learn about working in a group from this project that you will carry into your next group experience?
   - Proper planning & better decision making.

E. SELF-EVALUATION FORM FOR GROUP WORK (9054)

Name: JAMALAPURAM PRAHARSHITH KASHYAP (124009054)

	Seldom	Sometimes	Often
Contributed good ideas			✓
Listened to and respected the ideas of others			✓
Compromised and cooperated		✓	
Took initiative where needed			✓
Came to meetings prepared		✓	
Communicated effectively with teammates			✓
Did my share of the work			✓

My greatest strengths as a team member are: Leadership Skills, Team collaboration, communication, and adaptability.

The group work skills I plan to work to improve are: Time management skills & patience.

F. Peer Evaluation Form for Group Work (9199)

Name:- SANJAY BASKAR (124009199)

Write the name of each of your group members in a separate column. For each person, indicate the extent to which you agree with the statement on the left, using a scale of 1-4 (1=strongly disagree; 2=disagree; 3=agree; 4=strongly agree). Total the numbers in each column.

Evaluation Criteria	Group member: J. PRAHARSHITH KASHYAP
Attends group meetings regularly and arrives on time.	4
Contributes meaningfully to group discussions.	4
Completes group assignments on time.	4
Prepares work in a quality manner.	4
Demonstrates a cooperative and supportive attitude.	4
Contributes significantly to the success of the project.	4
TOTALS	24

Feedback on team dynamics:

4. How effectively did your group work?
   - Our group worked quite effectively with the given limited resources we had. We were able to pool our skills and knowledge, and prioritize tasks to ensure that we met our objectives. Despite the constraints, we demonstrated problem-solving abilities, allowing us to successfully complete our project.

5. Were the behaviors of any of your team members particularly valuable or detrimental to the team? Explain.
   - The determination and persistence of my teammates played a crucial role in this project. This positive behavior enabled us to overcome obstacles and achieve our goals effectively.

6. What did you learn about working in a group from this project that you will carry into your next group experience?
   - I gained insight into the importance of clear communication and collaboration, ensuring that everyone is on the same page and working toward common goals.

G. SELF-EVALUATION FORM FOR GROUP WORK (9199)

Name:- SANJAY BASKAR

	Seldom	Sometimes	Often
Contributed good ideas			✓
Listened to and respected the ideas of others			✓
Compromised and cooperated		✓	
Took initiative where needed		✓	
Came to meetings prepared			✓
Communicated effectively with teammates			✓
Did my share of the work		✓	

My greatest strengths as a team member are: ability to collaborate, communication skills and problem solving skills

The group work skills I plan to work to improve are: time management skills.