The Investigation and Optimisation of a Wind Turbine Gearbox

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Abstract

Wind energy plays a crucial role in mitigating climate change and decreasing reliance on fossil fuels. A significant challenge within this industry is optimising wind turbine gearboxes, which are essential for efficient power generation but are prone to failures that lead to substantial downtime and repair costs. This project focuses on enhancing the material components of gearboxes in 2MW wind turbines, targeting improvements in durability, performance, and cost-effectiveness.

The investigation begins with a thorough literature review to understand current gearbox technologies and materials, leading to a material selection process using Granta EduPack. This process evaluates potential materials based on their mechanical properties and environmental impact, refining choices for further testing. The selected materials undergo Finite Element Analysis (FEA) using ANSYS Static Structural to simulate real-world stresses and validate their performance. This methodological approach ensures a detailed comparison against an industry-standard material and identifies potential superior alternatives.

The main conclusions highlight the potential of AISI 5160 Steel and Tungsten Alloy to reduce gearbox failures, enhance operational efficiency, and reduce raw material cost. Recommendations for future work include deeper investigations into dynamic load conditions and full gearbox simulations to confirm the findings under more varied operational conditions and to extend the study's applicability to larger turbine systems.

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Abbreviations

Table A - Table of Abbreviations

Acronym	Full Meaning
AISI	American Iron and Steel Institute
CAD	Computer-Aided Design
FEA	Finite Element Analysis
RPM	Revolutions per Minute

List of Units

MW	Mega Watt
K_{IC}	Fracture Toughness
$MPa\sqrt{m}$	MegaPascals by Squareroot of Metres
HV	Hardness - Vickers
mm/m	Millimetre over Metre
mm	Millimetre
MPa	MegaPascals
£/kh	Pounds per Kilogram
£/m^3	Pounds per Metres to the power of Three
kg/m^3	Kilogram per Metre to the power of Three
GPa	Gigapascals
µstrain/^{o}C	MicroStrain per Degrees Celsius
m/mm	Metres per Millimetre
kg/kg	Kilogram per Kilogram

1. Introduction

Wind energy is a critical and rapidly growing source of renewable energy, playing a pivotal role in addressing the global challenge of climate change and reducing our dependence on fossil fuels. Appendix C and D showcase the UK total energy production and more importantly how much of this is wind energy, demonstrating the importance and potential impact of the project. According to Nelson and Starcher (2019), wind turbines are at the forefront of this transition to sustainable energy production. However, the efficient and reliable operation of wind turbines is contingent upon the performance of their components, particularly the gearbox, which plays a vital role in energy conversion and power generation. This project aims to investigate and optimise the material components of these gearboxes, focusing on a key area of failure and inefficiency and also the material properties and performance of the gears within the main gearbox of a 2MW wind turbine to address current challenges and enhance their performance.

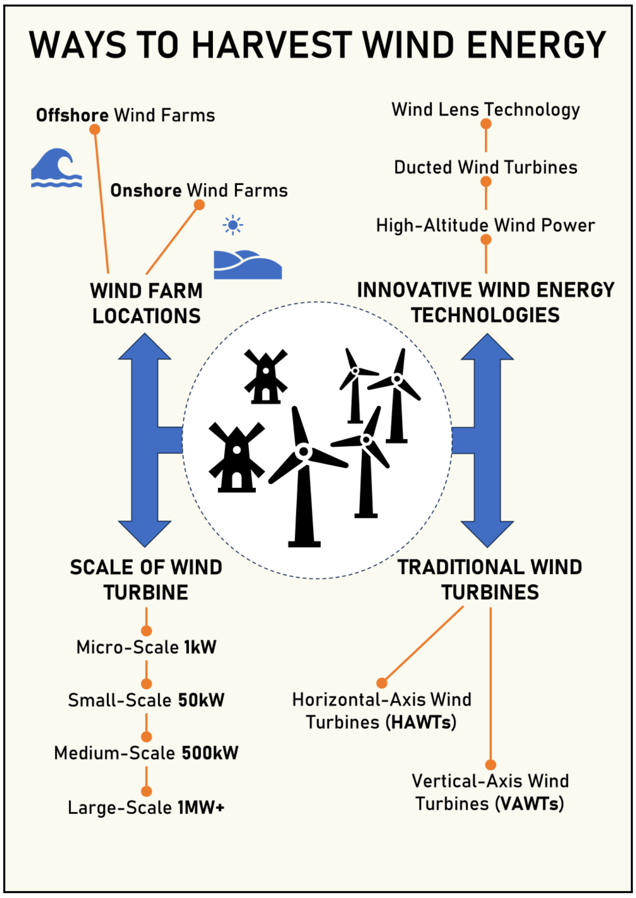


Figure 1 - Ways to Harvest Wind Energy

Firstly, there is the challenge of gearbox failures, which are among the most common and costly issues in wind turbine operation. Specifically, gear material failures lead to substantial downtime and financial implications due to maintenance and repair costs (Tavner, Xiang and Spinato, 2012). Additionally, the variable and unpredictable nature of wind patterns introduces cyclic loads and stresses that can induce fatigue in gear materials. These challenges underscore the need for materials that can withstand the dynamic operational environment while offering longevity and economic viability.

This project explores the mechanical behaviour of various materials under simulated operational stresses using FEA. The aim is to compare these materials with the currently used gear materials. However, with advances in material sciences and the evolving demands of wind energy technology, alternative materials may offer improved performance or cost benefits, (Salem, Abu-Siada and Islam, 2016). Through Granta EduPack a preliminary material selection will be conducted, eliminating materials based on their respective properties. The short list will then undergo a more rigorous simulation assessment using ANSYS Static Structural, analysing factors such as deformation, stresses, strains, and safety factors. The assessment will then be directly compared to the material used in the industry, and the two best performing materials will be selected for an in-depth analysis

By acknowledging the project's limitations, such as the focus on FEA for individual gear pairs rather than the entire gear system, this project not only aligns with the current body of knowledge but also paves the way for future research. The ultimate objective is to contribute to the development of more reliable, efficient and cost-effective wind turbine gearboxes, supporting the broader goal of advancing renewable energy technology.

1.1 Aim and Objectives

The aim of this project is to investigate and optimise a wind turbine gearbox for improved performance, reliability, and cost-effectiveness. By achieving this aim, the project aims to contribute to the advancement of wind energy technology and enhance the overall sustainability of renewable energy sources. This will be pursued through the following interrelated objects:

1. **Research and Investigate:** Conduct thorough research to understand current wind turbine gearbox technologies and materials used in the industry. This includes studying existing solutions and identifying areas that require improvement.
2. **Industry Material Benchmark:** Identify a commonly used material in the industry that serves as a benchmark for comparing other materials. This will set a standard against new materials that can be evaluated for performance, durability, and cost-effectiveness.
3. **Material Selection Process:** Utilise Granta EduPack software to identify and select materials that optimise the gearbox's performance in terms of durability, cost, and mechanical properties.
4. **Simulation Testing:** Using ANSYS Static Structural, conduct Finite Element Analysis (FEA) to simulate the operational stresses, strains, and factors of safety, thereby validating the chosen materials under realistic conditions.
5. **Identify Limitations in Material Properties and FEA Modelling:** Examine the limitations and potential yielding and failure points, assessing the implications for the real-world application and reliability of the gearbox.
6. **To Make Recommendations for Future Work:** Detailing further research needed to address the limitations found in the current analysis, including gearbox modelling, and dynamic load analysis.

1.2 Hypothesis

The use of advanced materials, selected through a thorough material selection process and validated through FEA, can significantly enhance the performance, reliability, and cost-effectiveness of wind turbine gearboxes compared to currently used materials. The optimisation of these materials will contribute to increased durability and efficiency, reducing maintenance costs and improving the overall sustainability of wind energy turbines.

By addressing this hypothesis through a methodical approach to material selection and testing, this project aims to significantly contribute to the development of more reliable and efficient wind turbine gearboxes, thereby supporting the broader adoption of wind energy.

1.3 Relevance and Impact

Wind energy is one of the fastest growing renewable energy sectors worldwide, primarily due to its lower environmental impact compared to fossil fuels. However, the efficiency and reliability of wind turbines are often compromised by gearbox failures, which are among the most common and costly issues associated with wind turbines. By focusing on gearbox optimisation, this project directly contributes to enhancing the efficiency and operational reliability of wind turbines, supporting the goal of increasing the adoption and effectiveness of wind energy. This research fits within the wider topic area by addressing a known technical challenge and providing solutions that could lead to more durable and economically successful wind turbines.

The beneficiaries of this project area are the wind turbine manufacturers and operators who face significant financial challenges due to gearbox failures. Florescu, Barabas and Dobrescu, (2019) explain that the industry can benefit from the development of more strong gearboxes that require less maintenance and less prone to failures, leading to reduced downtime and lower operational costs. For the academic and research community, this project offers data and validated methodologies that can be further explored and expanded upon. The use of advanced material selection tools like Granta EduPack and simulation software such as ANSYS for structural analysis contributes to the body of knowledge in mechanical and materials engineering. Civera and Surace (2022) suggests society will also benefit significantly from the outcomes of this project through the adoption of more reliable and efficient wind turbines. Wang et al. (2023) confirm this by stating that, improving the gearbox reliability translates into more consistent power generation, which can help meet the growing demand for clean energy. In addition, improving the economic aspect of wind turbines makes wind energy a more competitive alternative to fossil fuel energy sources, encouraging a shift towards sustainable living.

The environmental benefits of this project are clear and substantial, by improving the efficiency and lifespan of wind turbines, the project helps reduce the environmental impact associated with energy production. Fewer gearbox failures mean fewer replacements and repairs, which in turn leads to a reduction in the manufacturing demands, waste, and emissions. Ensuring the material used to optimise the gearbox is recyclable or at least downcycleable creates a circular economy, further reducing the environmental impact of wind turbines (Kasner et al., 2020).

2. Literature Review

2.1 Introduction to Wind Turbine Gearboxes

Wind turbine gearboxes are critical components that convert the low-speed, high-torque rotation of the turbine's blades into the high-speed, low-torque rotation required to drive the generator and produce electricity. They play a key role in the efficiency and reliability of wind turbines, translating aerodynamic power into electrical power. Gearboxes must withstand variable loads and environmental conditions, making their design, material selection, and maintenance crucial for the overall performance and lifespan of the wind turbine. Recent advancements aim to improve their durability, reduce maintenance needs, and enhance energy conversion efficiency (Spera and American Society Of Mechanical Engineers, 2009).

2.2 Helical Gear Systems

The key advantage of helical gear teeth over traditional spur gears is the ability for multiple teeth to be in contact at once. This is due to the helix angle of the gear teeth, which allows the teeth to engage gradually along their length rather than all at once, as is the case with spur gears.

Reasons Why Multiple Teeth Contact is Beneficial:

1. **Smooth Operation:** Lee and Kang (2014) indicate the gradual engagement and disengagement of the teeth in helical gears result in a smoother transmission of power with less vibration and noise. This is particularly advantageous in applications requiring quiet operation or those involving high-speed rotation.
2. **Increased Load Distribution:** With multiple teeth in contact, the load is distributed across several teeth rather than concentrated on a single tooth. This distribution can

significantly reduce the stress on individual teeth, potentially increasing the gear's lifespan and allowing for the transmission of higher loads (Hedlund and Lehtovaara, 2007).

3. **Improved Strength and Durability:** The increased load distribution and smoother operation contribute to improved overall strength and durability of the gear system. Helical gears can typically handle higher torques compared to spur gears of the same size.

Potential Issues and Considerations:

1. **Axial Forces:** Helical gears generate axial forces due to the helix angle of the teeth. Fuentes-Aznar, Ruiz-Orzaez and Gonzalez-Perez, (2016) state this requires careful design and selection of bearings that can accommodate the resulting axial loads to maintain gear alignment and system integrity.
2. **Lubrication:** Lubrication is essential to minimise friction and wear between contacting teeth, especially since helical gears tend to have a higher contact area than spur gears. Selecting the appropriate lubricant and maintaining the lubrication system is important for long-term operation.

2.3 Lubrication

Lubrication systems within wind turbine gearboxes play a critical role in ensuring the longevity and reliability of these crucial components. The lubrication system is responsible for reducing friction, cooling, cleaning, and protecting the internal parts from wear and corrosion. Recent research has focused on various aspects of lubrication systems, including cleanliness management, and the impact of lubricant quality on gearbox performance. Here's a summary of key findings from the literature:

Cleanliness Control and Management:

Filtration issues experienced in the field highlight the importance of maintaining optimum cleanliness levels in the lubrication system to prevent abrasion, corrosion, and premature failure (Zhang, Yuan Liao and Farooq, 2013).

Adaptive Lubrication Systems:

Adaptive lubrication systems have been designed to adjust the oil temperature, pressure, and quality based on the operating environment and state of the wind turbine, effectively reducing wear and tear and improving the reliability of the gearbox (Zeng et al., 2019).

Significance of Effective Lubrication:

Sinha et al. (2014) determines effective lubrication plays a significant role in mitigating system failures and is based on the physical and chemical properties of the lubricating oil. Periodic inspection and analysis of lubricating oil can help in assessing the system's condition and determining the need for re-lubrication to optimise gearbox life.

Lubricant Quality Impact:

The quality of gearbox lubricant significantly impacts the overall performance of wind energy conversion systems. Variations in contamination levels of gearbox lubrication can affect vibration signals and operational efficiency, underscoring the need for regular monitoring and maintenance to ensure optimal performance (Salem, Abu-Siada and Islam, 2016).

2.4 Common Gearbox Failures

Wind turbine gearbox failures are a concern in the operation and maintenance of wind turbines, as they can lead to high repair costs, downtime, and reduced efficiency. Roggenburg et al. (2020) discuss many common gearbox failures listed as follows;

- Gears can experience surface wear over time due to the constant friction during operation, leading to reduced efficiency and potential failure.
- Repeated cyclic loads can cause fatigue in the gear teeth, leading to cracks and eventual breakage.
- Excessive heat generated from friction can lead to thermal expansion and changes in material properties, compromising the gearbox's structural integrity.
- Defects in materials or errors in the manufacturing process can introduce weaknesses in gearbox components, leading to early failure.
- Exposure to harsh environmental conditions, such as moisture, salt, and chemicals, can lead to corrosion of metal parts, weakening them over time.

2.5 Material Selection

Material selection for wind turbine gearboxes involves balancing multiple criteria, including mechanical properties, environmental impact, cost, and manufacturing processes. Recent research in this area focuses on optimising these criteria to enhance the performance and longevity of wind turbines. Following are some key insights from the literature:

Strength and Fatigue Resistance:

Materials used in gearbox components need to have high strength to endure the loads and stresses from the wind turbine's operation. Additionally, fatigue resistance is crucial as the components are subjected to cyclic loads, and have an expected lifespan of 20 years.

Wear Resistance and Lubrication Compatibility:

The materials should exhibit low wear rates and be compatible with lubricants to ensure the long-term reliability and efficiency of the gearbox.

Corrosion Resistance:

Exposure to varying environmental conditions, including moisture, changes in temperature, and possibly corrosive environments, requires a standard of corrosive resistance.

Manufacturing and Cost:

The selected materials should be amenable to the manufacturing processes used for gearbox components. Cost-effectiveness is also a critical factor, balancing performance with economic viability.

Thermal Stability:

Gearbox materials should maintain their mechanical properties over the expected range of operating temperatures, ensuring consistent performance.

Tensile Strength

Tensile strength, the maximum stress a material can withstand while being stretched or pulled before breaking, is a fundamental mechanical property that influences the material's suitability for various applications, including gears subjected to high stress.

Considering the critical role and the high cost implications of gear failure, the material should comfortably exceed the maximum operational stress levels anticipated in the gear system. This ensures that the gears can operate under peak loads without the risk of material failure. High-strength alloys, such as advanced steel alloys, are commonly used in wind turbine systems due to their excellent tensile strength and other mechanical properties. (McQueen, 2020)

Coefficient of Thermal Expansion

The appropriate limit for the coefficient of thermal expansion depends on the specific engineering requirements of your gear system, including the operational temperature and dimensional stability required. Generally, for mechanical components like gears that require precise tolerances and dimensional stability across a range of temperatures, therefore a low coefficient of thermal expansion is preferred. Lagow (2016) recommends targeting the lower end of the coefficient of thermal expansion range typical for metals. Therefore an upper limit of 12 μStrain/ºC is considered for the remainder of the project.

Fracture Toughness

The high-demand application subjects the material to variable loads, vibrations, and possibly harsh environmental conditions, therefore choosing materials with a high fracture toughness is crucial. Launey and Ritchie (2009), consider a K_{IC} value above 50 $MPa\sqrt{m}$ is good for metals, indicating a higher resistance to crack propagation. Different classes of materials exhibit significantly different ranges of fracture toughness. For instance, many ferrous metals and titanium alloys have high K_{IC} values, making them suitable for the application. In contrast, certain ceramics and hard coatings might offer excellent wear resistance but have lower K_{IC} values, making them more brittle. Anandavijayan et al. (2021) suggest fracture toughness can also be impacted by the operational environment, for example, the presence of corrosive elements or extreme temperatures can affect the material's resistance to crack propagation.

Hardness - Vickers

For wind turbine gear systems, a Vickers hardness of 120 HV and above is common, this provides a good balance between resistance to wear and maintaining sufficient toughness. The exact hardness requirement may vary based on the gear design, and the type of loading it will experience. Higher hardness may be prioritised for the gear's surface to resist wear, while a tougher, slightly less hard material may be used for the core to absorb shocks and prevent brittle failure. (Sakthivel and Rajamani, 2014)

Materials can undergo surface hardening or heat treatments to achieve a high surface hardness while keeping the core less hard and more tough. Therefore the materials selected for simulation analysis should achieve the desired hardness without compromising other critical properties. Khatavkar, Swetlana and Singh (2020) suggest it is crucial to balance hardness with other material properties, as extremely high hardness can make the material more brittle. The selected material needs to maintain adequate impact toughness, especially for gears subject to variable loads and impacts.

3. Methodology

3.1 Justification for Methods Used

3.1.1 Material Selection Process

The material selection process using Granta EduPack software serves a crucial role in achieving the aim of enhancing the performance, reliability, and cost-effectiveness of a wind turbine gearbox.

Justification:

- **Alignment with Project Objectives:** This method directly addresses the objective of identifying and selecting materials that optimise the gearbox's performance in terms of durability, mechanical properties, and cost. The ability to compare a wide range of materials based on predefined criteria in section 2.5 ensures a systematic approach to material selection, crucial for the complex demands of wind turbine applications.
- **Efficient Analysis:** Granta EduPack provides a database of material properties, allowing for quick filtering and comparison across various attributes. This efficiency is vital for meeting the project aim's within the time frame.
- **Decision Making:** By utilising advanced software tools, the selection process is not only quick but also more accurate and reliable through data-driven decisions. This minimises the risk of selecting poor materials.

3.1.2 Simulation Testing

Conducting FEA using ANSYS Static Structural (ANSYS Workbench 2023 R2, 2023) is critical for simulating the operational stresses, strain, and safety factors of the chosen materials under realistic conditions.

Justification:

- **Alignment with Project Aim and Objectives:** This method ties directly into the project objective of testing and validating the chosen materials under realistic conditions. It helps identify any potential yielding and failure points before actual production, aligning perfectly with the project's aim to optimise for reliability and performance.
- **Validation of Material Selection:** FEA is essential for validating the materials selected during the material selection process. It provides a detailed insight into how these materials will behave under operational loads, which is crucial for verifying their suitability for use in wind turbines.

3.2 Gearbox Design and Dimensioning

Meda de Sousa (2017) investigated gearbox designs for a 2 MW wind turbine planetary gearbox, the study provides a full list of dimensions and specifications for a gear system rated for a 2 MW wind turbine. Therefore designs and dimensions were drawn upon to replicate the model. See appendix E for this information.

3.3 Step-by-Step Guide to Replicating Methods

3.3.1 Granta EduPack

For the project, the Granta EduPack 2023 R2 version is used to select materials for further investigation. Upon opening the software the user is presented with the following window shown in figure 3.3.1a below.

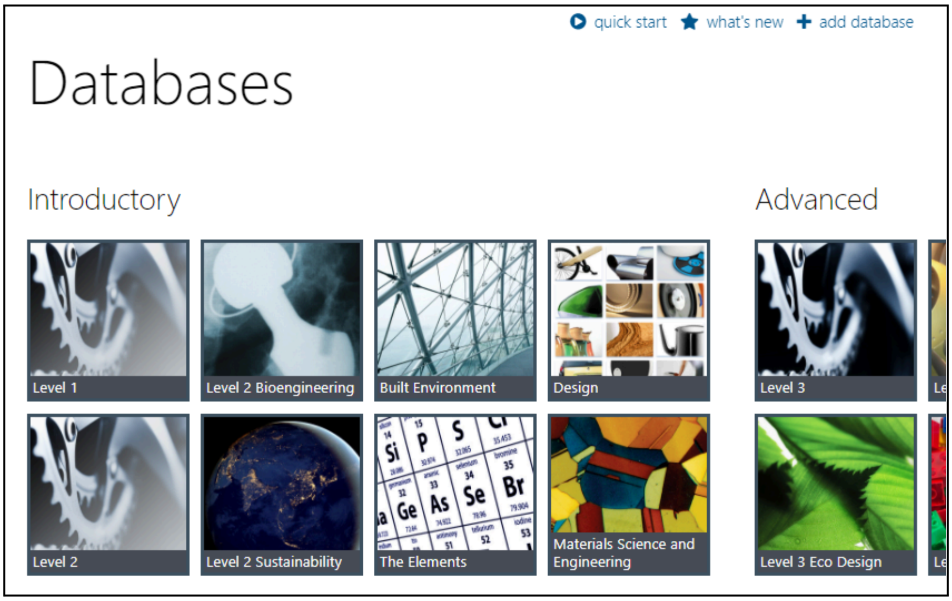


Figure 3.3.1a - Granta EduPack home page.

Select '*Materials Science and Engineering*', this will then take the user to another window, then to begin applying criteria select '*Chart/Select*' positioned at the top of the page. A pop-up will appear on the left-hand side of the screen, showcasing the material database, selection stages, and results, shown below in figure 3.3.1b.

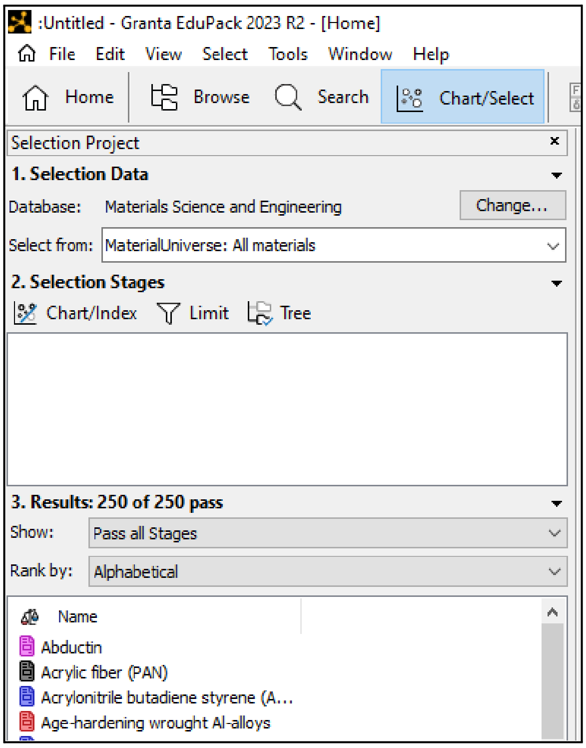


Figure 3.3.1b - Chart/Select Function.

Now to select the specific criteria click '*Chart/Index*' under "*2. Selection Stages*" also shown in figure 3.3.1b. This will open another window allowing the user to apply criteria, ultimately comparing two material properties. For the first stage apply '*Fatigue strength at 10^7 cycles*' as the X-axis and '*Tensile strength*' as the Y-axis. Then click '*OK*'. See the following figure 3.3.1c for guidance.

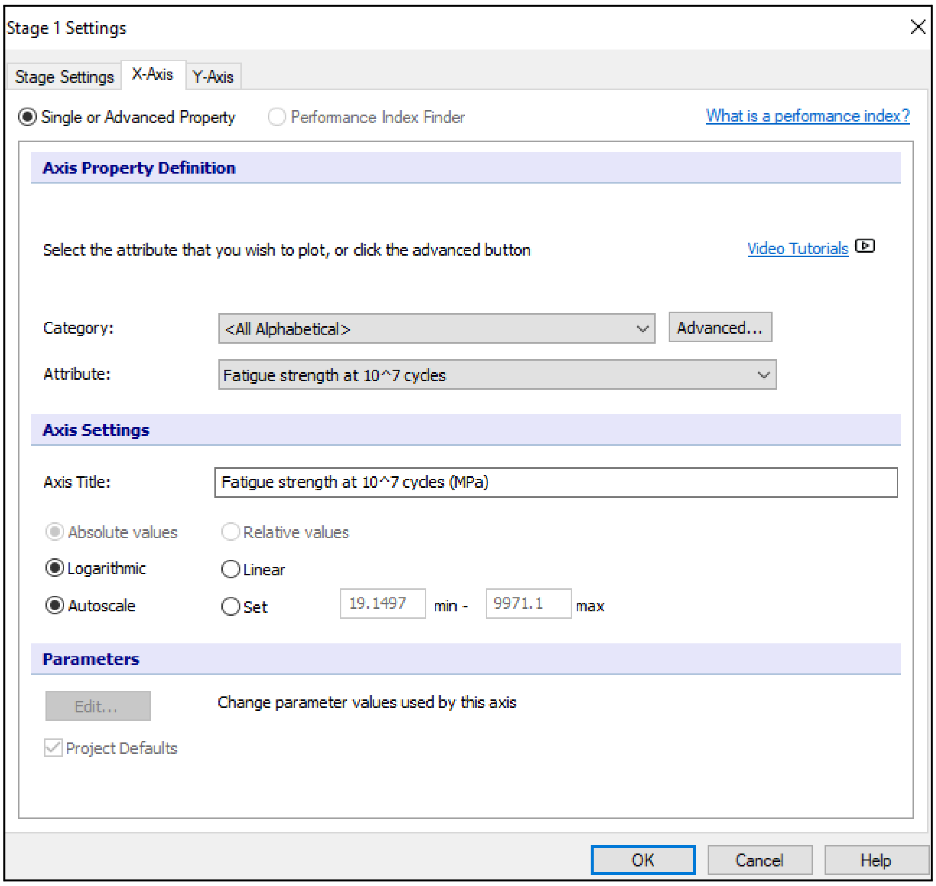


Figure 3.3.1c - Stage 1 Settings.

This will then display a chart comparing the two properties utilising all the materials in the database. To apply a numerical limit to these materials, select '*Box Selection*' located in the toolbar just above the chart itself, this enables the user to draw a box directly on the chart effectively establishing a numerical criteria. Any material inside this box will pass and will not be considered for further selection stages. The box selection can be manually altered by right-clicking on its edge. As shown in figure 3.3.1d below.

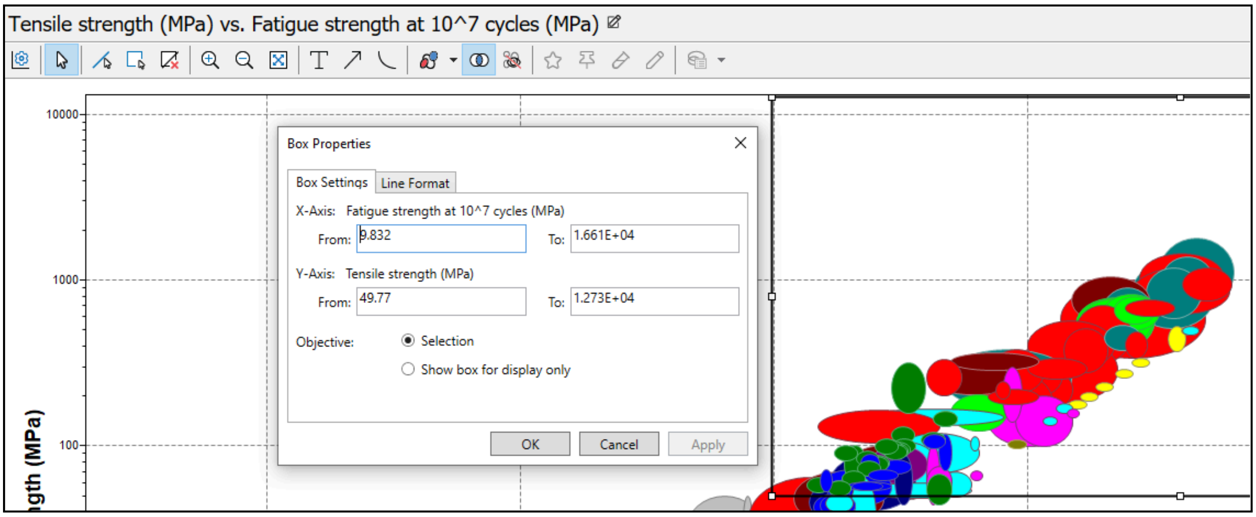


Figure 3.3.1d - Stage 1 Settings.

Repeat this process for other material properties such as Hardness, Fracture Toughness and Thermal Expansion Coefficient. Another selection method used within Granta EduPack was the '*Tree*' selection. Clicking this opens another window where the user can eliminate classifications of materials completely from the selection process, effective as it makes the database less overwhelming. This can be shown in figure 3.3.1e below.

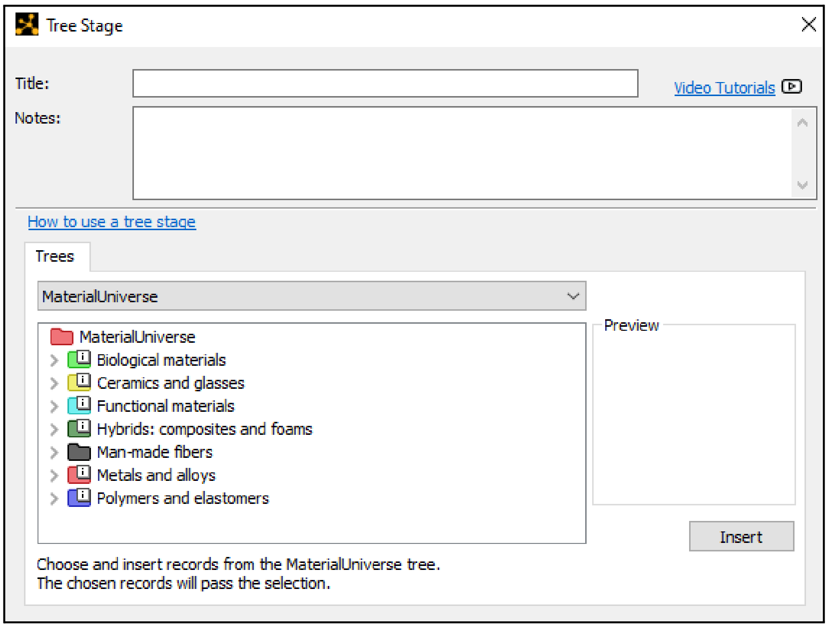


Figure 3.3.1e - Tree Stage.

3.3.2 AutoDesk Inventor

AutoDesk Inventor Professional 2024 version is used for designing the 3D model gear system. Once the software is opened the user should select '*Create New Assembly*'. This opens the main CAD environment, then click '*Design*' and '*Spur Gear*' located in the main toolbar at the top of the screen, within the '*Power Transmission*' section. See figure 3.3.2a for visual aid.

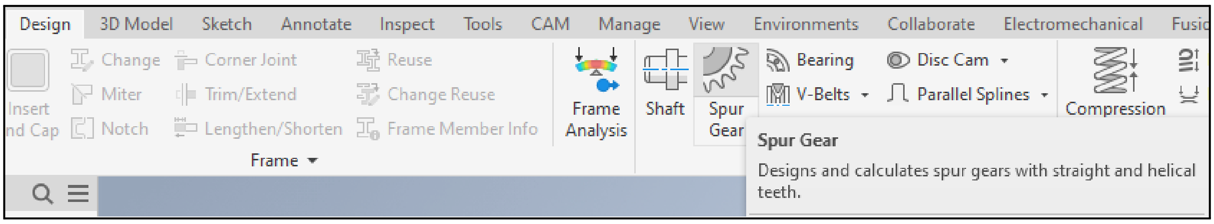


Figure 3.3.2a - Locating Spur Gear.

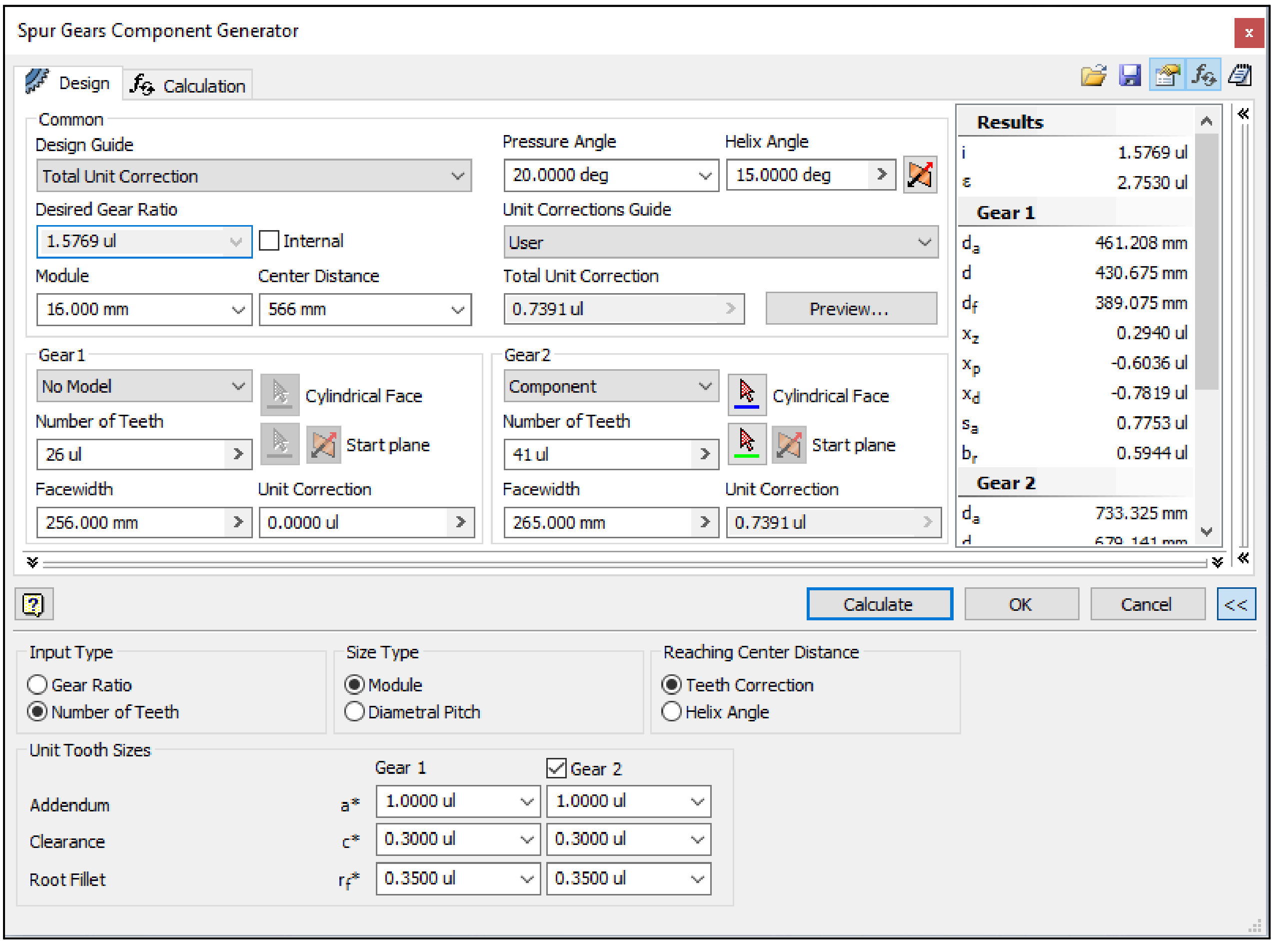


Figure 3.3.2b - Spur Gear Component Generator.

The figure 3.3.2b above displays a window which pops up after selecting spur gear; this allows the user to specify the desired gear design, variables such as Center Distance, and Number of

Teeth. Additionally, tooth-related features can be altered, as seen under '*Unit Tooth Sizes*', this section is vital for the project. After inputting the values as shown in figure 3.3.2b click '*OK*', this will generate the two gears and return the user to the main modelling environment.

Next to export this model for use on ANSYS software, follow figure 3.3.2c below. '*File*' > '*Save As'* > '*Save Copy As*', then save the file as a '*STEP*' file.

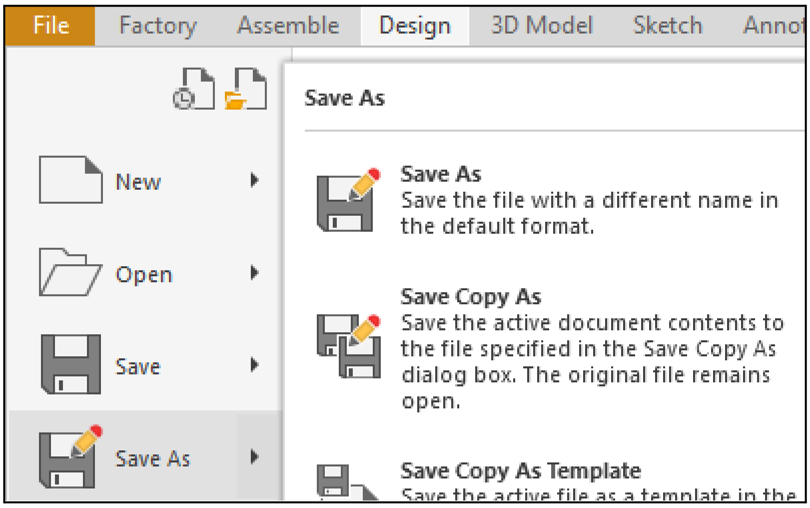


Figure 3.3.2c - Export Model.

3.3.3 ANSYS

Open ANSYS Workbench, version 2023 R2 is used for this project, the user should notice a '*Toolbox*' on the left-hand side of the screen. Under '*Analysis Systems*' click and drag '*Static Structural*', as shown in figure 3.3.3 below.

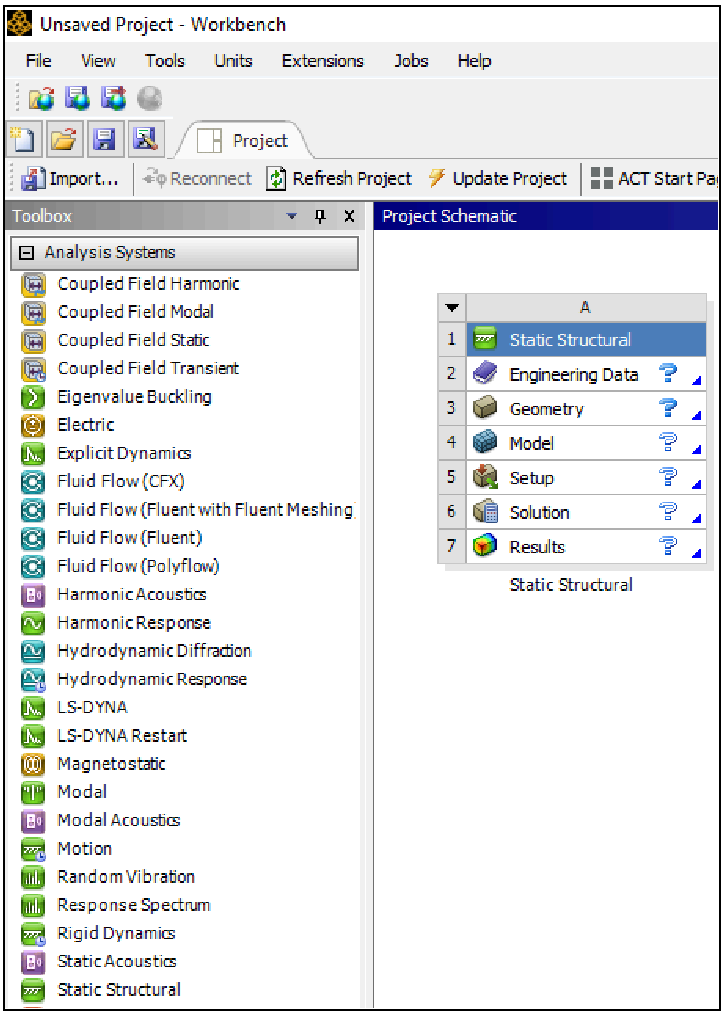


Figure 3.3.3 - Workbench Setup.

Next, right-click on '*Engineering Data*' and select '*Edit*', this will open a new tab within Workbench "A2:Engineering Data". Under the tab select '*Engineering Data Sources*' and as a data source select '*ANSYS GRANTA Materials Data for Simulation*'. Shown in Figure 3.3.3a.

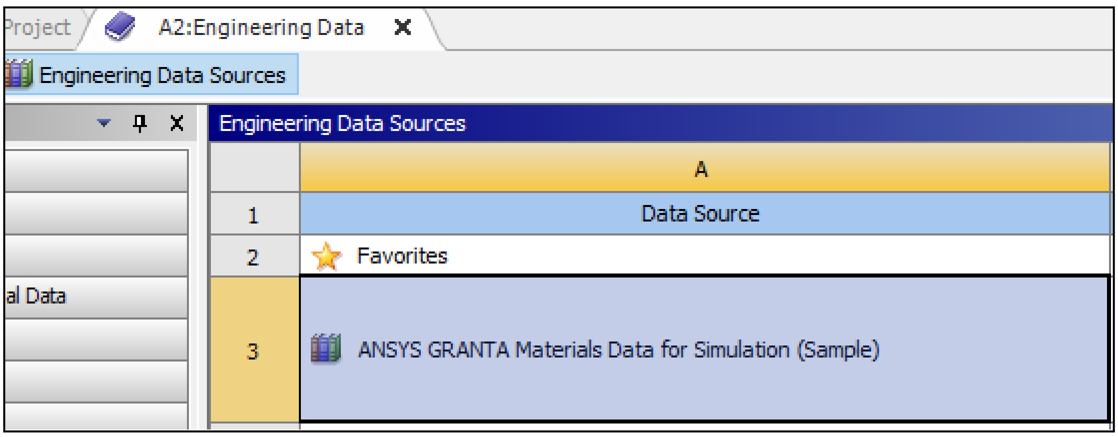


Figure 3.3.3a - Engineering Data.

This allows the user to choose materials for analysis, specifically from the preliminary material selection process previously conducted using Granta EduPack. A list follows of the materials selected for further analysis;

- Brass
- Bronze
- Carbon Steel
- Cast Iron
- Low Alloy Steel
- Stainless Steel
- Titanium Alloy
- Tungsten Alloy

Return to the Project tab and click '*Update Project*'.

To import the model previously made in AutoDesk Inventor, right-click on '*Geometry*', hover over '*Import Geometry*' and select '*Browse*'. As shown in figure 3.3.3b below.

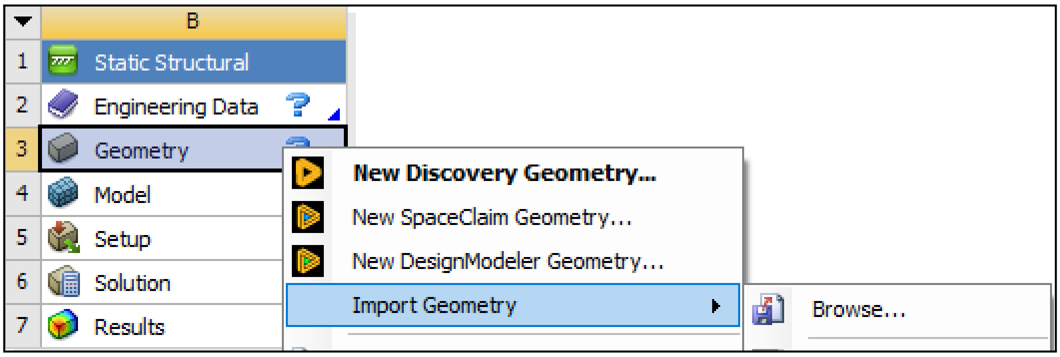


Figure 3.3.3b - Import Model.

After double clicking on '*Model*' a new program will open called Mechanical. There, the user can assign materials to the model under the project tree as shown below in figure 3.3.3c.

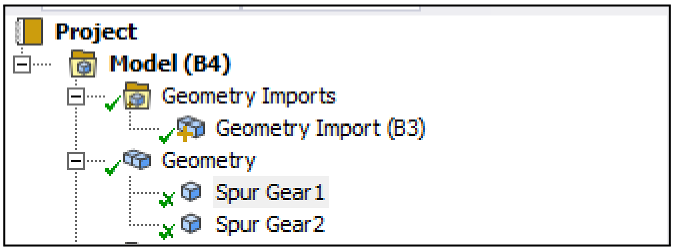


Figure 3.3.3c - Assign Material.

Similarly right click on '*Model (B4)*' and insert a remote point, this will add the feature to the project tree, click on the feature and apply the geometry shown in figure 3.3.3d below. This is the driven gear or sun gear.

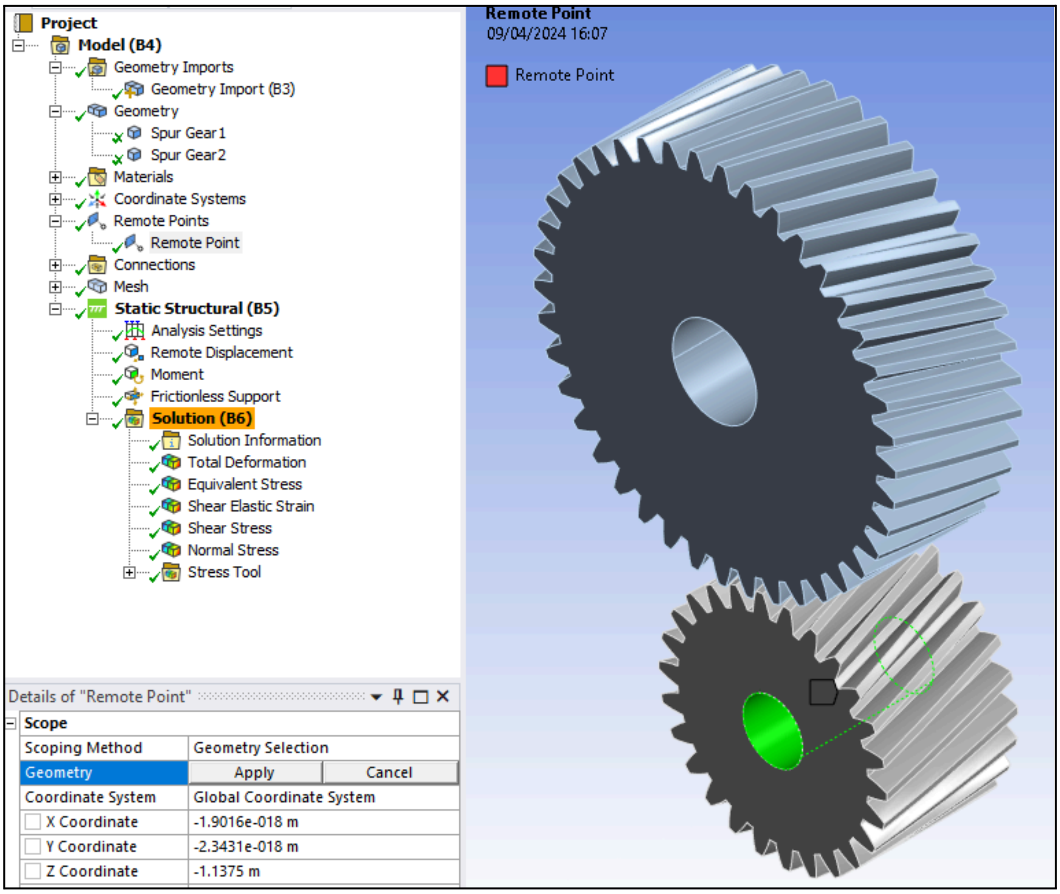


Figure 3.3.3d - Apply Remote Point.

Ensure the correct Contact Regions are set for this gear system there are three sets of teeth contacting at any given time, therefore there are three contact and three target faces. Once checked begin creating the mesh by selecting the feature in the project tree, and input 0.008125 metres as the element size. This is shown in figure 3.3.3e, it can also be seen that an additional mesh feature has been added called '*Contact Sizing*', this can be added by right-clicking on '*Mesh*' in the project tree, inputting 0.0008125 metres as that element size.

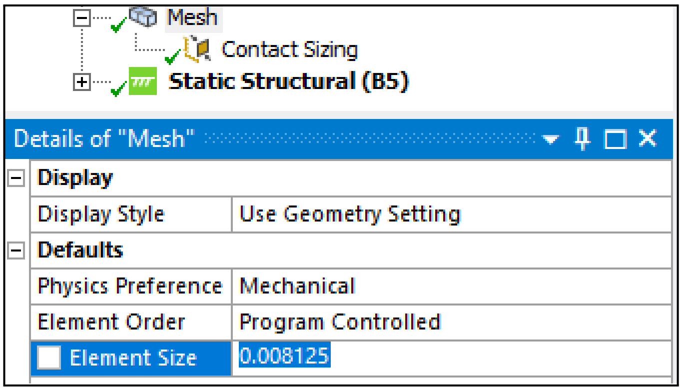


Figure 3.3.3e - Mesh Strategy.

Next, under '*Static Structural*', add the features shown in figure 3.3.3f below, and input the details of each shown in figures 3.3.3g, 3.3.3h and 3.3.3i respectively.

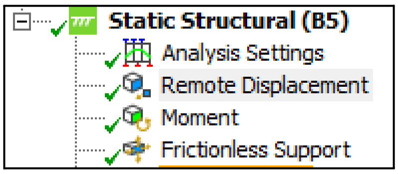
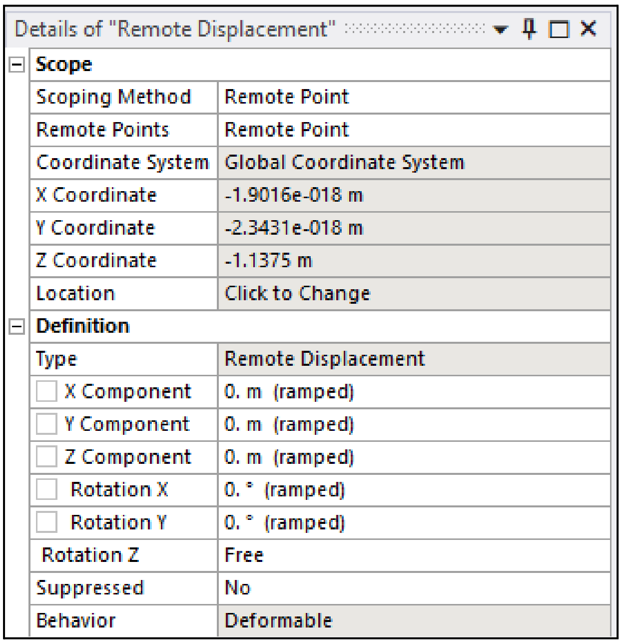


Figure 3.3.3f - Static Structural.



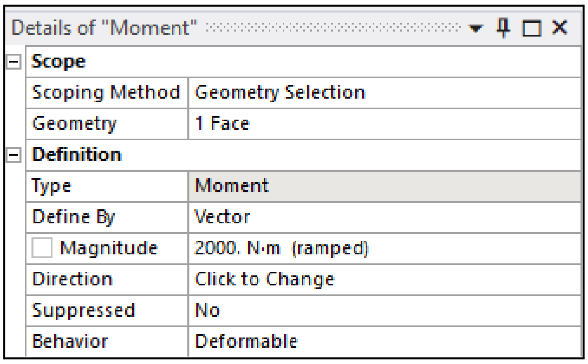


Figure 3.3.3g - Details of "Remote Displacement". **Figure 3.3.3h - Details of "Moment".**

Details of "Frictionless Support"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Type	Frictionless Support
Suppressed	No

Figure 3.3.3i - Details of “Frictionless Support”.

Within the details of remote displacement, under definition, it can be seen that many of the details are changed to zero. This acts as a constraint only allowing the model to rotate about the Z-axis, effectively simulating reality as the gear would be constrained this way.

The next major step in the simulation set-up is the solution section where once the simulation is run and solved, a set of results across the model will be available. The following figure 3.3.3j shows all the solutions that need to be included.

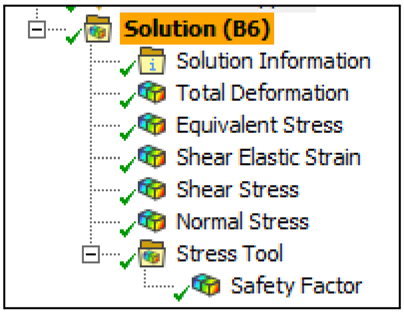


Figure 3.3.3j - Include Solutions

4. Results and Analysis

4.1 Data Analysis Techniques

4.1.1 Mesh Strategy

In conducting the FEA of the helical gear pair, a focused approach was adopted for meshing to ensure accurate simulation results while maintaining computational efficiency. The strategy was centred on the utilisation of contact meshing for the gear teeth interfaces between the two gears, along with the software-default settings for the remainder of the model. The decision to implement contact meshing at the gear teeth was to precisely model the complex contact mechanics inherent to helical gear operation, including load distribution, stress and strain concentrations. A visual example of the mesh strategy can be seen below in figure 4.1.1a.

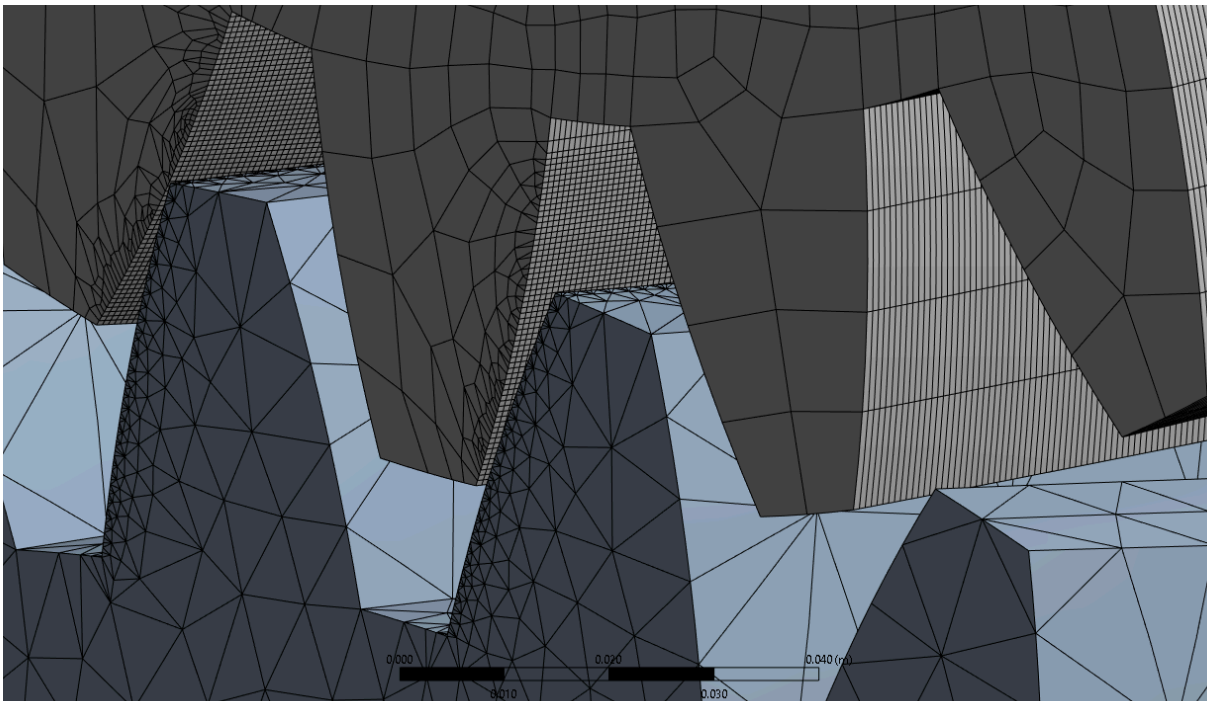


Figure 4.1.1a - Mesh Strategy.

By focusing on contact meshing for the gear teeth, the analysis benefitted from a heightened accuracy in simulating the physical behaviour of the gears under load. This approach is pivotal in identifying areas susceptible to wear or failure, thereby offering insights critical for the gearbox's reliability and performance optimisation.

4.1.2 Mesh Independence Study

Conducting a mesh independence study is crucial for ensuring that the FEA results in ANSYS are not significantly influenced by the size or density of the mesh. Therefore, a mesh independence study will be conducted. Using the default material, '*Structural Steel*' an initial mesh is generated using the mesh strategy discussion in section 4.1.1, using preliminary judgement on element size based on the gear's dimensions. In addition, following the step-by-step guide provided in section 3.3.3, boundary conditions and loads are applied including, torques, constraints and contact regions. The results used for comparison are the maximum Von Mises Equivalent Stress and Strain, as shown below in figures 4.1.2a and 4.1.2b respectively.

After the initial results are recorded, the mesh density is adjusted increasing and decreasing in element size globally and locally on contact regions where the high stress/strain gradients are expected. The analysis is then rerun to obtain a new set of results, for each mesh density. Below are the results in graphical format shown in figures 4.1.2a and 4.1.2b.

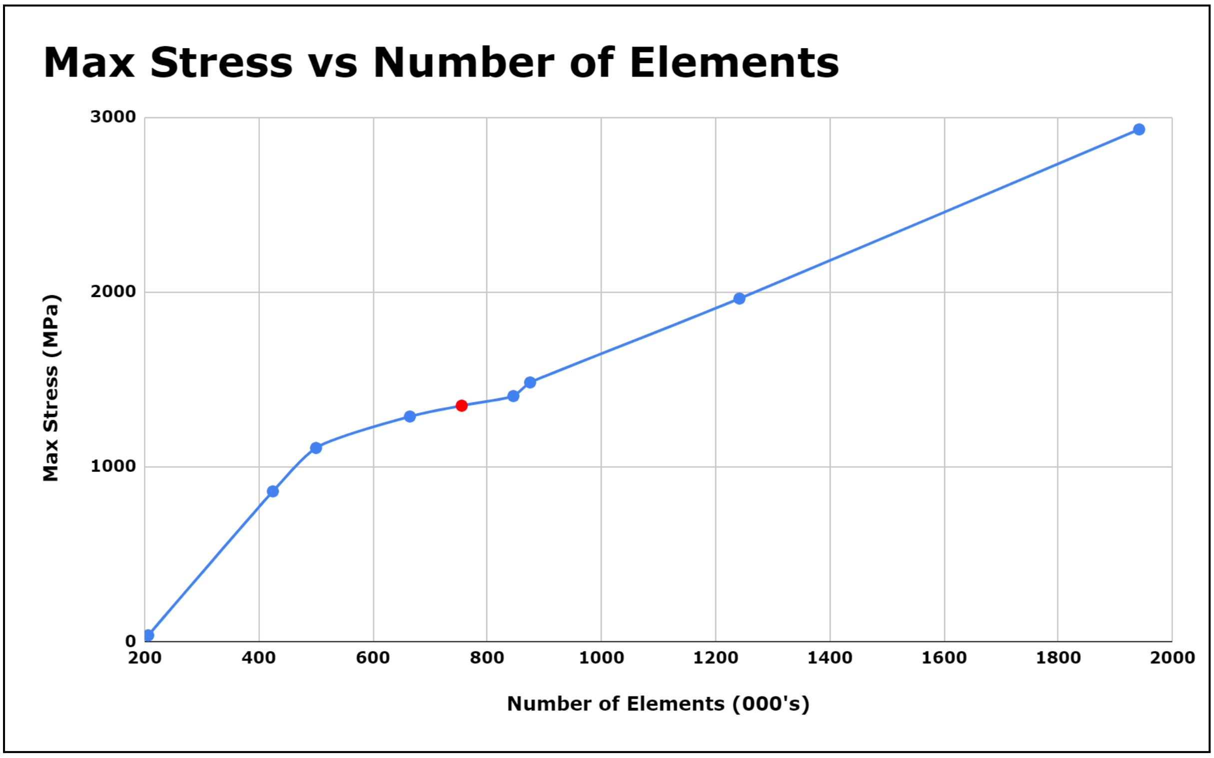


Figure 4.1.2a - Max Stress vs Number of Elements.

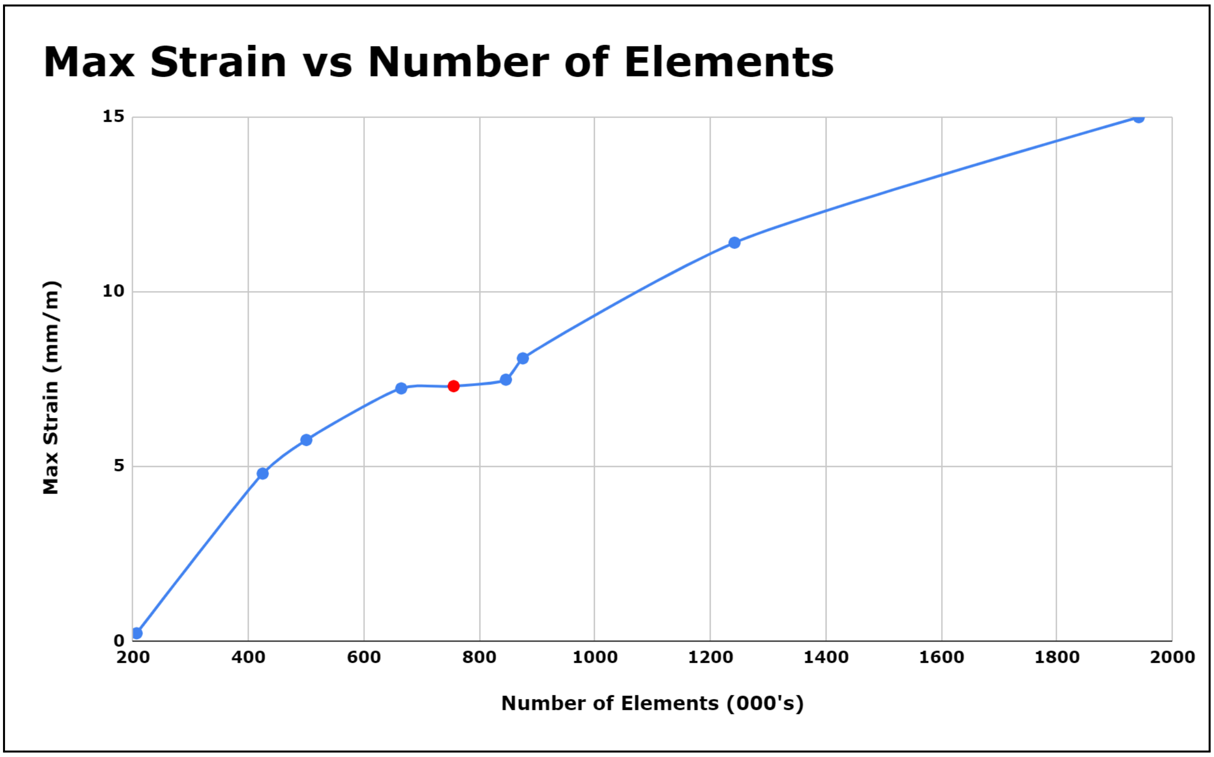


Figure 4.1.2b - Max Strain vs Number of Elements.

The mesh independence study ultimately seeks the optimum number of elements needed for result convergence, where results only change less than 5%, this balances accuracy with computational efficiency. It is seen in figures 4.1.2a and 4.1.2b above, that a mesh of around 755,000 elements, coloured in red, is optimal.

However, the subsequent increase after a certain point is not typical and warrants further investigation. One potential explanation for this behaviour is if the boundary conditions applied to the model are not representative of the actual constraints the system would experience, Abdulsalam (2021) suggests, refining the mesh might expose their inaccuracies as the solution becomes more sensitive to the applied conditions. In addition, Liu et al. (2018) discuss that very fine meshes can sometimes introduce poorly shaped elements, especially in complex geometries. These elements can lead to inaccurate stress/strain calculations and might explain why the values increase after initially levelling out. Table 4.1.2 provides the mesh statistics and results below.

Table 4.1.2 - Mesh Independence Study

Number of Elements (000's)	206	425	500	665	755	846	875	1242	1942
Max Stress (MPa)	38	862	1110	1290	1352	1407	1485	1965	2933
Max Strain (mm/m)	0.233	5	6	7	7	7	8	11	15
Mesh Element Size (mm)	50	50	10	8.75	8.125	10	7.5	6.25	5
Contact Mesh Element Size (mm)	5	1	1	0.875	0.8125	0.75	0.75	0.625	0.5

4.2 Material Evaluation Outcomes

Appendix F, displays the first filtering stage comparing tensile strength and fatigue strength crucial properties for the application as discussed in section 2.5. Material groups are labelled indicating these are the highest performing compared to the complete library. The following stage removed ‘Biological Materials’ and ‘Man-made fibres’ from the selection process due to the following discussion.

The exclusion of biological materials from the selection process can be justified based on several critical factors. Vincent (1979), claims that biological materials typically do not possess the high strength, fatigue resistance, and fracture toughness required for wind turbine components that are subjected to extreme mechanical loads and cyclic stresses. The operational life of a wind turbine is designed to last 20-25 years, during which the materials must resist wear, corrosion, and environmental degradation. Amini and Miserez (2013), support previous claims adding that biological materials generally lack durability and may degrade faster under environmental exposures, leading to more frequent maintenance or replacements. While biological materials offer advantages in certain applications due to their sustainability and eco-friendliness, their mechanical and physical properties, durability, and environmental resistance fall short of the requirements for wind turbine gear systems.

While the high-performance man-made fibres prove to have the highest tensile and fatigue strength, there are other material properties which lead to the exclusion of the class of material. The application requires a material that can withstand extremely high mechanical loads, including torque, bending moments, and high compressive loads. Bachmann, Wiedemann and Wierach, (2018) suggest that man-made fibres may not provide the desired wear resistance or surface hardness required for the application, potentially leading to rapid wear and material failure. In addition, Usachev et al., (2020) also suggest that consistent contact between gears will also expose the material to significant thermal loads due to frictional heating, which could affect gear performance and alignment. The advantages of man-made fibres, such as lightweight and high-strength, are overall outweighed by the many other properties that do not align with the specific demands of a wind turbine gear system.

Appendix G, displays stage 3 of the process, this applies the maximum thermal expansion coefficient discussed in section 2.5. Appendix H shows the final stage, accessing the remaining materials against hardness and fracture toughness; the importance and requirements for the properties is again discussed in section 2.5.

Only 8 materials, listed below, pass all stages:

- Brass
- Bronze
- Cast Iron
- High Carbon Steel
- Low Alloy Steel
- Stainless
- Titanium Alloys
- Tungsten Alloys

4.3 Testing and Validation Findings

A comparison of various stress measures and safety factors for eight different materials subjected to the same loading conditions in an FEA simulation with the addition of one material sourced for the literature review as the most commonly used material in modern wind turbine gearboxes, 18 CrNiMo7-6.

Table 4.3 - All FEA Results

	Total Deformation (mm)	Equivalent Von Mises Stress (MPa)	Shear Stress (MPa)	Normal Stress (MPa)	Shear Strain (mm/m)	Safety Factor	
Average	0.130	4.395	1.001	-0.422	0.0269	14.765	BRASS
Maximum	0.150	1378	430	445	11.6		
Minimum				-333		0.267	
Average	0.121	4.395	1.001	-0.422	0.0250	14.853	BRONZE
Maximum	0.140	1378	430	445	10.8		
Minimum				-333		0.367	
Average	0.149	4.482	1.004	-0.413	0.0283	13.661	CAST IRON
Maximum	0.173	1433	437	475	12.3		
Minimum				-331		0.0557	
Average	0.0624	4.449	1.003	-0.416	0.0122	14.895	LOW ALLOY STEEL
Maximum	0.0721	1414	435	461	5.28		
Minimum				-331		0.461	
Average	0.0624	4.449	1.003	-0.416	0.0122	14.660	CARBON STEEL
Maximum	0.0721	1414	435	461	5.28		
Minimum				-331		0.208	
Average	0.0683	4.471	1.004	-0.414	0.0131	14.559	STAINLESS STEEL
Maximum	0.0789	1427	436	470	5.68		
Minimum				-331		0.177	
Average	0.117	4.401	1.001	-0.421	0.0241	14.927	TITANIUM ALLOY
Maximum	0.136	1382	431	442	10.4		
Minimum				-333		0.612	
Average	0.0391	4.460	1.004	-0.415	0.00756	14.932	TUNGSTEN ALLOY
Maximum	0.0452	1421	436	466	3.28		
Minimum				-331		0.633	
Average	0.0663	4.454	1.0034	-0.415	0.0129	14.944	18CrNiMo7-6
Maximum	0.0767	1418	435	464			
Minimum				-331		0.729	

KEY: **Red = Average** **Light Red = Maximum** **White = Minimum**

4.3.1 Total Deformation

As seen in figure 4.3.1a below all materials exhibit small deformations, indicating good rigidity under the applied loads. The maximum values represent the points of greatest deformation on the gear, likely where the load is highest or the geometry induces stress concentration. Lower deformation is typically desired for precision components like gears, suggesting all the materials maintain their shape well under stress. The following figure 4.3.1b displays the pattern of gear deformation, all materials displayed the same pattern therefore the same figure has been used.

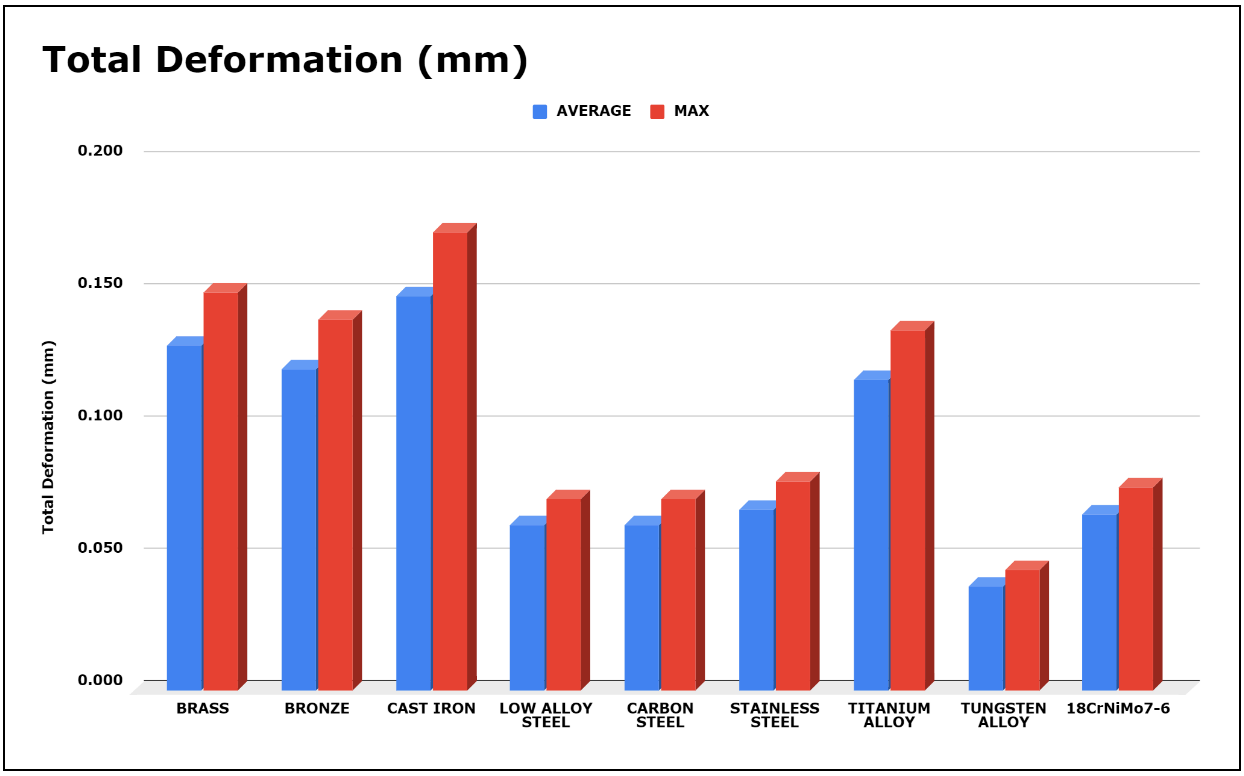


Figure 4.3.1a - Total Deformation Results (Graph)

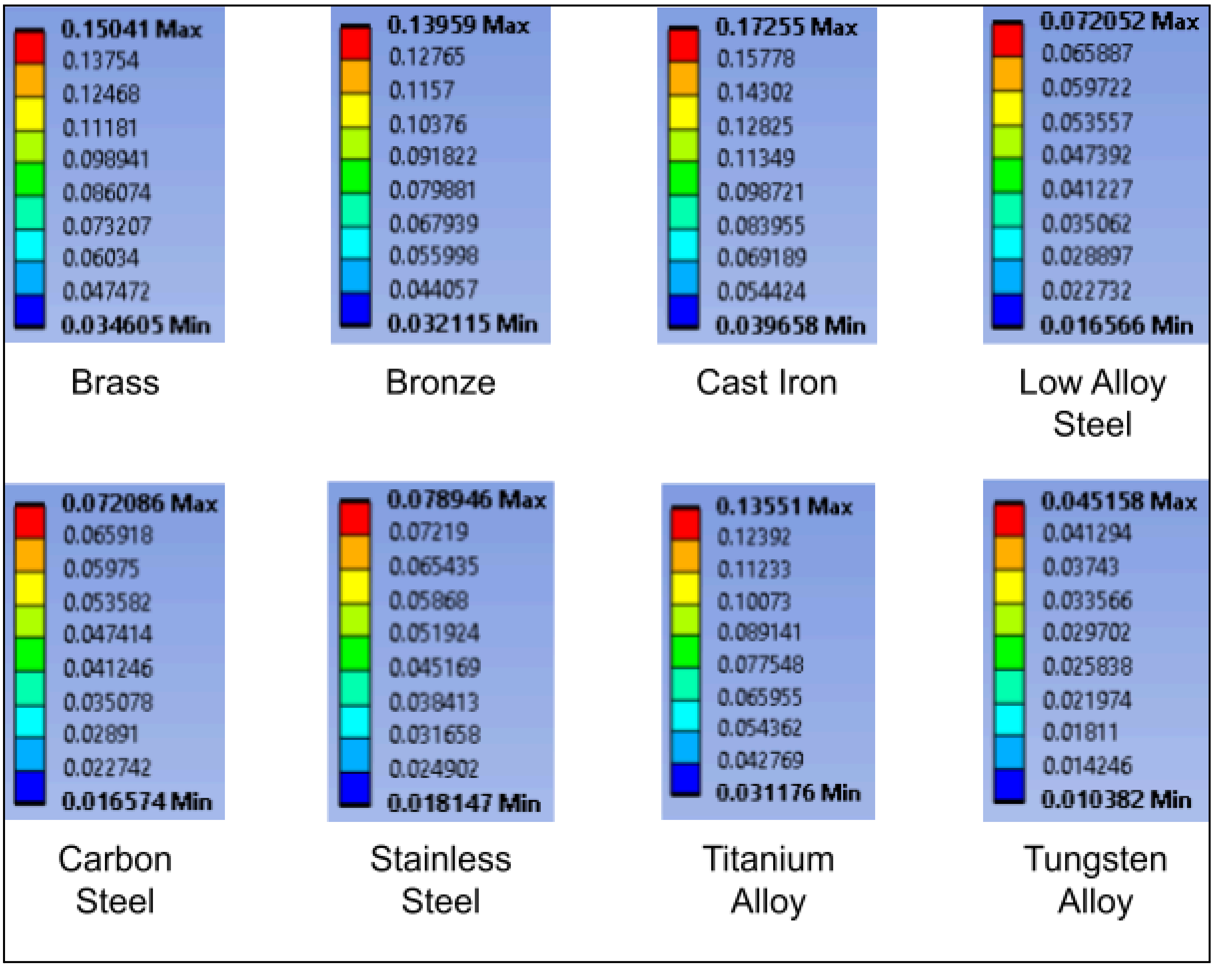


Figure 4.3.1b - FEA Total Deformation Results

4.3.2 Von Mises Equivalent Stress

Figure 4.3.2a below displays the maximum Von Mises stress values for all materials, with the maximum values likely occurring at critical stress points such as gear teeth contact zones. Table 4.3.2 compares FEA results with material strengths from Granta EduPack.

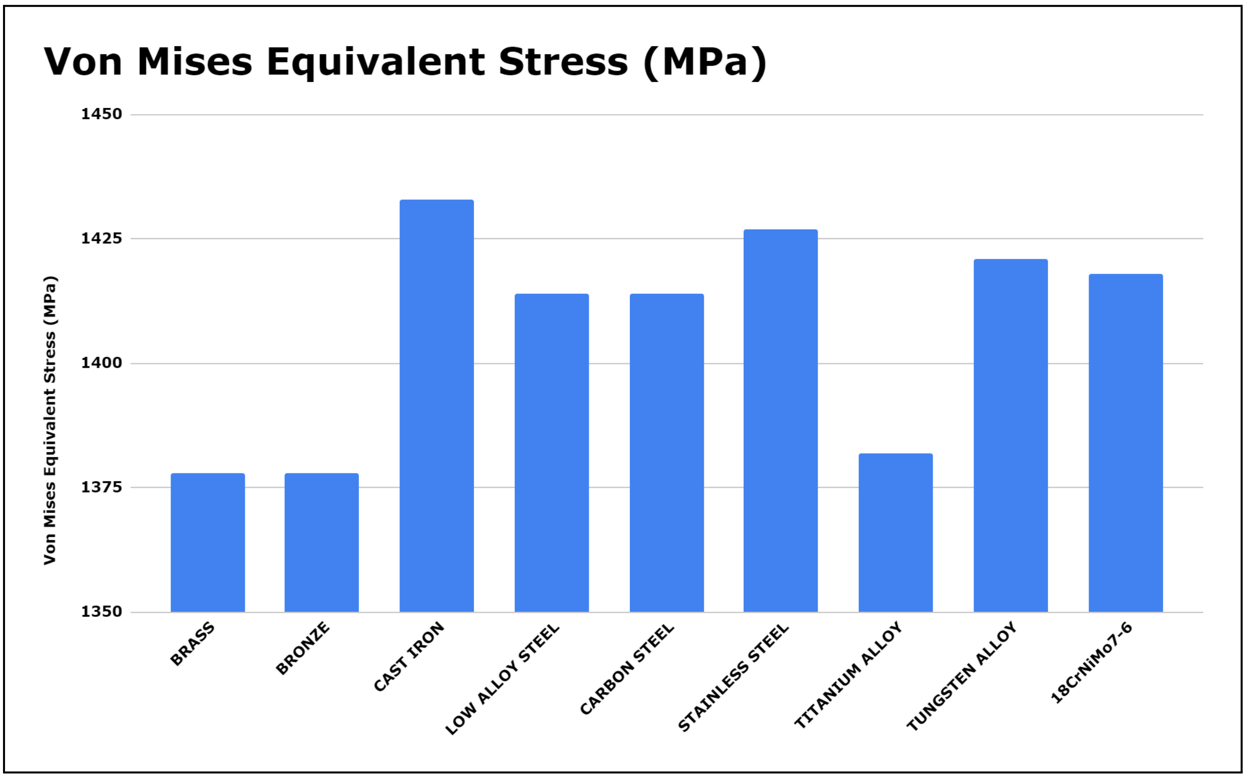
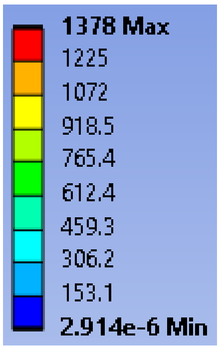
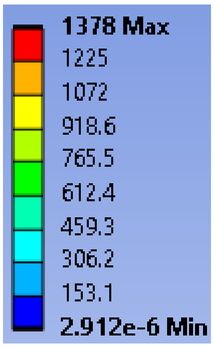
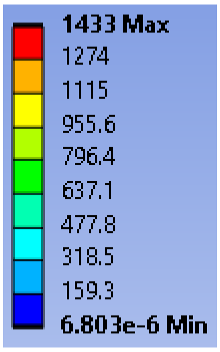
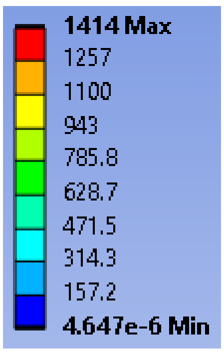
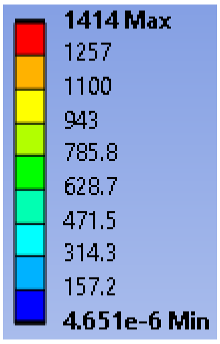
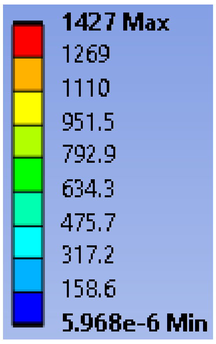
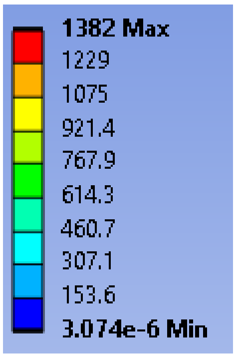
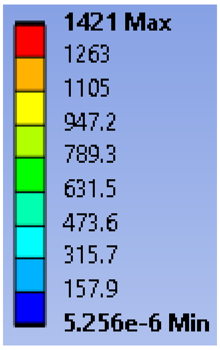


Figure 4.3.2a - Von Mises Equivalent Stress Results (Graph)

Table 4.3.2 - FEA and Material Comparison (Von Mises Equivalent Stress)

Material	Yield Strength	Results (MPa)	Comments
Brass	198 MPa		Maximum stress is 1387 MPa, which far exceeds the yield strength, indicating potential yielding.
Bronze	320 MPa		Maximum stress is 1387 MPa, suggesting a risk of yielding, especially on the lower end of the yield strength spectrum.
Cast Iron	438 MPa		Maximum stress is 1433 MPa, well beyond the yield strength, indicating a high likelihood of material failure.
Low Alloy Steel	1035 MPa		Maximum stress is 1414 MPa, suggesting a risk of yielding, especially on the lower end of the yield strength spectrum.

Carbon Steel	653 MPa		Maximum stress is 1414 MPa, suggesting a potential for yielding or even failure.
Stainless Steel	699 MPa		Maximum stress is 1427 MPa, which is well above the yield strength, indicating that the material may undergo plastic deformation.
Titanium Alloy	896 MPa		Maximum stress is 1382 MPa, while this stress value is high, it is closer to the yield strength of this material, suggesting it may perform better than other materials under operational load, but still at risk.
Tungsten Alloy	860 MPa		Maximum stress is 1421 MPa, given the high yield strength of tungsten alloys, this material could potentially withstand the applied loads without yielding, but specific alloy properties would be needed to confirm this.
18CrNiMo7-6	1034 MPa		Maximum stress is 1418 MPa, this value is the closest to the material strength, suggesting it is the best performer amongst all materials. The

			stress is still above the strength of the material indicating risk of yielding.

Significance

The Von Mises stress is used to predict yielding, with values exceeding the material's yield strength indicating a likelihood of plastic deformation. In this case, most materials show a maximum Von Mises stress that exceeds the typical yield strength values, suggesting that under the maximum load conditions simulated, these materials would likely yield and possibly fail.

Conclusion

Most of the materials, with the possible exception of the low alloy steel, titanium and tungsten alloys, appear to be unsuitable for this application, as indicated by their maximum Von Mises stresses exceeding typical yield strengths. If the loading conditions used in the FEA are representative of the maximum expected operational loads, then the gear design may need to be revised to reduce the stresses or a different material selection may be necessary.

Among the tested materials, low alloy steel, titanium and tungsten alloys appear to be the most promising due to their higher yield strengths, However, the choice of material should also consider factors such as cost, weight, and machinability.

4.3.3 Shear Stress

Shear stress is an important consideration in gear design as it affects the teeth's ability to transmit torque without failure. Viewing the results shown in figure 4.3.3a below, it can be analysed that the average shear stress values are very close across all materials, hovering around 1 MPa. These low average values indicate that, generally, the materials are not subjected to high shear stress during normal gear operation, which is good for the longevity and reliability of the gear teeth.

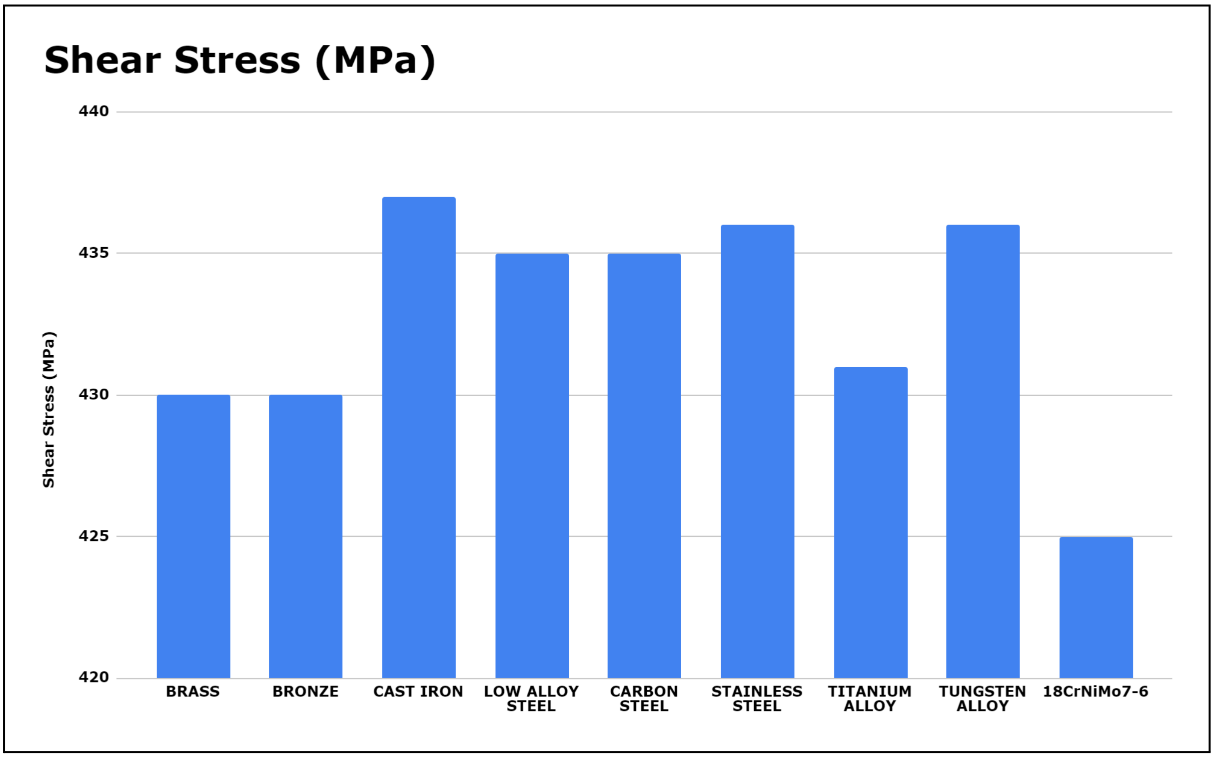


Figure 4.3.3a - Shear Stress Results (Graph)

The maximum shear stress values are significantly higher than the average, ranging from 430 - 437 MPa. These peaks suggest localised areas where shear stress is concentrated. The maximum shear stresses for all materials are substantially below the typical ultimate shear strengths for these materials. For instance, the ultimate shear strength for many steels can be roughly 0.6 times the tensile yield strength, which would put their allowable shear stress well above the maximum values observed here. Therefore, none of the materials are likely to fail under these maximum shear stresses. The following figure 4.3.3b shows all FEA results.

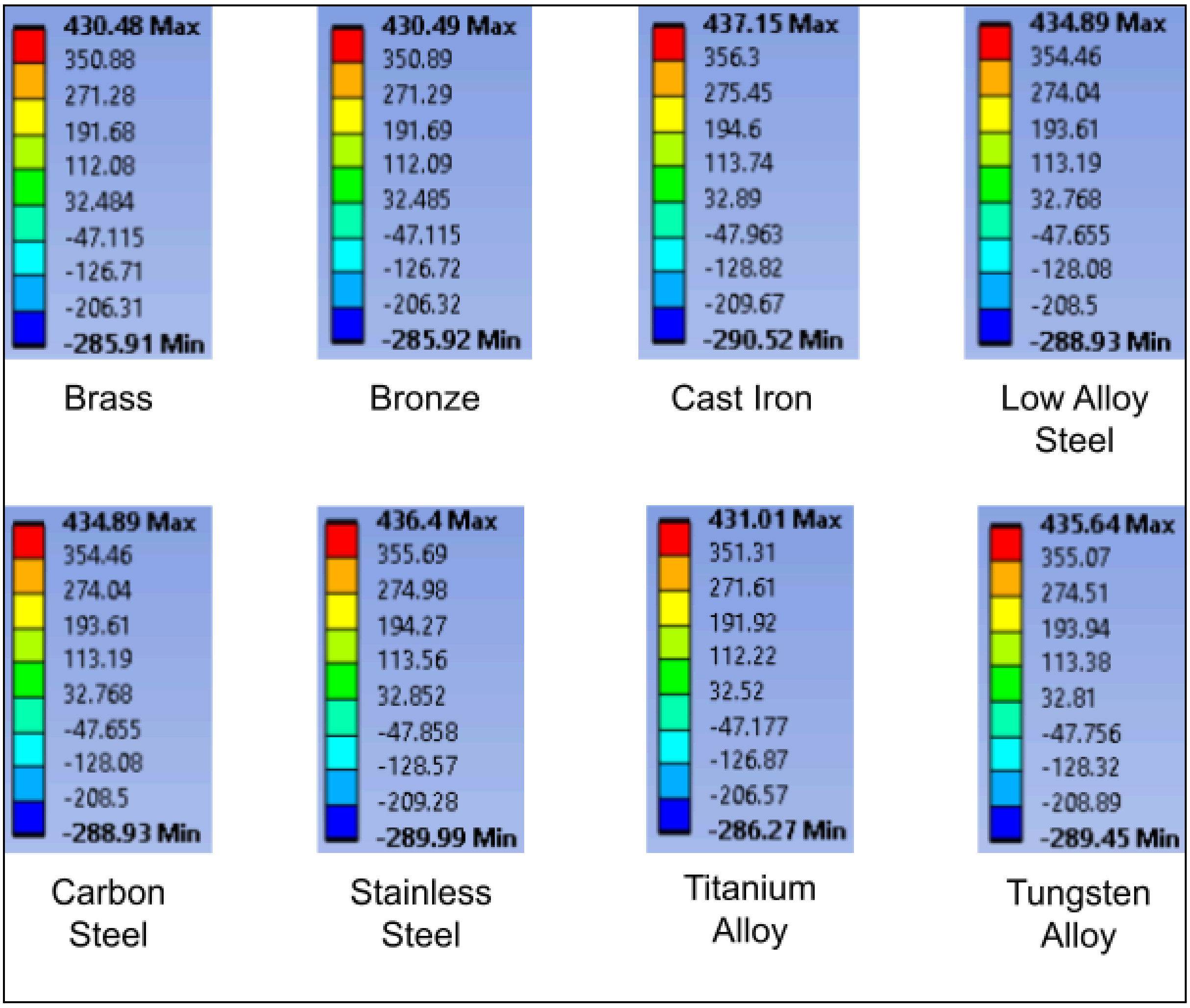


Figure 4.3.3b - FEA Shear Stress Results

4.3.4 Normal Stress

Normal stresses in gear systems can be representative of the load distribution across the gear teeth during meshing. Table 4.3.4 displays all the normal stress values, a negative average normal stress across all materials suggests that, on average, the gear experiences compressive stress. Compressive stress is typical at gear contact surfaces where the teeth contact and transmit force. The magnitude of this average is quite low around -0.4 MPa, which suggests that the average loading condition on the gears is mild and should not be a concern for any of the materials.

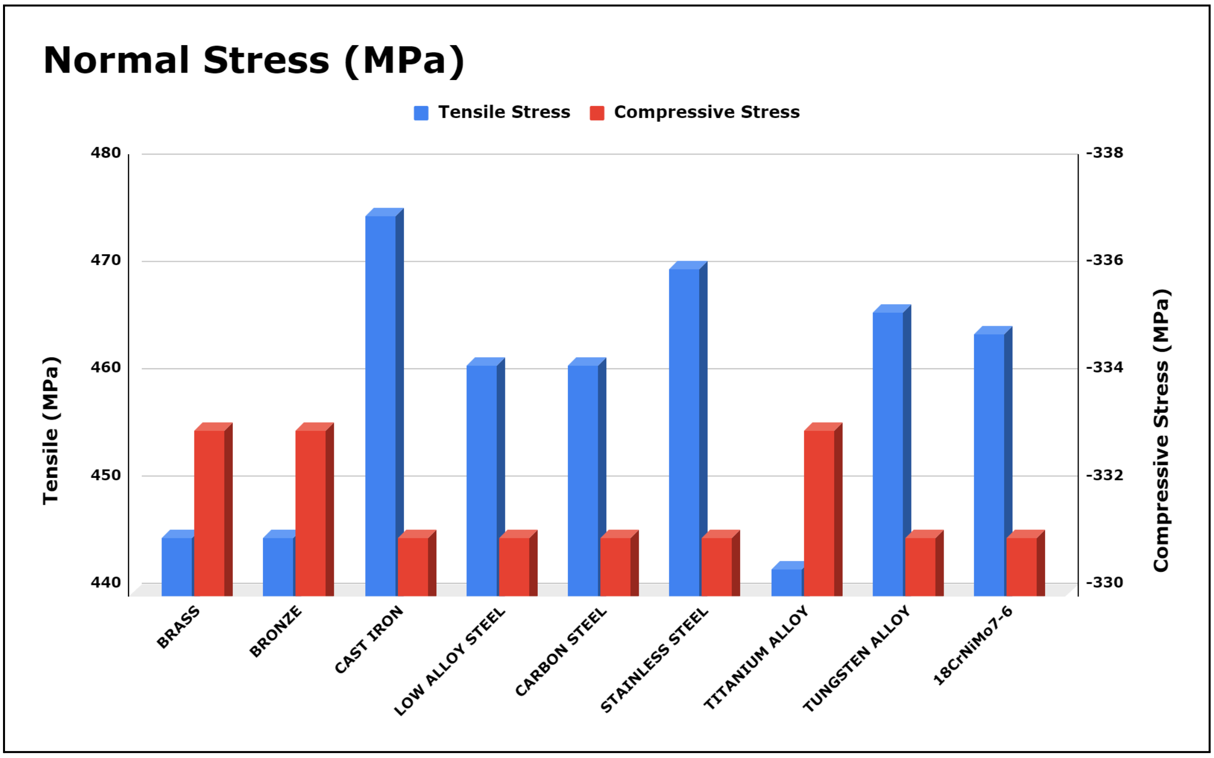
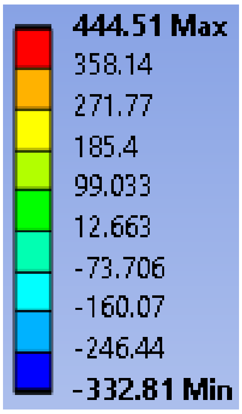
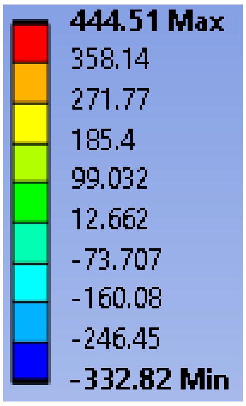
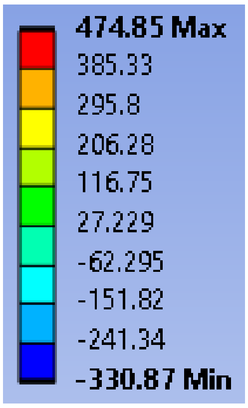
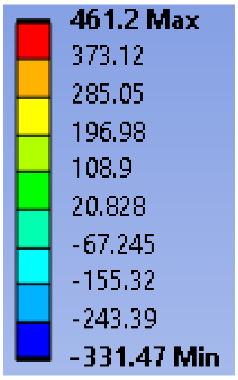
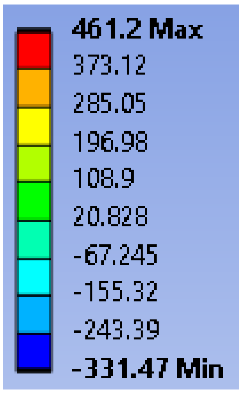
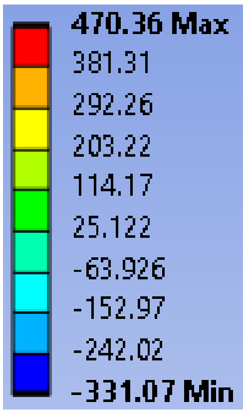
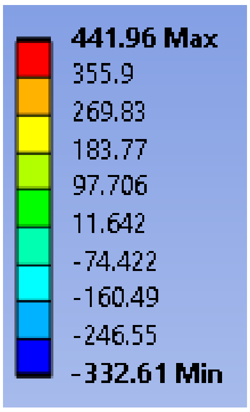


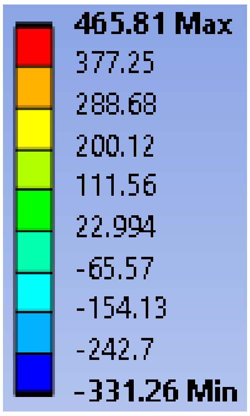
Figure 4.3.4a - Normal Stress Results (Graph)

The maximum normal stress values range from 436 to 475 MPa, graphical formatted data shown in figure 4.3.4a, representing the peak tensile stress at the most stressed point of the gear. These values are critical since tensile stress can lead to crack initiation and propagation, especially under cyclic loading conditions. The minimum normal stress values are all negative and relatively similar only ranging from -331 to -333 MPa, indicating compressive stresses are present. This is likely to occur at the point of contact between meshing teeth, which are in compression due to the gear meshing forces.

Table 4.3.4 - FEA Analysis (Normal Stress)

Material		Results (MPa)	Comments
Brass			
Tensile Strength	396 MPa		The maximum normal stress is 445 MPa is above tensile strength, suggesting the possibility of failure.
Compressive Strength	198 MPa		The minimum normal stress is -333 MPa is above the compressive strength suggesting the possibility of failure.
Bronze			
Tensile Strength	511 MPa		The maximum stress of 445 MPa, is below yield strength, indicating that it is safe from tensile yielding.
Compressive Strength	320 MPa		The minimum stress is -333 MPa, marginally above the compressive strength, which leaves some element of risk.
Cast Iron			
Tensile Strength	650 MPa		The maximum stress is 475 MPa, significantly lower than tensile strength, indicating low risk of tensile yielding.
Compressive Strength	456 MPa		The minimum stress is -331 MPa, again lower than material compressive strength, indicating low risk of compressive yielding.

<table>
<tr><td colspan="2">Low Alloy Steel</td><td rowspan="3">
</td><td rowspan="3">Maximum and minimum normal stress is 461 MPa and -331 MPa, both lower than the tensile, and compressive strength. Providing a safety margin against yielding and failure.</td></tr>
<tr><td>Tensile Strength</td><td>1250 MPa</td></tr>
<tr><td>Compressive Strength</td><td>1045 MPa</td></tr>
<tr><td colspan="2">Carbon Steel</td><td rowspan="3">
</td><td rowspan="3">Maximum and minimum normal stress is 461 MPa and -331 MPa, both lower than the tensile, and compressive strength. Providing a safety margin against yielding and failure.</td></tr>
<tr><td>Tensile Strength</td><td>891 MPa</td></tr>
<tr><td>Compressive Strength</td><td>653 MPa</td></tr>
<tr><td colspan="2">Stainless Steel</td><td rowspan="3">
</td><td rowspan="3">Maximum and minimum normal stress is 470 MPa and -331 MPa, both lower than the tensile, and compressive strength. Providing a safety margin against yielding and failure.</td></tr>
<tr><td>Tensile Strength</td><td>908 MPa</td></tr>
<tr><td>Compressive Strength</td><td>726 MPa</td></tr>
<tr><td colspan="2">Titanium Alloy</td><td rowspan="3">
</td><td rowspan="3">Maximum and minimum normal stress is 442 MPa and -333 MPa, which is well below all strengths. Indicating that titanium alloy should not experience tensile or compressive yielding under these conditions, with a considerable safety margin.</td></tr>
<tr><td>Tensile Yield Strength</td><td>976 MPa</td></tr>
<tr><td>Compressive Strength</td><td>915 MPa</td></tr>
</table>

Tungsten Alloy			
Tensile Yield Strength	1096 MPa		Maximum and minimum normal stress is 466 and -331 MPa. This is well below the material's tensile and compressive strength, suggesting no risk of yielding under operational conditions, with a considerable safety margin.
Compressive Strength	877 MPa		
18CrNiMo7-6			Maximum and minimum normal stress is 464 and -331 MPa. This is well below the material’s tensile and compressive strength, suggesting no risk of yielding under operational conditions, with a considerable safety margin.
Tensile Ultimate Strength	1158 MPa		
Compressive Strength	N/A		

Conclusion

The three groups of Steels, Titanium and Tungsten Alloys appear to have tensile and compressive stresses well within their strength capacities, making them more suitable for the application. For materials with stresses near or above their yield strengths, gear designs may need to be optimised to reduce these stresses.

4.3.5 Shear Strain

Shear strain measures the deformation of a material in response to shear stress; it’s a dimensionless ratio that describes how much one layer of material has shifted relative to another. Figure 4.3.5a below provides a graphical representation of these maximum values, along with the FEA results presented in figure 4.3.5b.

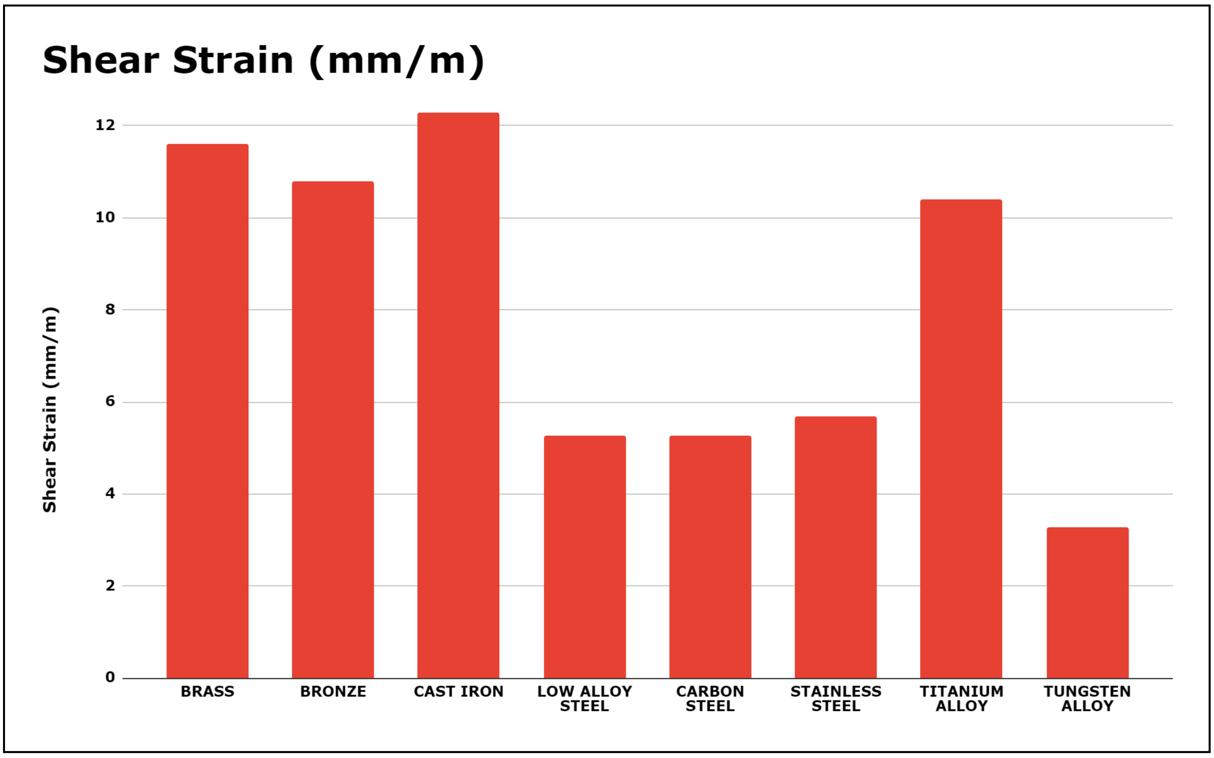


Figure 4.3.5a - Shear Strain Results (Graph)

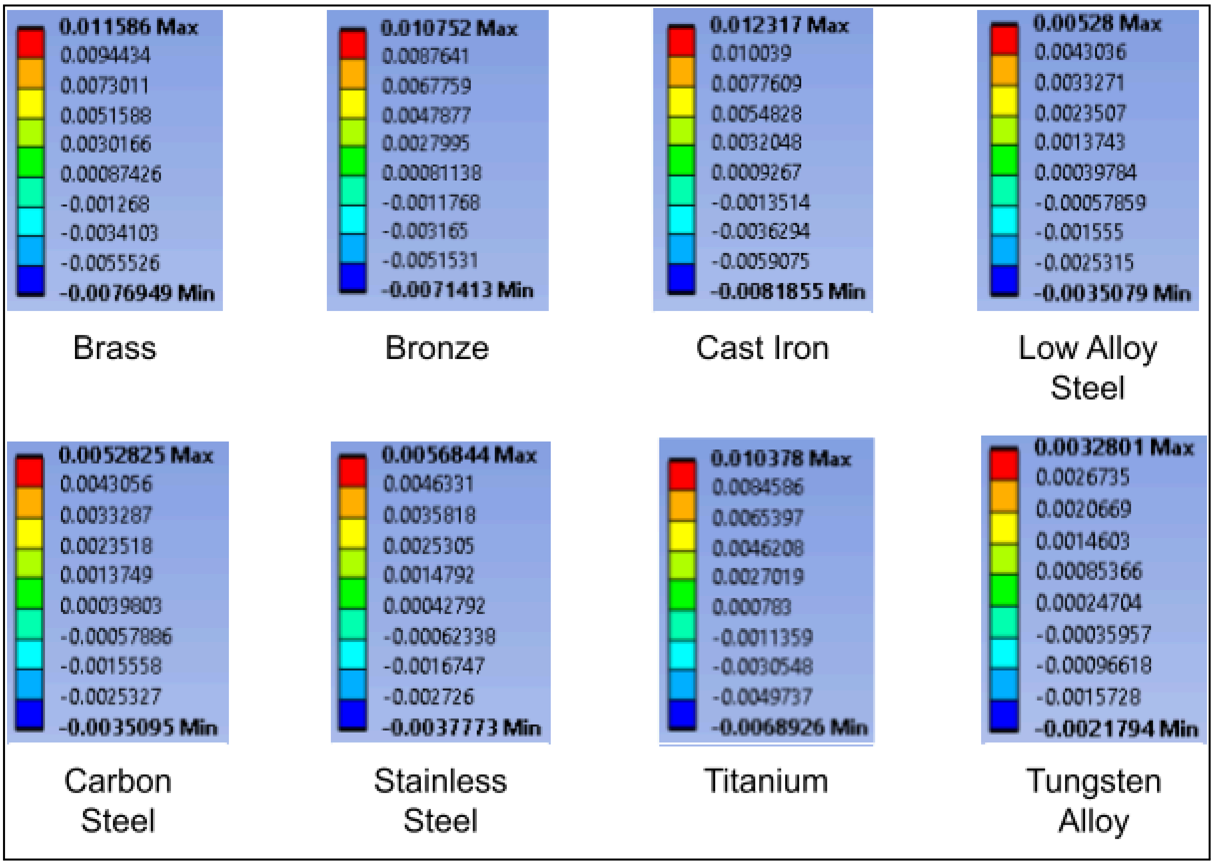


Figure 4.3.5b - FEA Shear Stress Results

Table 4.3.5 - FEA Analysis (Shear Stress)

Material	**Max Shear Strain**	**Comments**
Brass	11.6 (mm/m)	Higher values may indicate areas of significant deformation, possibly at gear tooth roots.
Bronze	10.8 (mm/m)	
Cast Iron	12.3 (mm/m)	The highest maximum shear strain among all tested materials suggests cast iron may be more susceptible to localised deformation.
Low Alloy Steel	5.28 (mm/m)	Significantly lower than brass, bronze and cast iron, which suggests these steels are less prone to shear deformation.
Carbon Steel	5.28 (mm/m)	
Stainless Steel	5.68 (mm/m)	Offers a small amount of shear deformation but is slightly overshadowed by other steels.
Titanium Alloy	10.4 (mm/m)	Lower than cast iron but comparable to brass and bronze, indicating potential for deformation.
Tungsten Alloy	3.28 (mm/m)	The lowest maximum shear strain, suggests that tungsten alloy has a high resistance to deformation even at points of highest stress.

The maximum shear strain values are important for understanding how the gear might behave under peak load conditions, such as during sudden changes in torque. The materials with the lowest maximum shear strain (low alloy steel, carbon steel, and tungsten alloy) would likely maintain dimensional stability over the gear’s lifespan, which could be especially important for the application that requires high precision and minimal wear.

4.3.6 Safety Factor

$$Safety\ Factor\ =\ \frac{Yield\ Strength}{Max\ Stress}$$

If the safety factor is less than 1, it implies that the maximum stress is greater than the yield strength of the material, and the material is likely to undergo permanent deformation. In a safety-critical component, this would be unacceptable as it implies a risk of failure.

The average safety factors for all materials are significantly high, suggesting that on average, the gears are designed to handle far more stress than they typically experience under operational conditions.

The minimum safety factor reported for materials like cast iron (0.00557), carbon steel (0.208), stainless steel (0.177), and brass (0.267) is significantly below 1. This suggests that at the point of maximum stress, the material is not strong enough to withstand the applied load without failing. Such a condition would typically require a redesign or the selection of a more robust material to ensure safety.

For bronze (0.367), low alloy steel (0.461), titanium alloy (0.612) and tungsten alloy (0.605), the minimum safety factors are also below 1 but less drastically. These values still indicate that the stress at certain points exceeds the yield strength, which is a cause for concern, still requiring a redesign, material change, or both to increase the safety factor above 1. Figure 4.3.6a below provides a graphical representation of these values for comparison, along with the FEA results presented in figure 4.3.6b.

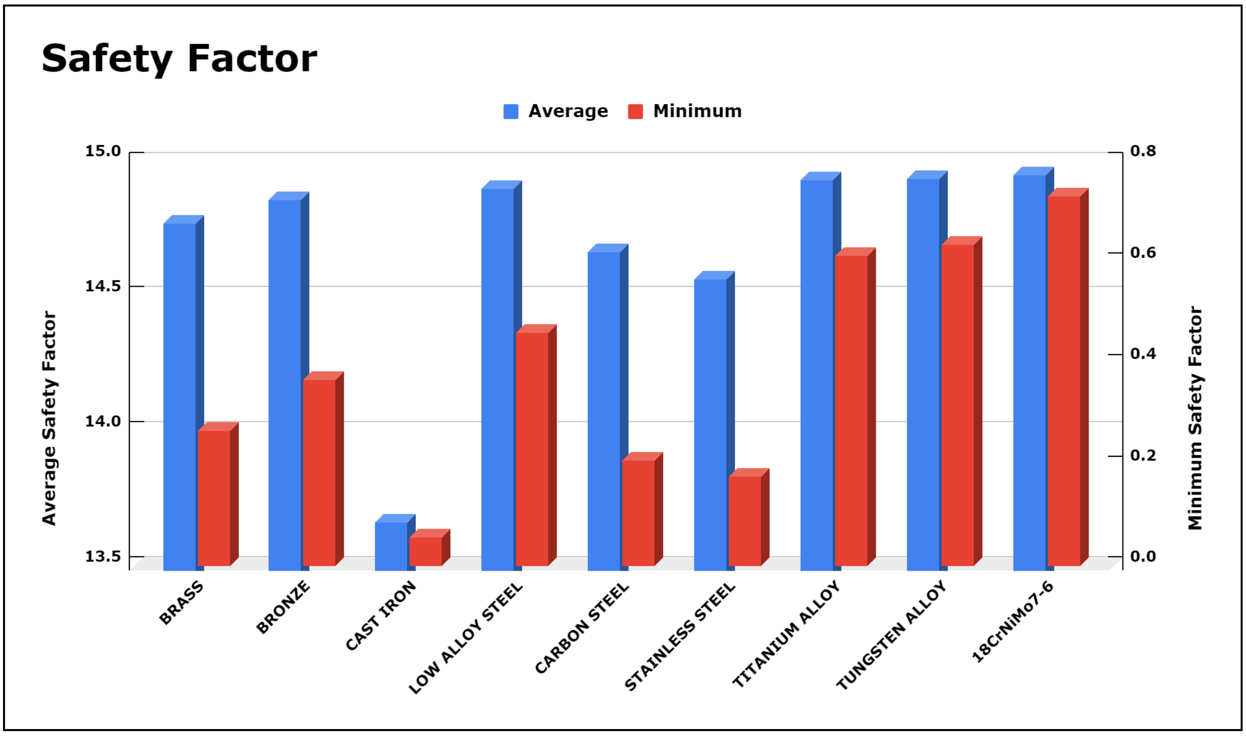


Figure 4.3.6a - Safety Factor Results (Graph)

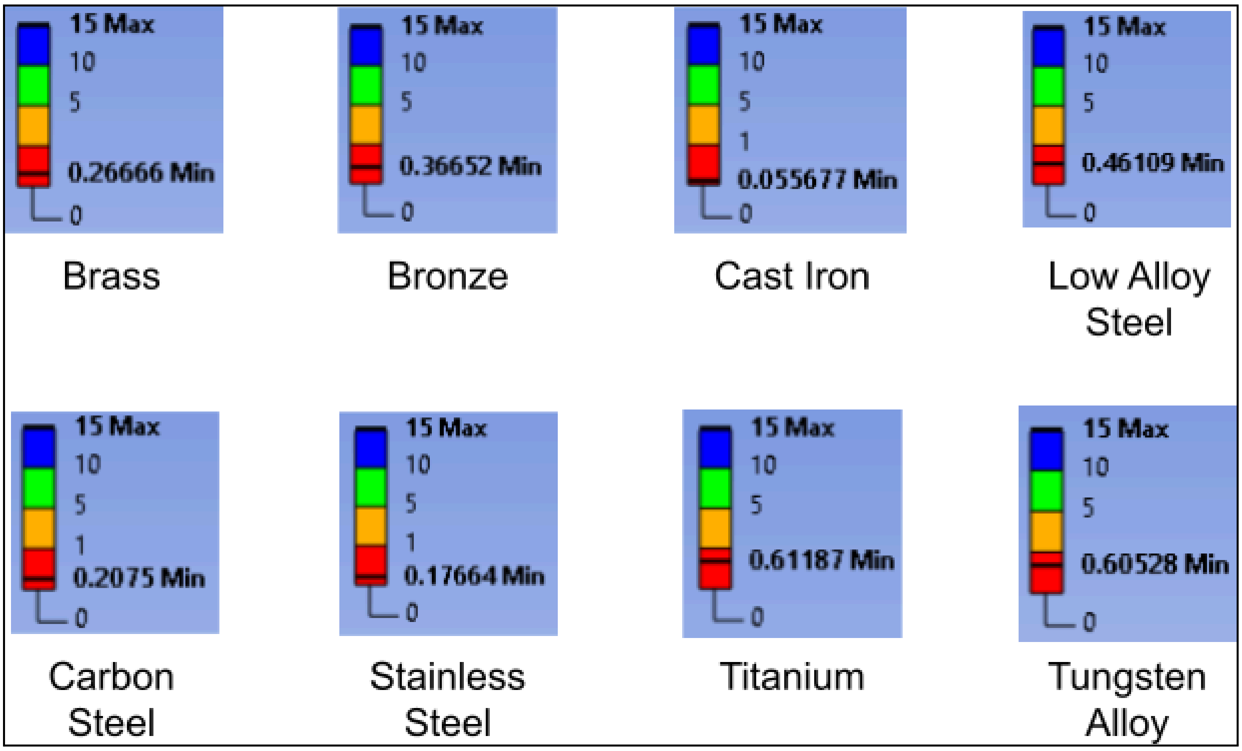


Figure 4.3.6b - FEA Safety Factor Results

For the base material interestingly the minimum safety factor is (0.729), this indicates that the material is the most safe of all the materials. On the other hand it shows us the design is potentially flawed, failing at the point of maximum stress, because the material is backed by multiple sources, it only leaves the simulation set-up or the overall design of the gear set to blame.

4.4 Low Alloy Steel and Tungsten Alloy In-depth Analysis

Table 4.4a - FEA Performance Index

Total Deformation (mm)	Equivalent Von Mises Stress (MPa)	Shear Stress (MPa)	Normal Stress (MPa)	Shear Strain (mm/m)	Safety Factor	Total	
9	10	5	10	5	5	**44**	**BRASS**
8	9	4	2	5	4	**32**	**BRONZE**
10	8	3	0	5	10	**36**	**CAST IRON**
3	1	2	0	2	3	**11**	**LOW ALLOY STEEL**
3	6	2	0	2	6	**19**	**CARBON STEEL**
4	5	3	0	2	7	**21**	**STAINLESS STEEL**
7	3	4	0	4	1	**19**	**TITANIUM ALLOY**
1	4	1	0	1	1	**8**	**TUNGSTEN ALLOY**

Table 4.4a above displays a performance index where each material is rated based on their respective FEA performance, where a lower number is a rating of better performance and a larger number is an indication of a worse performance. Shear Stress and Shear Strain are only rated between 1 - 5 as the FEA results have shown all materials are more than capable to handle shear focus, therefore the “punishment” of receiving a higher rating seemed unnecessary. All other analysis factors are rated between 0 - 10. Using this performance index it is clear that Low Alloy Steel and Tungsten Alloy are the two best performers, therefore an in-depth analysis of these materials is required.

Table 4.4b - Material Data Sheet

Material Grade	18 NiCrMo 7-6	AISI 5160	Tungsten-Rhenium Alloy W-25Re	
Material Type	**Low Alloy Steel**	**Low Alloy Steel**	**Tungsten Alloy**	Units
Price				
Price	1.19	1.02	258	£/kg
Price per Volume	9270	7975	5085000	£/m^3
Physical Properties				
Density	7865	7850	19700	kg/m^3
Mechanical Properties				
Young's Modulus	200	209	400	GPa
Yield Strength	1034	1795	1590	MPa
Tensile Strength	1158	2225	1725	MPa
Compressive Strength	614	1795	1590	MPa
Hardness - Vickers	589	628	518	HV
Fatigue Strength at 10^7 cycles	390	748	795	MPa

Fracture Properties				
Fracture Toughness	72	37	135	MPa×$\sqrt{m}$
Thermal Properties				
Thermal Expansion Coefficient	12	12.25	4.5	μstrain/ºC
Manufacturability				
Metal Hot Forming	Excellent	Excellent	Limited use	
Machining Speed	22.6	7.32	3.35	m/min
Weldability	Good	Poor	Good	
Environmental Impact				
CO_2 Footprint	1.845	1.125	201.5	kg/kg
Recycle	Yes	Yes	Yes	
CO_2 Footprint (Recycling)	0.619	0.5675	18.8	kg/kg
Downcycle	Yes	Yes	Yes	

Table 4.4b above utilities Granta Edu pack once again, where data has been collected for the highest performing grades of the materials mentioned above, along with the base material found in literature so comparisons can be made assessing each material property.

4.4.1 Material Suitability

When considering density specifically, there are both advantages and disadvantages to using a more dense material. McQueen (2020) states that typically, more dense materials tend to have higher strength and fatigue resistance. Where this may be true generally, this is not the case between the three materials in table 4.4b as AISI 5160 the least dense material, has the highest yield, tensile and compressive strength. The tungsten alloy is considerably the most dense material but offers an increase in strength over the base material 18 NiCrMo7-6.

Spera and American Society Of Mechanical Engineers (2009) suggest, one of the main drawbacks of using dense materials is their higher weight, increasing the structural requirements of the tower and foundation, as well as transportation and installation costs of the wind turbine. Therefore, the tungsten alloy poses a massive disadvantage.

Materials with good machinability are easier to shape and form into complex geometries, such as gear teeth profiles, selecting a material with good machinability can facilitate the manufacturing process, reduce production time, and lower costs. In addition, when the gearbox is assembled various components may need to be welded together during manufacturing or even maintenance. Considering these factors the three materials in table 4.4b above provide mixed results, the base material offers excellent ability under metal hot forming, and good ability under weldability, which is the best of the options. Whereas, AISI 5160 falls short in weldability and tungsten alloy falls short in metal hot forming.

The suitability of materials can be significantly influenced by their CO_2 footprint, recyclability, and downcycle-ability due to the increasing importance of environmental sustainability in material selection. Lenzen and Munksgaard (2002) suggest the production of materials with a lower CO_2 footprint typically requires less energy, contributing to reduced greenhouse gas emissions, they also are often produced using sustainable practices, aligning with the green credentials of the wind energy industry. From table 4.4b, both low alloy steels offer a significantly lower CO_2 footprint than tungsten alloy, but it is the AISI 5160 steel grade that offers the lowest, making it the most suitable in this category.

Jensen (2018) states that recyclable materials can reduce the lifecycle cost of wind turbine gears since the material retains value at the end of its service life, again adding to sustainable practices required in today's world. Downcycling can also contribute to a circular economy, minimising the environmental impact by repurposing the material. From table 4.4a, all materials can be recycled and downcycled indicating the benefits of each one.

Liu et al. (2019) propose hard materials can resist surface wear better than softer ones, which is crucial for gears that need to maintain precise tooth profiles over many cycles of use. It also correlates with an ability to withstand surface pressure without deformation. From table 4.4b, AISI 5160 steel has the highest value of hardness with tungsten alloy possessing the lowest, indicating AISI 5160 steel is the best choice to resist surface wear and deformation.

Wang et al. (2019) argue wind turbine gear systems experience variable and cyclic loads due to changing wind speeds, therefore materials with high fatigue strength can endure these loads without failure, contributing to the longevity of the gears, leading to less frequent maintenance and replacements. From table 4.4b, it is the tungsten alloy with the highest fatigue strength with AISI 5160 steel close behind, notably both possess a much higher strength over the baseline material, suggesting either option would be an improvement.

Fracture toughness indicates a material's ability to resist the propagation of cracks, a high value provides a margin of safety, ensuring that even if a crack forms, it does not lead to immediate gear failure (Bai et al., 2020). From table 4.4b, it is the tungsten alloy with the highest fatigue strength, but AISI 5160 steel has the lowest value. This indicates only the tungsten alloy would better the base material.

Lagow (2016) demonstrates materials with a low coefficient of thermal expansion will have minimal size changes with temperature fluctuations, maintaining gear alignment and meshing accuracy. In addition, it reduces the risk of thermal stresses building up in the material, which can lead to warping, fatigue, or fracture over time. From table 4.4b, it is the tungsten alloy that massively outperforms the other materials, suggesting the material is the best option under this criteria.

4.4.2 Cost-Benefit Analysis of Material Selection

Table 4.4.2 - Material Performance Index

Material Type	**Low Alloy Steel**	**Low Alloy Steel**	**Tungsten Alloy**
Material Grade	**18 NiCrMo 7-6**	**AISI 5160, hardened and tempered at 205°C**	**Tungsten-Rhenium Alloy W-25Re**
Price	2	3	1
Price per Volume	2	3	1
Density	2	3	1
Young's Modulus	1	2	3
Yield Strength	1	3	2
Tensile Strength	1	3	2
Compressive Strength	1	3	2
Hardness - Vickers	2	3	1
Fatigue Strength at 10^7 cycles	1	2	3
Fracture Toughness	2	1	3
Thermal Expansion Coefficient	2	1	3
Metal Hot Forming	2	2	1
Machining Speed	3	2	1
Weldability	2	1	2
CO2 Footprint	2	3	1
Recycle	2	2	2
CO2 Footprint (Recycling)	2	3	1
Downcycle	2	2	2
Total	**32**	**42**	**32**

The above table 4.4.2 scores each criteria, where 1 being least favourable and 3 the most favourable, scores are then totaled for each material. It can be clearly seen that AISI 5160 offers the best balance of properties, manufacturability, environmental sustainability, and cost. Although there are some trade-offs which provide a reason to consider other materials. AISI 5160 compared to 18 NiCrMo7-6, only falls short on fracture toughness, thermal expansion coefficient, and weldability. Therefore, if these criteria are of utmost priority then one of the other materials may be more suitable.

The tungsten alloy outperforms under fatigue strength, fracture toughness, and thermal expansion coefficient, this decreases the need for regular maintenance extending the life of the component, ultimately reducing the lifetime cost of using the material. These are areas where AISI 5160 underperforms, suggesting the tungsten alloy may outperform for certain applications. Overall these benefits are out-weighed by the tungsten alloys' poor performance in manufacturability and environmental impacts, in addition the massive increase in density and material cost. The increase in weight and limitations in manufacturability could lead to an increase

The base material 18 NiCrMo7-6 performs moderately overall, with no clear advantage over the other materials. Although the cost and density is significantly less than the tungsten alloy, AISI 5160 is less expensive and dense, performs better in mechanical and physical properties, and has slightly less impact on the environment. Zorgani (2009) studies more than 50 steels for various applications, one of which is manufacturing gears. In the study he concludes AISI 5160, hardened and tempered at 205^{o}C, is ranked the best for fatigue strength, 4th under ranking of wear resistance, and 3rd against cost to benefit analysis. He concludes the material is one of the highest overall performers and should be especially considered for applications that require a material with a high fatigue strength. This in turn validates my final results which suggest AISI 5160 as the best material for the application.

5. Discussion

5.1 Achieved Project Aims and Objects

The project successfully met its aim by systematically addressing performance, through material selection and simulation testing and analysis, the project identified materials that potentially offer better performing materials such as AISI 5160 and Tungsten Rhenium Alloy. The analysis highlighted potential materials which would enhance the reliability of a wind turbine gearbox, through an increase of fatigue strength and fracture toughness. By integrating a cost-benefit analysis, the project assessed the economic viability of the shortlisted materials, considering not only raw material costs but also long-term savings from reduced maintenance and longer service life. This approach provided some advancement towards wind turbine technology with a focus on sustainability, setting the foundations for future innovations. A discussion on how each objective was met follows.

Research was conducted to understand the current state of gear materials used in wind turbine gearboxes. This included reviewing existing literature and industry standards to identify critical performance criteria for gearbox materials. This initial research phase established a strong foundation for material selection and testing phases, enabling a focused approach toward optimising a wind turbine gear system.

The industry standard material, 18 CrNiMo 7-6, was identified and used as a benchmark for comparing new materials. Using an established industry benchmark enabled a clear comparison framework, setting a target for improvements.

Utilising Granta EduPack software, in conjunction with the literature review, a range of materials were evaluated, and several were identified as potential candidates to improve performance, reliability and cost-effectiveness. The software enabled an effective assessment of numerous materials based on performance criteria, leading to a data driven selection process.

FEA using ANSYS Static Structural was employed to simulate operational stresses, strains, deformation and factors of safety. This helped validate their performance under realistic load conditions.The simulations provided critical insights into the mechanical behaviour of each material, highlighting their strengths and potential weaknesses under operational conditions. This testing was crucial for confirming the theoretical advantages proposed by Granta EduPack.

5.2 Critical Review of Methods Used

5.2.1 Material Selection

Strengths

Granta EduPack provides a vast database of materials and their properties, making it a valuable tool for initial material screening. It allows users to compare a wide range of materials based on specific criteria such as mechanical properties, environmental impact, cost, and more. The software is designed with education in mind, making complex material selection concepts more accessible to students. It introduces users to a systematic approach to material selection. Complementing Granta EduPack with academic literature allows for a deeper understanding of material behaviour under specific conditions that might not be fully captured in the database. Literature can provide insights into recent advancements, case studies, and real-world applications of materials.

Weaknesses

While Granta EduPack offers extensive data, it may not always be up to date with the latest material innovations or specific materials. Similarly, literature can vary in quality and relevance, requiring careful selection and critical evaluation to ensure reliability. The complexity of the software's interface and the sheer volume of data available can be overwhelming for new users. Integrating literature effectively into the material selection process requires a solid understanding of both the theoretical background and practical considerations, which can be challenging for those less experienced in research methodologies. In addition, the software may not fully capture the application-specific requirements for material selection. Factors such as manufacturing processes, compatibility with other materials, and local environmental conditions, might require additional investigation beyond what Granta EduPack can offer.

Overall, integrating Granta EduPack in the material selection process offers an excellent approach to the initial material screening, which is fast and effective. However, users must navigate the challenges of data overload, ensuring that their choices are informed by the most current and application-specific information available. This method requires a balance between applied data and critical analysis, underlining the importance of continuous learning and adaptation in the field of materials science and engineering.

5.2.2 Simulation Testing

Strengths

ANSYS FEA provides a powerful platform for predictive modelling, allowing engineers to simulate how different materials respond to physical forces, including stress, strain, deformation, and other environmental effects. This predictive capability is crucial for material selection, as it identifies materials that will perform optimally under expected operational conditions. Besides material selection, ANSYS FEA is significant in design testing and optimisation. By analysing stress distribution, deformation, and other critical factors, engineers can refine designs to improve performance, reduce material usage, and identify potential failure points before physical prototypes are developed. Using FEA for material selection and design testing can lead to significant savings in both time and cost. Simulations can replace or reduce the need for physical testing, speeding up the development cycle and allowing for the exploration of a wider range of materials and design configurations without the expense of fabricating multiple prototypes.

Weaknesses

One of the main challenges of using ANSYS FEA is its complexity. Successful simulations require a deep understanding of both the software and the principles of finite element analysis. Misinterpretation of results or incorrect simulation setups can lead to misleading outcomes, potentially guiding material selection and design decisions in the wrong direction. Running simulations requires a high amount of computational resources, especially those involving complex geometries or advanced material models. This can limit the speed at which simulations are performed and results are obtained, impacting project timelines. In addition, the accuracy of FEA simulations heavily depends on the availability and quality of material property data. Incomplete or inaccurate data can compromise simulation results, making it challenging to reliably select materials based solely on simulation outcomes.

6. Conclusions and Future Work

6.1 Conclusions

The project successfully identified materials that could potentially enhance the reliability and efficiency of wind turbine gearboxes, whilst reducing cost. Using Granta EduPack for preliminary selection and ANSYS for detailed simulation testing, AISI 5160 steel and Tungsten Alloy were found to offer better mechanical properties compared to the standard industry material, 18 CrNiMo7-6.

The project objectives to optimise the material for improved gearbox performance were met with significant insights. However, while the materials showed promising mechanical properties in simulations and via data sheets supplied by Granta, real-world applications might vary due to environmental and operational conditions not fully replicated in the simulations.

6.2 Relevance and Impact

This research directly contributes to the sustainability of renewable energy sources by potentially reducing the frequency of gearbox failures, which are costly and detrimental to wind turbine efficiency. By enhancing gear reliability, the project supports broader adoption of wind energy, reducing reliance on fossil fuels and the effects of climate change.

Society and environment benefit from the improved gear material could lead to more durable wind turbines, reducing waste and energy consumption associated with maintenance and materials production. This aligns with global efforts toward sustainable energy and reduced environmental footprint.

6.3 Limitations of Research

1. **FEA Model Assumptions:**
    a. **Limitation:** FEA relies heavily on the assumptions made during the modelling process, including load distributions, material uniformity, and boundary conditions. These assumptions may not perfectly capture the real-world complexities of wind turbine operations.
    b. **Implications:** The results might overestimate or underestimate the actual performance of the materials under operational conditions. This affects the validity and potential transferability of the findings to other similar applications or slightly varied operating conditions.
2. **Material Data Variability:**
    a. **Limitation:** Material properties such as yield strength and ultimate tensile strength can vary significantly depending on the source and treatment of the material. The range of values for properties like compressive strength in materials such as bronze and cast iron also introduces uncertainty into the analysis.
    b. **Implications:** There's a risk that the chosen values do not represent the worst-case or typical scenarios, potentially leading to incorrect conclusions about the material's suitability.
3. **Static Structural Load Analysis:**
    a. **Limitation:** The analysis primarily considered static loads, which may not fully represent the dynamic and cyclic loading conditions that gears in a wind turbine gearbox typically experience.
    b. **Implications:** This limitation could lead to an underestimation of fatigue failure risks, impacting the longevity and reliability predictions for the gear system.

4. **Gearbox Model**
    a. **Limitation:** In real-world applications, a wind turbine gearbox has multiple interlocking gears along with bearings, shafts, and housing, all of which contribute to the system's overall dynamic and structural behaviour. By focusing FEA on just a single pair of gears, many interactions that might significantly affect the stresses and strains experienced by each component have been excluded.
    b. **Implications:** This limitation could lead to an underestimation or overestimation of stress concentrations and load distributions. For instance, adjacent gears and their interactions can distribute loads differently, potentially affecting stress on the gears analysed. The findings from your FEA might not fully translate to operational conditions within a complete gearbox.

6.4 Recommendations for Future Research

1. **Dynamic Load Analysis:**
    a. **Recommendation:** Conduct dynamic FEA that includes fatigue analysis under variable loading conditions typical of wind turbine operations. This should involve the use of more sophisticated FEA models that incorporate load spectrum data from actual turbine operations.
    b. **Link to Limitation:** Directly addresses the limitation of using static load analysis by providing a more realistic simulation environment.
2. **Material Variability Studies:**
    a. **Recommendation:** Perform verifiable testing on materials to obtain specific mechanical properties for the actual materials used in production. This could include tensile, compressive, and fatigue testing under controlled conditions to better define the material properties used in FEA.

b. **Link to Limitation:** Responds to the limitations related to material data variability, ensuring the analysis is based on precise, application-specific material data.

3. **Enhanced Material Modelling:**
    a. **Recommendation:** Incorporate microstructure-based modelling in FEA to predict how microstructure features affect material behaviour under different loading conditions.
    b. **Link to Limitation:** Enhances the FEA model assumptions by incorporating detailed material behaviour, reducing the gap between theoretical analysis and real-world performance.
4. **Gearbox Modelling:**
    a. **Recommendation:** Future studies should aim to incorporate full gearbox simulations that include all gears, bearings, shafts, and housings. Cho et al., (2013) suggest this approach would provide a more accurate depiction of the gearbox dynamics and stress responses under operational conditions.
    b. **Link to Limitation:** Directly addresses the study’s limitation by expanding the scope of the FEA to include all critical components, enhancing the validity and applicability of the simulation results.
5. **Component Interaction Study:**
    a. **Recommendation:** Conduct research focused on the interaction effects between multiple gears and other components within the gearbox. This could involve looking at how load distribution changes with different gear arrangements or operational conditions.
    b. **Link to Limitation:** This would mitigate the limitation related to neglecting inter-component dynamics and would provide insights into how these interactions impact gearbox performance.

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Appendix A: Ethical Disclaimer Form

RESEARCH ETHICS

Disclaimer Form

STAFFORDSHIRE UNIVERSITY

The following declaration should be made in cases where the researcher and the supervisor (where applicable) conclude that it is not necessary to apply for ethical approval for a specific research project.

PART A: TO BE COMPLETED BY RESEARCHER

Name of Researcher:	Nicholas Hawkins
School	Staffordshire University

Student/Course Details (If Applicable)			
Student ID Number:		19021457	
Name of Supervisor(s)/Module Tutor:		Andrew Cash	
PhD/MPhil project:	☐		
Taught Postgraduate Project/Assignment:	☐	Award Title:	BEng(Hons) Mechanical Engineering
Undergraduate Project/Assignment:	☒	Module Title:	Individual Engineering Project

Project Title:	The investigation and optimisation of a wind turbine gearbox.		
Project Outline:	This project investigates wind turbines and the gearboxes currently used. A comprehensive review of exisiting literature is made on wind turbine gearboxes, followed with simulation modelling and testing. Optimisation objective are to improve material choice, design enhancements, whilst accessing cost benefit. Summary of results is then given with potential impact on the wind industry.		
Give a brief description of research procedure (methods, tests etc.)	Literature Review of existing literature related to wind turbine gearboxes. Problem identification, analyse data on performance, failures, and maintenance. Research and evaluate materials suitable for wind turbine gearboxes. Explore design enhancements. Model and simulate optimised features using software. Analyse results and prepare detailed report.		
Expected Start Date:	24/11/2023	Expected End Date:	01/05/2024

Declaration

I/We confirm that the University's Ethical Review Policy has been consulted and that all ethical issues and implications in relation to the above project have been considered. I/We confirm that ethical approval need not be sought. I/We confirm that:

The research does not involve human or animal participants	☒
The research does not present an indirect risk to non-participants (human or animal).	☒
The research does not raise ethical issues due to the potential social or environmental implications of the study.	☒
The research does not re-use previously collected personal data which is sensitive in nature, or enables the identification of individuals.	☒
Has a risk assessment been completed for this project?	☒ Yes

University Research Ethics Committee – February 2018

☐ N/A

Signature of Researcher:	Nicholas Hawkins	Date:	14/11/2023
Signature(s) of Project Supervisor(s) (If student) OR Signature of Head of Department/ Senior researcher (if staff)		Date:	17/11/23

NB: If the research departs from the protocol which provides the basis for this disclaimer then ethical review may be required and the applicant and supervisor (where applicable) should consider whether or not the disclaimer declaration remains appropriate. If it is no longer appropriate an application for ethical review **MUST** be submitted.

Appendix B: Risk Assessment Form

STAFFORDSHIRE UNIVERSITY

GENERAL RISK ASSESSMENT FORM

Severity multiplied by **Likelihood** equals **Risk Rate**.

NB: Calculated after taking in to account existing precautions

School/Service: Staffordshire University - DTA	
Task/Activity/Area: Computer based modelling and simulation, general write up, and 3D printing.	
Assessed By: Andrew Cash	Signature:
~~Dept Manager: (Print Name)~~	~~Signature:~~
Date of Assessment: 14/11/2023	Review Date:

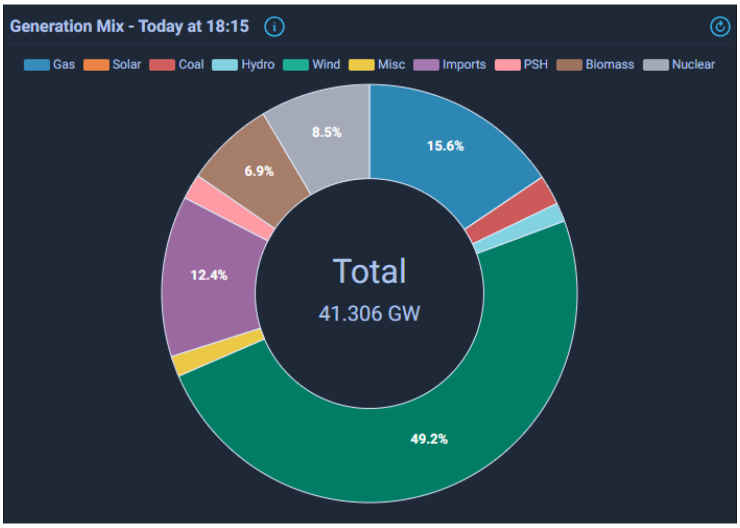
Likelihood \ Severity	Insignificant (1)	Minor (2)	Moderate (3)	Serious (4)	Fatal / Critical (5)
Almost Certain (5)	5	10	15	20	25
Likely (4)	4	8	12	16	20
Possible (3)	3	6	9	12	15
Unlikely (2)	2	4	6	8	10
Rare (1)	1	2	3	4	5

	Activity/Process/Machines	Hazard	Persons in Danger	Severity 1-5	Likelihood 1-5	Risk Rate	Measures/Comments	Result
1	Computer Aided Design Modelling and Simulation/General Write-up	Repetitive strain injuries, eyestrain, musculoskeletal disorders.	Nicholas Hawkins	3	3	9	Employ ergonomic workstations and encourage regular breaks to reduce the risk of injuries.	A
2	Computer Aided Design Modelling and Simulation/General Write-up	Electrical Hazards	Nicholas Hawkins	4	2	8	Regularly inspect and maintain equipment and ensure compliance with electrical safety standards.	A
3.	Computer Aided Design Modelling and Simulation/General Write-up	Cyber Security Risks	Nicholas Hawkins	3	1	3	Implement robust cybersecurity measures, including secure networks, and regular updates to software.	A

	Activity/Process/Machines	Hazard	Persons in Danger	Severity 1-5	Likelihood 1-5	Risk Rate	Measures/Comments	Result
4	Computer Aided Design Modelling and Simulation/General Write-up	Physical Environment, Poor Ventilation and Inadequate Lighting	Nicholas Hawkins	1	2	2	Ensure a safe and comfortable working environment.	A
5	3D Printing	Exposure to Particulate Matter	Nicholas Hawkins	3	3	9	Use appropriate personal protective equipment (PPE).	A
6	3D Printing	Burn and Fire Hazards	Nicholas Hawkins	3	2	6	Implement safety features on printers, use of proper electrical setup, and fire extinguishing equipment.	A
7	3D Printing	Electrical Hazards	Nicholas Hawkins	4	2	8	Regularly inspect and maintain equipment and ensure compliance with electrical safety standards.	A
8	3D Printing	Post-Processing Risks	Nicholas Hawkins	2	2	4	Use of PPE, such as respiratory protection and eye protection. Perform in well-ventilated areas.	A

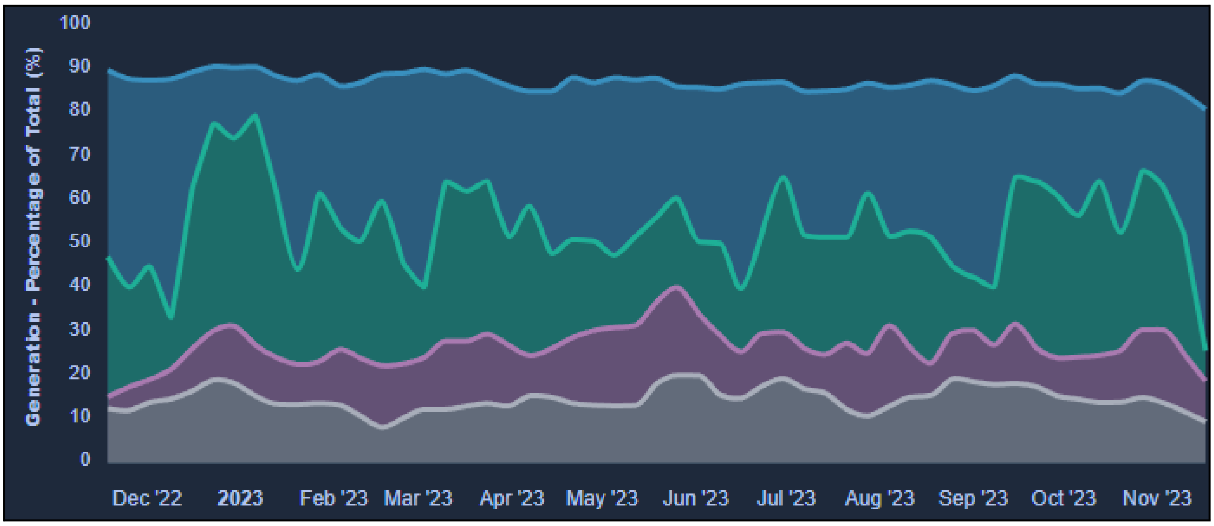
Key to result T = Trivial Risk **A** = Adequately Controlled **N** = Not Adequately Controlled **U** = Unable to decide (further information required).

Appendix C: Live Energy Dashboard - Generation Mix



Energy Dashboard (2023).

Appendix D: Energy Dashboard - Generation Percentage of Total



Energy Dashboard (2023).

Appendix E: Gearbox Design and Dimensioning

3.1.12 Results

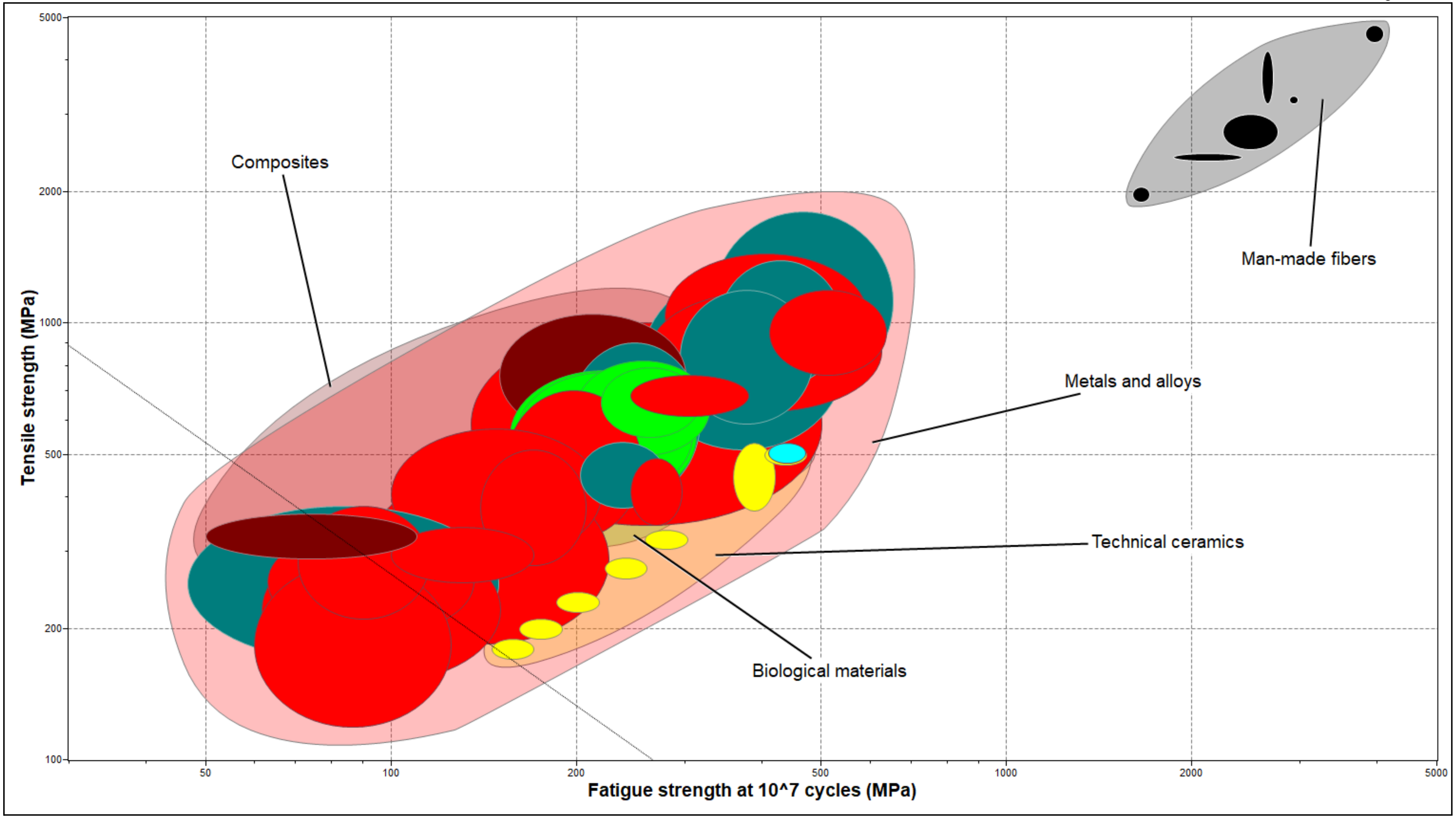
Table 3.15: First gear stage dimensioning results from KISSsoft® regarding the nominal rated power.

		Sun	Planets	Ring
Power	**kW**		2000	
Speed	**rpm**	77.9	39.9	0
Speed planet carrier	**rpm**		15	
Number of teeth	**-**	26	41	109
Normal module	**mm**		16	
Overall transmission ratio	**-**		5.18:1	
Center distance	**mm**		566	
Facewidth	**mm**	265	256	265
Pressure angle at normal section	^{o}		20	
Helix angle at ref. circle	^{o}		15	
Accuracy grade	**ISO1328:1995**	6	6	7
Reference diameter	**mm**	430.7	679.1	1805.5
Tip diameter	**mm**	473.8	720.7	1790.3
Material	**DIN**	18 CrNiMo 7-6		42 CrMo 4
Heat treatment		Case-carburized		Flame hard.
Surface hardness	**HRC**	61		56
Profile shift coefficient	**-**	+0.3934	+0.3457	-0.5244
Sum of profile shift coef.	**-**	+0.7391		-0.1786
Specific sliding at the tip	**-**	0.488	0.488/0.167	0.195
Specific sliding at the root	**-**	-0.952	-0.952/-0.242	-0.201
Circumf. speed at tip circle	**m/s**	1.506	1.933	0
Transverse contact ratio, ϵ_α	**-**	1.424		1.650
Overlap ratio, ϵ_β	**-**	1.318		1.318
Total contact ratio	**-**	2.742		2.968
Safety f/ tooth root stress*, S_F	**-**	2.12	1.44/ 1.72	2.06
Safety f/ pitting resistance* , S_H	**-**	1.26	1.32/ 2.79	2.26
Safety f/ scuffing resistance* , S_B	**-**	3.746		28.909
Mass	**kg**	313.397	739.722	924.625
Total mass	**kg**		3457.187	
Mean friction coef. by Niemann	**-**	0.041		0.029
Wear sliding coef. by Niemann	**-**	0.694		0.302
Gear power loss	**kW**	2.680		0.573
Total power loss	**kW**		9.760	
Total efficiency	**%**		99.5	

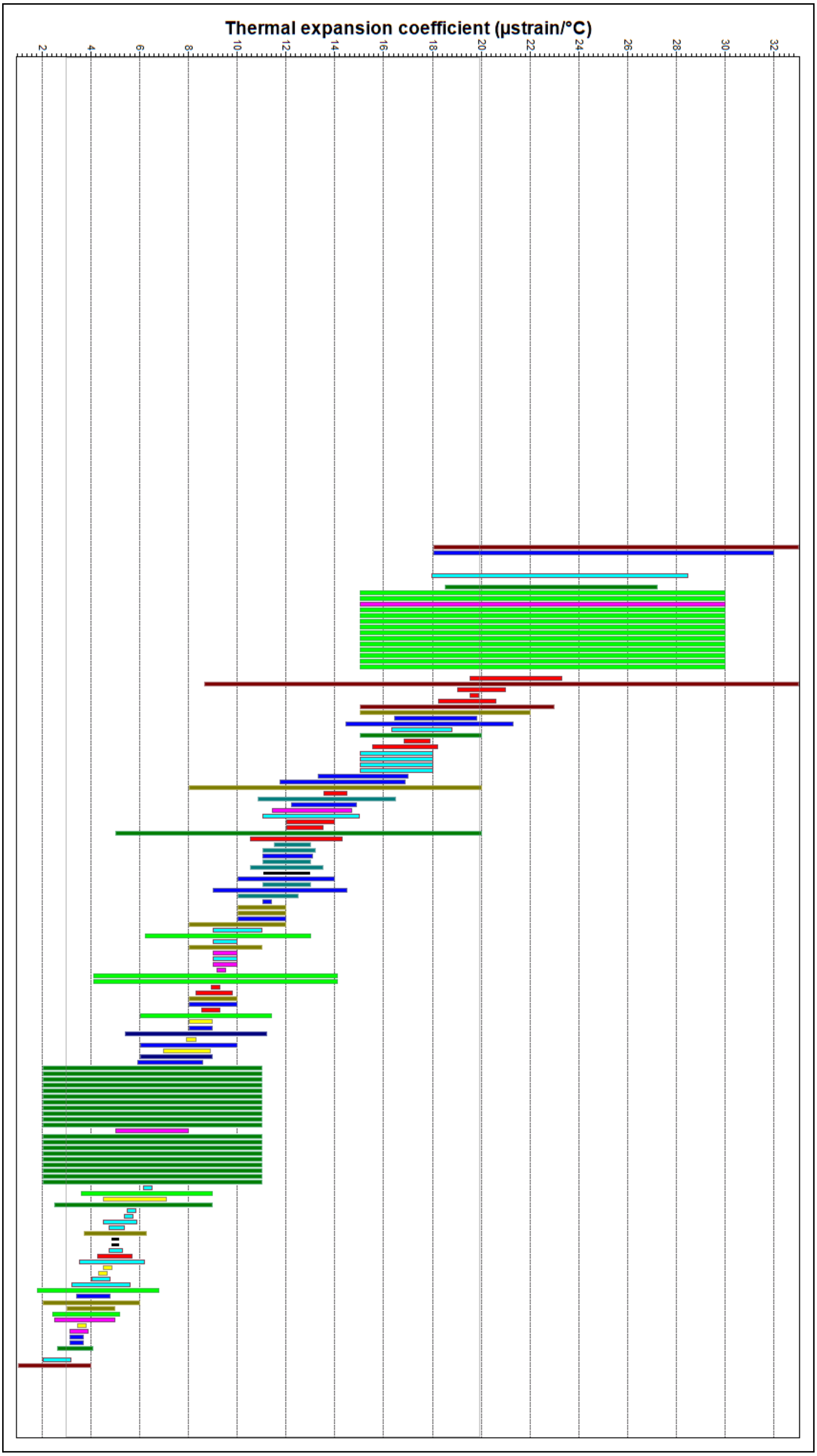
* Safety coefficient according to the nominal load, without considering any load spectrum. The final solution can be consulted in Section 4.1.1 of the optimization chapter.

(Meda de Sousa, 2017)

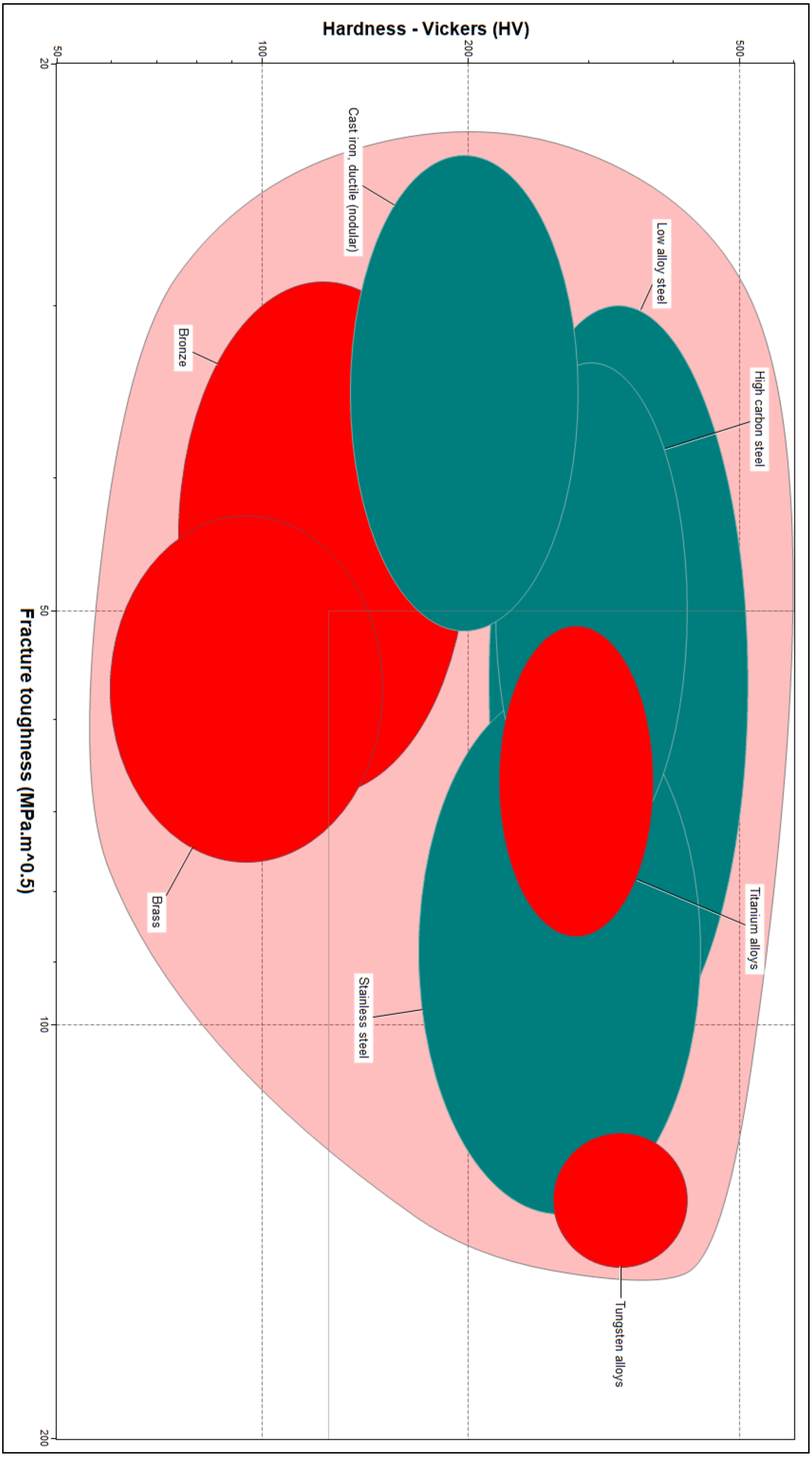
Appendix F: Granta EduPack Stage 1 Graph


Composites
Man-made fibers
Metals and alloys
Technical ceramics
Biological materials
Tensile strength (MPa)
Fatigue strength at 10^7 cycles (MPa)
5000
2000
1000
500
200
100
50
100
200
500
1000
2000
5000

Appendix G: Granta EduPack Stage 3 Graph


Thermal expansion coefficient (μstrain/°C)
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

Appendix H: Granta EduPack Stage 4 Graph



Hardness - Vickers (HV)
Fracture toughness (MPa.m^0.5)
50
100
200
500
20
50
100
200
Cast iron, ductile (nodular)
Low alloy steel
High carbon steel
Bronze
Brass
Titanium alloys
Stainless steel
Tungsten alloys