CSVTU Research Journal
Vol. 10(2), 173-183, 2021 ISSN: 0974-8725

Research Article

Finite Element Analysis of Mg Alloy Based Gear Set Using ANSYS

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Received November, 2021; Received in revised form December 25, 2021; Accepted December 28, 2021, Published 2021

Abstract

Now magnesium alloy is the lightest metal materials of in engineering application, it has a wide application in automobile sector, aerospace, biomedical and other fields. Magnesium alloy gear is utilized in the present research, and a gear-pinon cad model is utilized by utilizing finite element software ANSYS, under loads. In this study, the model is created in ANSYS SpaceClaim and then imported into ANSYS commercial software to calculate the interface stress of mating gears for various materials and compare the findings to the Mg alloy gear. Gears are a common component in engineering and technology, and they have played an important part in power transmission. In most cases, contact stress is the deciding factor in determining the required gear dimensions. The fact that next to has been proven by research on gear action. The most important attribute in gears is the interface stress; it is dictated by the evolution of the model and the material properties; when the material properties change, the contact stress will change as well. Modal analysis and harmonic replication are required for gear system analysis. This project's purpose is to figure out how to recreate the contact stress and frequency of gear for diverse materials. Modal analysis is performed on mode shapes and natural frequencies, as well as harmonic analysis for various materials such as magnesium alloys, cast iron, and aluminium alloys.

Keywords: Mg alloy, FEA, Gear-Pinon Se, Harmonic Analysis, Model Analysis

1. Introduction

Magnesium alloys have been widely used in automotive, aircraft, medical, and other industries due to their cheap weight, density, good categorical vigor, and high damping capability [1]. In example, the magnesium alloy outperforms conventional metal alloys in load-bearing components in car applications such as wheels, gearboxes, and grips from an economic standpoint. In addition, as compared to aluminium alloys and other ferrous materials, the magnesium alloy offers significant weight savings [2]. However, because the cost of a magnesium alloy is limited by its low vigour, wrought magnesium alloys can be used for higher vigour because they produce a vigorous grain refinement with no pores and a uniform composition distribution after the elongation process [3]. The magnesium is the lightest material (from 1.74 g/cm3 to 2.0 g/cm3 range), being 77 % lighter than steel and 33 % lighter than aluminum. The material engineers verbally express thanks to the magnesium alloy because of its great vigor-to-weight ratio. In automotive and aerospace applications, it shows better performance due to its stiffness, high damping capacity and excellent machining performance [4-8]. However, because the cost of a magnesium alloy is limited by its low vigour, wrought magnesium alloys can be used for higher vigour because they produce a vigorous grain refinement with no pores and a uniform composition distribution after the elongation process [9]. In the air environment, however, Mg alloys have excellent fatigue resistance; in fact, it is nearly unaffected by industrial requirements [10]. When compared with the aluminum corrosion resistance of modern high-purity magnesium alloys, they are better than that of conventional aluminum die-cast alloys. Mg and its alloys for automotive applications are typically manufactured by a casting method [11]. Table 1 shows the application of Mg alloys in the automobile industry.

Table 1 Use of Mg alloys in the automobiles

S. No	Organizations	Items
1	Volkswagen, BMW, Ford, Audi, Mercedes Benz,	Transmission Casings
2	Honda, BMW, Ford, Volvo, Hyundai, KIA,	Cylinder Head Cover
3	Ford, Toyota, BMW, Lexus, GM	Steering Components
4	BMW	Engine Block
5	Toyota, Porsche, Marti Suzuki	Wheels/Rims
6	Mercedes Benz, Lexus, Hyundai, KIA	Seat Frame

1.1 The production process of Mg alloy

The electrolyte method, thermal reduction methods are the most common methods for extracting metallic magnesium. The electrolyte method following Dow process and electron process is the most cost-effective and widely used; its only drawback is that it requires a high-purity cell victual. It is fairly simple to use the thermal truncation method, but it has significant economic disadvantages, such as high labour and maintenance costs.

1.2 Manufacturing process

Gravity and pressure die casting methods, such as sand, sempiternal and semi-sempiternal mould, and steel and investment casting, are commonly used to produce magnesium alloys. Mg alloy mechanical and thermal properties: Material density and concrete stiffness (weight/deformation), vigour (tensile vigour, yield vigour, etc.) are extremely essential elements in the design of weight-preserving components in car and aircraft applications due to fuel consumption, energy savings, and power constraints. When compared to other materials like aluminum and iron, the Young's modulus and the hardness are lower than aluminum and iron, as given in Table 1. But it is noted that the thermal coefficient factor is maximized. It is a very consequential factor to surmount the vigor and modulus inhibitions. From Table 3 and the above issues Mg alloys have distinct advantages over aluminum. These include better manufacturability and machinability, and because of the lower latent heat it gives more expeditious solidification and a longer die life.

1.3 **Magnesium alloy (Mg alloy)**

To analyse the properties of Mg alloys it is indispensable to describe the sources, relegation, and manufacturing process and advantages, disadvantages predicated on manufacturing process and applications as well as the mechanical properties and thermal properties. Davy acquired impure magnesium for the first time in 1808. Magnesium was first commercially produced in 1866 in Germany, using a modified Bunsen electrolytic cell. The sources from which magnesium is produced in commercially amounts are:

i. Natural brines – $MgCl_2$
ii. Salt water(sea) – $MgCl_2$`+ $MgSO_4$- Mg – 0.13 %
iii. Magnetite – Mg CO_3 – Mg – 28 %

iv. Dolomite – Mg Ca $(CO_3)_2$– Mg 13 %
v. Brucite – Mg $(OH)_2$ – Mg 43 %

Table 3: Properties of Mg, Al and cast iron [12]

Sl. No	Property	Mg alloys	Al alloys	Cast iron
I	Crystal property	hcp	fcc	bcc
2	Density (MG/m^3)	1.74-1.95	25-2.9	7.05-7.25
3	Melting Temperature (°C)	447-649	475-617	1130-1250
4	Youni's modulus *E* (GPa)	41-47	68-82	165-180
5	Yield strength (MPa)	70-400	30-500	215-790
6	Tensile strength (MPa)	185-475	*58-550*	350-1000
7	Fracture toughness	12-18	12-35	22-53
8	Thermal conductivity (W/mK)	50-156	76-235	2944
9	Thermal expansion (10^{-6}/°C)	24.6-28	21-24	10-12.4

1.4 Advantages & limitations of Mg Alloy

Below are the benefits and drawbacks of magnesium alloys over traditional alloys such as stainless steel, aluminium, titanium, plastics, and natural fibres.

Benefits of magnesium alloys are listed below:

• Lowest density of all metallic constructional materials

• Provides maximum acceleration due to lower density

• High specific strength

• Good cast competency, ideal for high-pressure die casting

• Can be turned and milled at high speeds

• Good weldability

• Much improved corrosion resistance using high-purity magnesium

Better mechanical qualities when compared to polymeric materials

– Senescent-resistant

– Improved thermal and electrical conductivity

– Recyclable

Compared with Aluminium:

– It has a low latent heat, allowing for greater casting per unit time.

– It has a better surface polish and dimensional ability.

- Curved surfaces and a smaller draught angle.

- Exceptional specific strength (14 percent higher than Al alloy)

The Table 4a) describes the environmental resistance of magnesium alloys, aluminium alloys and cast iron [13].

Table 4a) Environmental resistance of Alloys

Sl. No.	Mate rial	Flamm ability	Salt water	Sun light	Wear resistance
1	Mg Alloy	very good	poor	very good	average
2	Al Alloy	good	good	very good	average
3	Cast Iron	very good	avera ge	very good	very good

2. Methodology

2.1 FEM Steps

Pre-processing

Pre-processing is the first step in the FEM. It involves defining model geometry, deciding element form, and breaking the geometry down into components. After that, the physical properties of the elements should be defined. The process of determining the element's size and creating connectivity between the elements is known as meshing. Boundary conditions are then created. this process is known as meshing. Then boundary conditions are specified. Then apply the loads on the form.

Solution/Processing

Equations are generated in matrix form and are algebraic during this process. The matrices are solved for the values of unknown field variables. Stresses are determined once the primary field variables are known as the derived variables powers.

Post processing

Post processing is the method of analysing the findings obtained. This move entails sorting the outcomes. The required results are sorted and evaluated at this level. In this step, the final task of printing and presenting the results takes place.

2.2 Design of Spur Gear

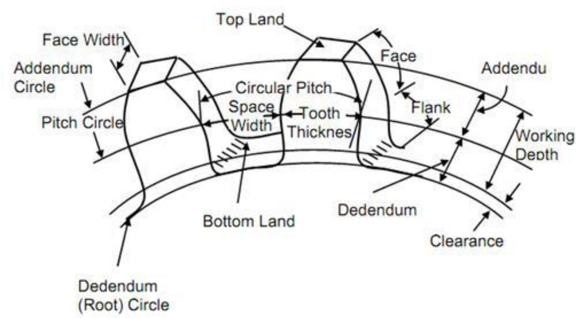

Fig 1 Gear Nomenclature

Radial disunion between the Pitch Circle and the apex of the teeth is an addendum. On cross section gear, clearance is the distance between the apex of a tooth and the base of the space into which it fits. The radial distance between the bottom of the space between teeth and the top of the teeth is known as the dedendum (Figure 1).

Table 4b) Specification of gear sets

S. no	Parameter	Gear	Pinion
1	No. of teeth	20	12
2	Module	2	2
3	Pressure angle	20	20
4	Pitch dia.	40	24
5	Face width	15 mm	15 mm
6	Addendum	44.02	28.03
7	Dedendum	35.5	19.52
8	Centre distance	32	
9	Torque	250 Nm	

Specification of gear sets used:

Radial disunion between the Pitch Circle and the apex of the teeth is an addendum. On cross section gear, clearance is the distance between the apex of a tooth and the base of the space into which it fits. The radial distance between the bottom of the space between teeth and the top of the teeth is known as the dedendum. Parameters considered are presented in Table 4b).

2.3 Geometry CAD Design

Parametric 3D CAD model of gear set created in ANSYS SpaceClaim and then important in ANSYS workbench for the analysis.

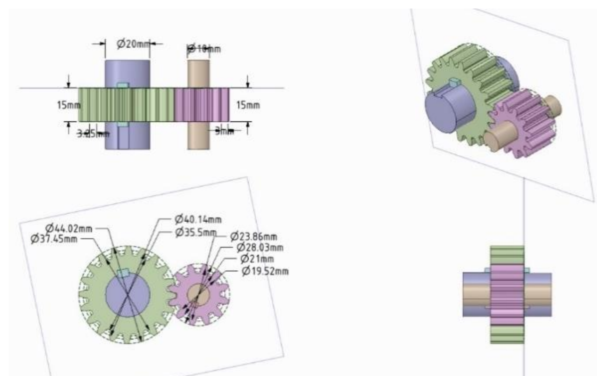

Figure 2 Gear set CAD model

This process is the same for both gear and pinion; after importing both driver and driven gears, use congruous contact implements to bring the gear and pinion teeth into contact, as illustrated in the diagram (Fig 2).

2.4 Meshing

Analysis of the model meshing is a crucial stage; fine mesh is required for accurate results. Making fine mesh for a full model takes a long time, and achieving precise fine mesh takes much longer, therefore turn the full model into a sub model to save time (Figure 3).

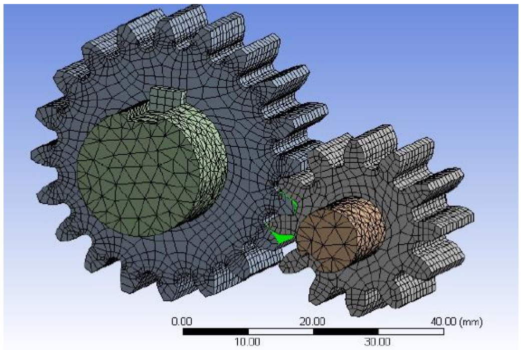

Fig. 3 Meshing geometry

3. Application of Mg alloys based on a FE analysis

All three materials possess very good mechanical properties among the Mg, Al, and cast-iron group of materials, FEA in ANSYS workbench software was used to explore the mechanical behaviour of Mg alloys and compare them to Al and cast-iron materials.

Table 5 (a) Material details of Mg, Al and cast iron

Properties	Unit	Mg	Al	Cast iron
Density	kg/m^3	1700	2700	7500
Modulus of elasticity (E)	GPa	46	70	180
Poisson's ratio	-	0.3	0.33	0.29
Yield Strength (Tensile)	M Pa	310	216	200
Tensile strength (Ultimate)	M Pa	230	370	310

The purpose of this paper is to investigate utilization of Mg alloy for gears. Table 5 a) lists the mechanical parameters of all three materials. The materials and the compositions of all the three materials are given in Table 5b. This research compares three materials in spur gear based on FE analysis variants such as modal vibration and fatigue analysis under various stress situations. One of the most important factors in the design of spur gears is the material. The material can determine how much vibration it can sustain and whether or not the information rush will generate reverberation. All of these are dependent on the expected frequencies, which ANSYS Workbench takes into account. If the gears system is subjected to dynamic action, vibration will result. Mode forms, natural frequencies, and harmonic analysis are used to determine this vibration.

Table 5 (b) Materials and composition

S. No.	Alloy	Name	Composition
1	Mg alloy	AZ61	Mg-Al-Zn-M n-Si--Cu-Ni-Fe
2	Al alloy	Aluminum 6061-T6	Al-Mn-Mg-Si- -Cu-Cr
3	Cast iron	ASTM Grade 40	Fe-C-Si-Mn-P-S

3.1 Linear static structural analysis of gear set with Mg, Al and Structural steel

The materials from Table 5a were used in the linear static structural analysis, and FEA analysis in ANSYS workbench software was used to estimate the stress-strain for all three materials in the numerical technique. Figure 4a depicts the loading condition, while Figure 1 depicts the gear set's dimensions. The analytical approach is used to analyse all of the materials, which includes FEA and the values shown in Figures 4 b-d. The numerical method yields the stress, strain, and deformation values, which may be used to create the table shown in Figures 4b-d. The maximum stress, strain, and deformation results of spur gears for various materials are shown in the diagrams above. Constrained in the gear set by applying fine-tuned support to one gear and frictionless support to the other (i.e pinon).

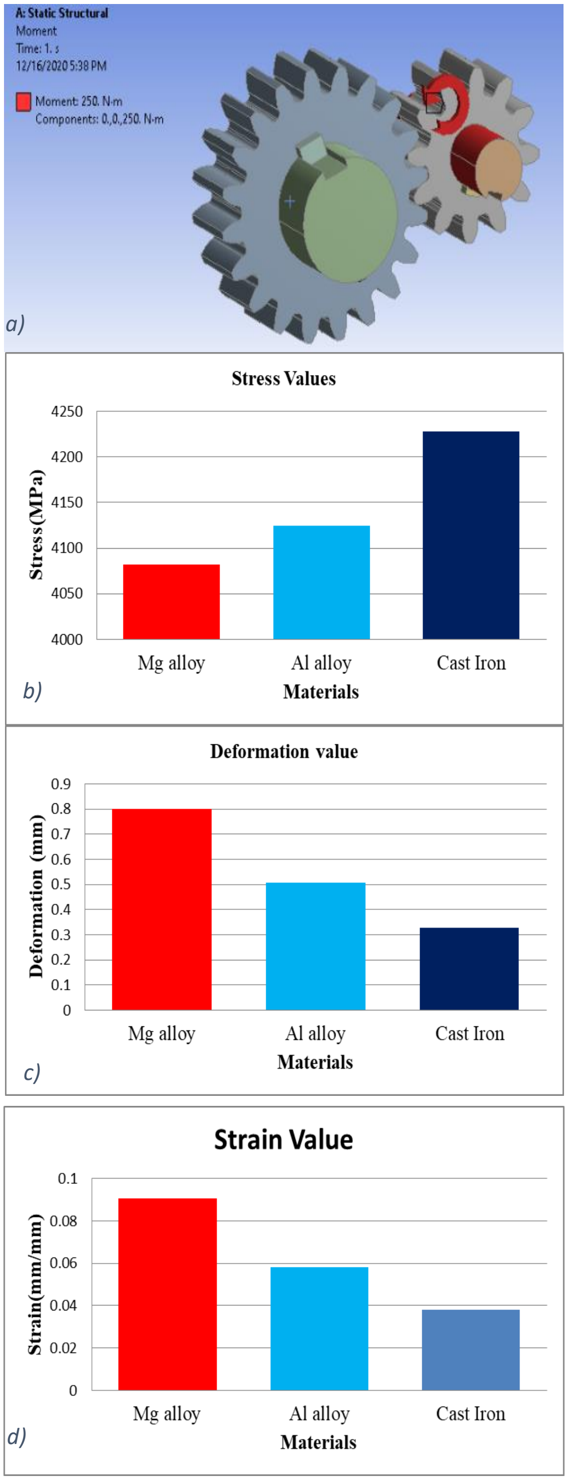

Figure 4 linear static analysis: a) static load condition, b) stress values, c) deformation values, d) strain values

And torque is always delivered to the area where frictionless support is used. The stress value of the magnesium alloy was visually examined in Figure 4b stress for the magnesium alloy, aluminium alloy, and cast iron, and it was found to be very low when compared to the other two materials, owing to the composition of Zr material in the magnesium alloy composition, making it suitable for high stress load applications such as fatigue load, etc. [14]. Figure 4d shows that the strain values of the magnesium alloy are slightly greater than those of the other two materials, indicating that magnesium alloys have very poor stiffness and are not suitable for heavy load applications.

According to the static structural study of gears, magnesium alloy is not suitable for gears.

3.2 Modal and Natural Frequency Analysis

Modal analysis is used to determine the vibration characteristics of a mechanical structure or component (such as natural frequencies and mode shapes), as well as the kineticist of different components of the component or structure under various dynamic loading conditions, such as those caused by electrostatic inputs. Natural frequencies and mode shapes are secondary criteria in the design of a component structure for dynamic loading. ANSYS workbench software was used to do a modal analysis of the gear-pinon.

3.4 Mode shapes and natural frequency for Al alloy

Here are 9 mode shapes with distinct natural frequencies derived from the modal analysis; from these, we observed mechanical behavior with mode shapes. Noise and vibration are linked, therefore changing the natural frequency is a crucial factor in lowering noise. Table 6 provides the natural frequencies of the gear-pinion set for its distinct vibration modes with entire deformation for Al alloy gear set, and Figure 6 shows the mode shape of the gear-pinion set at its fundamental frequencies for Al alloy gear set. Figure 6 mode 2 shows the natural frequency of 14007 Hz and the mode shape for this frequency is in the lateral direction, despite the fact that figure 6 depicts the mode forms and natural frequencies for Al alloy gear-pinion systems.

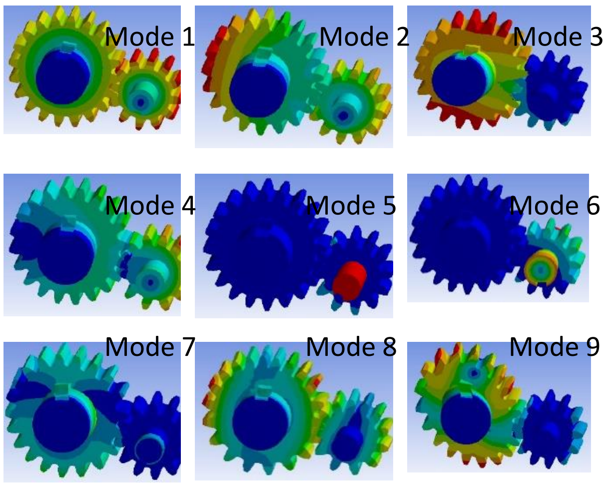

Fig. 6 The fundamental mode shape of the Al Alloy gear-pinon set.

The figure 6 mode 4 shows that the natural frequency of 20494 Hz and the mode shape for this frequency is in longitudinal direction.

Table 6 Frequencies of different resonant modes with total deformations

object name	Total Deformation - Mode 1	Total Deformation- Mode 2	Total Deformation - Mode 3	Total Deformation - Mode 4
Maximum(mm)	275.19 mm	273.76 mm	172.62 mm	214.45 mm
Frequency	6203.4 Hz	14007 Hz	17217 Hz	20494 Hz
Total Deformation - Mode 5	Total Deformation - Mode 6	Total Deformation - Mode 7	Total Deformation - Mode 8	Total Deformation - Mode 9
428.94 mm	451.68 mm	1013.9 mm	397.95 mm	309.33 mm
32809 Hz	41624 Hz	45240 Hz	51074 Hz	52364 Hz

The figure 6 mode 8 shows that the natural frequency of 51074 Hz and the mode shape for this frequency is in twisting mode. The figure 6 mode 9 shows that the natural frequency of 52364 Hz and the mode shape for this frequency is in bending mode.

Table 7 Frequencies of different resonant modes with total deformations of Mg alloy gear set

Object name	Total Deformation - Mode 1	Total Deformation - Mode 2	Total Deformation - Mode 3	Total Deformation - Mode 4
Maximum (mm)	222.06 mm	220.9 mm	172.62 mm	344.97 mm
Frequency	6203.4 Hz	14007 Hz	17217 Hz	20494 Hz
Total Deformation - Mode 5	Total Deformation - Mode 6	Total Deformation - Mode 7	Total Deformation - Mode 8	Total Deformation - Mode 9
366.7 mm	366.94 mm	661.91 mm	321.06 mm	250.55 mm
32809 Hz	41624 Hz	45240 Hz	51074 Hz	52364 Hz

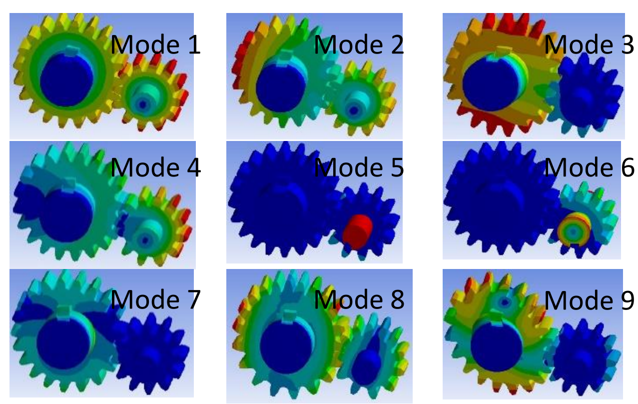

Fig. 7 the fundamental mode shape of the Mg alloy gear-pinon set.

3.5 Mode shapes and natural frequency for Mg alloy

Table 7 provides the natural frequencies of the gear-pinion set for its distinct vibration modes with entire deformation for Mg alloy gear set, and Figure 7 shows the mode shape of the gear-pinion set at its fundamental frequencies for Mg alloy gear set.

3.6 Mode shapes and natural frequency for Cast Iron

Table 8 provides the natural frequencies of the gear-pinion set for its distinct vibration modes with entire deformation for cast iron gear set, and Figure 10 shows the mode shape of the gear-pinion set at its fundamental frequencies for cast iron gear set. Figure 8 depicts the natural frequencies and mode shapes for a cast iron gear-pinion set. The natural frequency of 14007 Hz is seen in figure 10 mode 2, and the mode shape for this frequency is lateral.

Table 8 Frequencies of different resonant modes with total deformations of cast iron gear set

Object name	Deformation - Mode 1	Deformation - Mode 2	Deformation - Mode 3	Deformation - Mode 4
Maximum (mm)	138.06 mm	137.42 mm	106.68 mm	212.73 mm
Frequency	6203.4 Hz	14007 Hz	17217 Hz	20494 Hz
Total Deformation - Mode 5	Total Deformation - Mode 6	Total Deformation - Mode 7	Total Deformation - Mode 8	Total Deformation - Mode 9
404.12 mm	233.52 mm	502.59 mm	199.5 mm	157.2 mm
32809 Hz	41624 Hz	45240 Hz	51074 Hz	52364 Hz

Figure 8 depicts the natural frequencies and mode shapes for a cast iron gear-pinion set. The natural frequency of 14007 Hz is seen in figure 10 mode 2, and the mode shape for this frequency is lateral. The natural frequency of 20494 Hz is shown in figure 10 mode 4, and the mode shape for this frequency is in the longitudinal direction. The figure 8 mode 8 shows that the natural frequency of 51074 Hz and the mode shape for this frequency is in twisting mode. The figure 8 mode 9 shows that the natural frequency of 52364 Hz and the mode shape for this frequency is in bending mode.

3.7 Harmonic Analysis of Gear Set

A harmonic analysis is used to determine the replication or deportment of a structure under steady-state sinusoid (i. e. Harmonic) loading at a certain frequency; in this study, the natural frequency was determined by modal analysis of the gear set for all of the materials. When 250 Nm moments are delivered on the pinion side, the behaviour of the Al alloy gear set will be visually inspected. 3.7 Harmonic Analysis of Al alloy gear set.

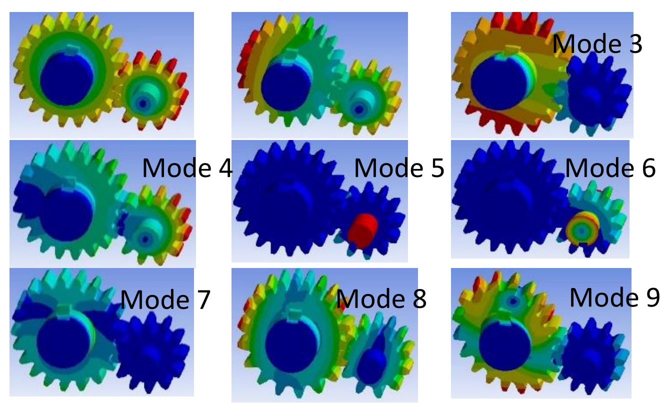

Fig 8 Directional deformation v/s frequencies for cast iron alloy gear set

Figure 9 depicts deformation versus frequency for an Al alloy gear set. As seen in the picture, the highest deformation 1.8674e-4 occurs at a frequency of 42000 Hz. The deformation is minimal at the beginning frequency of 5400 Hz, while the maximal deformation occurs at the frequency of 42000 Hz, where the resonance occurs.

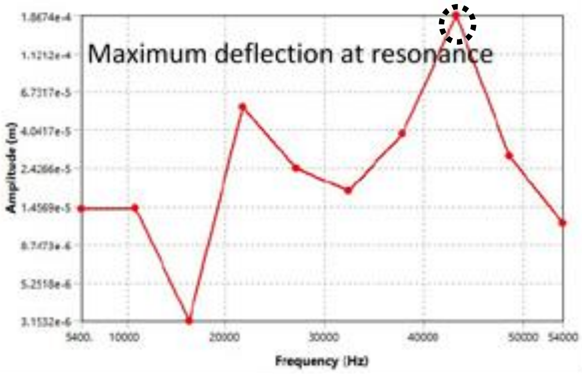

Figure 9 Directional deformation v/s frequencies for Al alloy gear set

3.8 Harmonic Analysis of Mg alloy gear set

Figure 10 shows directional deformation vs. frequency for a magnesium alloy gear set. As seen in the picture, the highest deformation 1.6684e-4 occurs at a frequency of 42000 Hz. The deformation is minimal at the beginning frequency of 5400 Hz, while the maximal deformation occurs at the frequency of 42000 Hz, where the resonance occurs. Mg alloy gear has a resonance frequency of 42000 Hz, which is the same as Al alloy gear. Though the maximum resonance is nearly identical, Mg alloy gear deforms less than Al alloy gear.

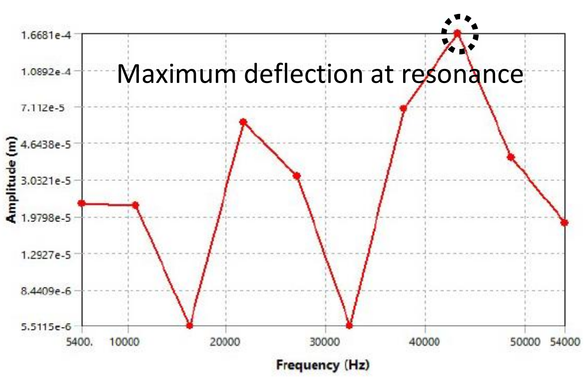

Figure 10 Directional deformation v/s frequencies for Mg alloy gear set

3.9 Harmonic Analysis of cast iron gear set

The cast iron alloy gear set's directional deformation v/s frequencies are displayed in Figure 11. As seen in the picture, the highest deformation 1.0585e-3 occurs at a frequency of 16000 Hz. The deformation is reduced at the beginning frequency of 1.023 Hz, while the maximal deformation occurs at the frequency of 16000 Hz, where the resonance occurs.

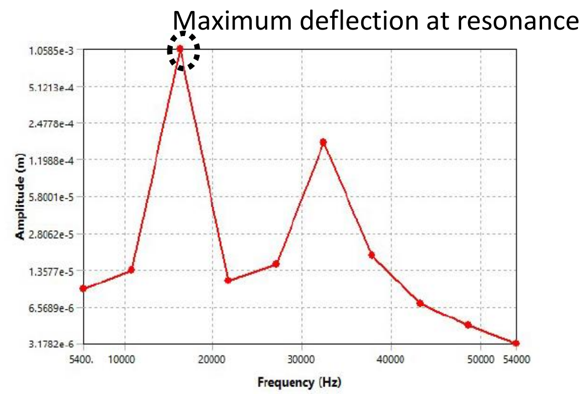

Figure 11 Directional deformation v/s frequencies for cast iron gear set

3.10 Fatigue behavior of Mg alloy, Al alloy and cast-iron gear set

Fatigue is a critical property in transmission applications such as gears, hence the material should be studied for fatigue behaviour. The materials are considered in this analysis and are given in Table 5. This is due to the fact that these materials have a very high vigour when compared to the alloy group of materials. The fatigue demeanour was determined using FEA analysis in ANSYS workstation.

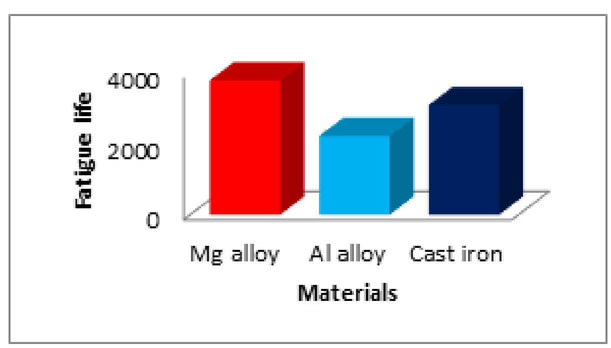

Figure 12 Fatigue life of Mg, Al and cast-iron gear set

Figure 12 shows the fatigue values or life of all three materials, which are shown on a bar chart.

For the fatigue analysis, 100 N-m torques were applied to the pinion side. The fatigue life of all the three materials was taken from the above analysis and the values are plotted in figure 12.

3.11 Cost Analysis of Mg alloy, Al alloy and Cast iron

Magnesium alloys have a significant disadvantage in terms of cost. Mg alloy costs $2.16 per pound, nearly double the price of Al alloys, and it is more expensive than cast iron [15]. However, Mg alloy is pricey, yet in some cases, price is irrelevant. For orthopaedic and dental implants, magnesium alloys have been proven to be the most suitable [16-17]. The biggest challenge with this material, however, is its rate of degradation/wear in vivo [18].

Table 8: Cost analysis of Mg alloy, Al alloy and Cast iron

S. No.	Item	Price (INR) per Kg.
1	Magnesium alloy AM 70	2867.00
2	Aluminum alloy 6061	326.00
3	Heavy duty cast-iron	100.00

Table 8 shows the cost of all three materials in India as of 2018. Figure 14 visually depicts the cost value variety of the three materials. Because of the small market size and limited number of sources, the price of magnesium alloys has risen in India. When it comes to the global market, China is the most astronomically enormously engendered, producing roughly 88 percent of the magnesium alloy. Considering world market, China is the most astronomically immense engendered and they are manufacturing approximately 88 % of the Mg alloy materials in the world. The market values of all three materials were plotted in the bar chart in Figure 13. The cost of the Mg alloy is significantly higher when compared to the other materials in the Indian market because of less availability in India.

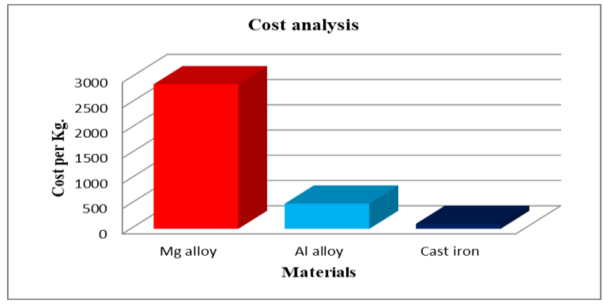

Figure 13: Cost analyses for Mg, Al and cast iron

Conclusion

The light weighting, physical characteristics, fatigue vigour, corrosion, biocompatibility, and cost of magnesium alloys are examined based on the literature from various study publications. Based on the aforesaid literature review and FEA study, the following optical conclusions are drawn. Magnesium alloys have proven to be dependable and are in high demand in industries such as automotive, aerospace, and biomedicine. We'll need a high-performance magnesium alloy with stronger corrosion resistance, high fatigue vigour, low costs, superior biocompatibility, better stiffness, and creep resistance in the future, which will necessitate additional research and development. According to the results of the FEA research, the Mg alloy is suitable for high stress, improved damping capacity, and fatigue load applications. Where the wear rate is necessary to be kept to a low, Mg alloy is used for the gear-pinion set. According to the cost analysis of Mg alloy, the material is expensive to use as gears, but it can be utilised where requirements such as light weight, low wear rate, and higher straight are necessary. Mg alloy is used in several orthopaedic and dental implants to suppress human components, and it is also used in high-precision robotics. More breakthroughs in the research and development of magnesium alloys are urgently required.

Conflict of interest

The author declares no conflict of interest.

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