Contact and bending load capacity enhancement through high entropy alloys

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Abstract. The present work attempts to study the load carrying capacity of normal contact ratio spur gear by high strength less weight materials. In this study, High Entropy Alloys (HEA) AlCrFeNiMo0.5, Al80Li5Mg5Zn5Cu5, Al7075-T6, and Ti-6Al-4V are considered and have high stiffness with high strength to weight ratio compared to conventional steel used for gear. The bending and contact load capacity of each material is determined through finite element analysis and validated analytically. The contact and bending stresses are determined for the selected materials. It has less induced stress and load carrying capability enhancement of symmetric spur gear compared with an EN24 steel gear. The numerical result shows that the contact stress determined for Al80Li5Mg5Zn5Cu5 (HEA) and Al7075-T6 alloy gear is less compared to EN 24 steel gear. Hence, high strength to weight ratio is achieved by using high entropy alloys.

Nomenclature

E  Young’s modulus (GPa)
μ  Poisson’s ratio
m  Module (mm)
Z  No. of teeth
i  Gear ratio
αo  Pressure angle (deg)
Fn  Normal load (N)
(S_c)max  max. contact stress (MPa)
(σ)max  max. bending stress (MPa)

Abbreviations

HEA  High Entropy Alloy
LSR  Load Sharing Ratio
APDL  ANSYS Parametric Design Language
FEM  Finite Element Method
NCR  Normal Contact Ratio
1. Introduction

Gear is a machine part used in the power transmitting system. There is a vast requirement for enhancing the load bearing rate by higher strength and less weight in power transmission gear drives. The load bearing capability of gear can be developed through several factors such as high strength material, heat treatment process, and gear parameter modification. Under fatigue loading condition, the gear tooth failure emerges on root fillet and critical contact point by high bending and contact stress respectively [1]. Excessive bending stress causes failure at the tooth root of the gear, and it can be calculated based on the Lewis formula. Contact stress arises at the contact point causes pitting failure on gear tooth, and it can be calculated analytically using Hertz formula [2]. Thirumurugan and Muthuveerappan [3] have determined the stress analysis by parameter modification from the load sharing ratio of the spur gear. Bekheet [4] has found the analysis of contact and root fillet stress of different materials to examine the effect of Young’s modulus using AGMA and finite element method (FEM). Marimuthu and Muthuveerappan [5] have determined the maximum contact and bending stress through altering the geometry of asymmetric spur gear and examined through load sharing ratio using a numerical method. Rameshkumar et al. [6] have dealt with the numerical investigation on contact and bending stress through contact points of gear tooth without changing the module and center distance of NCR and HCR spur gear. Li [7] has determined the root fillet stress of spur gear tooth, and contact surface stress are minimized by the alteration of the addendum factor and contact ratio. Du [8] has found the enhancement of load withstand capability and wear resistance of polymer gear by implementing holes over the gear for the reduction of heat generation. Biernacki [9] has developed a fusion of plastic and steel cycloid gear to enhance the load bearing capacity. Yeh et al. [10] have found new gear geometry to withstand higher load by derivation function approach and the outcome of gear surface stress and root fillet stress reduces. Nikoli and Atanasovska [11] have determined the changes in the distribution of stress on the contact position of gear tooth along the contact path through finite element analysis, and results are compared analytically.

It is found that very limited literature is available to find high load bearing capability enhancement of gear through materials. Hence, the present work is endeavored to enhance the load bearing capability of normal contact ratio spur gear through high strength and less weight materials. The main intent of this work is to determine the bending and contact stress difference through contact points of gear tooth for less weight, and high strength gear materials attempted for this study and the stresses are compared with alloy steel (EN24) gear. The contact and bending stresses value are determined by the FEM and validated analytically.

2. Material selection

The most common material used for gear is alloy steel, due to its stronger material properties. In the avoidance of high weight materials, substituting the alternative materials having less weight with high strength to improve the load bearing capability of gear. The light weight gears with comparable strength as that of existing gears will reduce the overall weight and improve transmission efficiency. The robustness of the selected materials is almost equal to steel (EN24) with weight reduction. The material selected for gear is high entropy alloys (HEA) AlCrFeNiMo0.5, Al80Li5Mg5Zn5Cu5, Al-7075-T6, and Ti-6Al-4V having a high strength to weight ratio. The materials and its properties examined for this study are shown in Table 1.

| Materials | Yield strength (MPa) | Density (ρ) (g/cm³) | Elastic modulus (E) (GPa) | Poisson’s ratio (µ) |
|-----------|----------------------|----------------------|--------------------------|-------------------|
| Alloy Steel (EN24) | 680 | 7.84 | 207 | 0.3 |
| Al80Li5Mg5Zn5Cu5 [13] | 488 | 2.9 | 69 | 0.3 |
| Al7075-T6 [15] | 505 | 2.81 | 70 | 0.32 |
| AlCrFeNiMo0.5 [13] | 1749 | 6.8 | 205 | 0.34 |
| Ti-6Al-4V [14] | 880 | 4.43 | 110 | 0.31 |
3. NCR spur gear through FEM

Figure 2 shows FEM of NCR spur gear with three teeth developed using APDL code in 2D. The NCR gear specifications used for this study were mentioned in Table 2. The ratio of load sharing [12] is the contact load \( F_{ni} \) acting on the individual gear tooth pair to the normal force \( F_n \) applied on the gear tooth (equation (1)). The crucial contact positions of the gear tooth along the contact path are shown in Figure 1.

\[
LSR = \frac{\text{contact load at a pair}}{\text{Total contact load}} = \frac{F_{ni}}{F_n}
\]  

Table 2. Specifications for NCR gear

| Specification               | Value       |
|-----------------------------|-------------|
| Module, m                   | 1.75 mm     |
| Pressure angle, \( \alpha_o \) | 20°         |
| Teeth on pinion, \( Z_1 \)  | 21          |
| Teeth on gear, \( Z_2 \)    | 26          |
| Face width, b               | 1 mm        |
| Gear ratio, i               | 1.238       |
| Normal force, \( F_n \)     | 58 N        |

Figure 1. Prime contact points along the contact path of NCR spur gear

Figure 2. 2D meshed FEM of NCR gear pair. (a) 2D-Three teeth meshed gear model (b) Amplification at tooth engagement

4. Stress Analysis

In this present work, less weight and high strength materials are approached to estimate the bending and contact stresses through LSR using two-dimensional (2D) gear model. The contact and bending stresses are determined through APDL code [16] (ANSYS 12.1). The normal force of 58N with equivalent torque applied to the pinion which rides the gear. The numerical value of root fillet and contact surface stresses is validated analytically. Minimizing the contact stress enhances the service life and condenses pitting of gear tooth. The root fillet and contact stresses are analytically determined by Lewis equation and Hertzian equation, respectively.
The Hertz equation is specified by [2],

\[ S_c = \sqrt{\frac{0.35 F \left(\frac{1}{R_1} + \frac{1}{R_2}\right)}{L\left(\frac{1}{E_1} + \frac{1}{E_2}\right)}} \]  \hspace{1cm} (2)

Where \( F \) is a normal force acting on the tooth, \( R_1 \) and \( R_2 \) are radii of curvature of tooth profile, \( E_1 \) and \( E_2 \) are the modulus of elasticity and \( L \) is the face width of tooth profile.

The Bending stress estimation based on Lewis Equation [1],

\[ \sigma = \frac{W_t}{F_m I} \]  \hspace{1cm} (3)

Where \( W_t \) is tangential tooth load, \( M \) is a module, \( Y \) is Lewis form factor, and \( F \) is face width.

4.1. Numerical study of contact and root fillet stress

Load sharing between teeth of gear and pinion at the contact position was determined is shown in Figure 3(a). Maximum load acted on the tooth of NCR spur gear at the HPSTC is determined. The effect of contact and bending stresses difference along the contact path for the materials selected are shown in Figure 3 (b) and 3 (c). The graph between the contact stress variations for selected materials and the corresponding contact position are shown in Figure 3 (b). Initially the contact stresses for all materials are high due to sharp tooth tip contact, and this can be condensed by tooth tip relief. The maximum contact stress occurs at HPSTC and minimum contact stress at HPTC. It is observed that the level of contact surface stress decreases when Young's modulus decreases. The contact stress for Al80Li5Mg5Zn5Cu5 spur gear is 465.64MPa, which is less compared to EN24 steel, which has a contact stress of 791.29 MPa. The Al80Li5Mg5Zn5Cu5 High Entropy Alloy (HEA) and Al7075-T6 have less contact stress of 465.64 MPa and 476.94 MPa respectively compared to all other materials investigated. It can be observed that the contact stress of Aluminium alloy (Al7075-T6) and HEA (Al80Li5Mg5Zn5Cu5) are lower than that of steel which can be attributed to lower Young's modulus. The weight of these two materials is about 60 – 65% lesser than of steel. The graph between the bending stress and the corresponding contact position for selected materials are shown in Figure 3(c). There is no change in bending stresses of the selected materials, but the safety factor varies due to different yield stress. The flank safety factor and root safety factor of gear is to verify the strength of the gear tooth. The minimum flank safety factor is 0.873 for steel, and the minimum root safety factor is 5.07 for Al80Li5Mg5Zn5Cu5. The flank safety factor and the root safety factor are determined for each material is shown in Figure 4. The FEM and analytical results of contact and bending stresses are determined, and these comparison results are shown in Figure 5 (a) and 5 (b). The variation of contact stress based on Hertz equation and FEA seems to vary between 1.56 % to 5.27 %. Hence the results of the present model are comparable with the analytical equation. Similarly for estimation of bending stress based on Lewis equation and FEA vary between 9.7% to 9.8%.
Figure 3 Effect of bending and contact stresses for selected materials through LSR. a) LSR vs. contact point. b) Contact stress vs. contact point. c) Bending stress vs. contact point.

Figure 4 Flank and root safety factor determined for the selected gear materials

Figure 5 Comparison of contact stresses and bending stress are determined by FEA, Hertz equation, and Lewis equation. (a) Contact stress evaluation of FEA and Hertz equation. (b) Bending stress evaluation of FEA and Lewis equation
5. Conclusions
Based on load sharing ratio the effect of bending and contact stresses are determined for high strength and less weight materials for NCR spur gear. The finite element analysis results are validated analytically. The contact stresses determined for Al$_{80}$Li$_5$Mg$_5$Zn$_5$Cu$_5$ (HEA), and Al7075-T6 alloy is less compared to EN 24 steel material. The contact stress for Al$_{80}$Li$_5$Mg$_5$Zn$_5$Cu$_5$ and Al7075-T6 spur gear is 41.15% and 39.72% respectively less compared to EN24 steel. Similarly, weight of Al7075-T6 (aluminium alloy) and HEA (Al$_{80}$Li$_5$Mg$_5$Zn$_5$Cu$_5$) are about 60 – 65 % lesser when compared to that of steel. The variation of contact stress based on Hertz equation and FEA is varying between 1.56 % to 5.27 %. Hence the FEA result of contact stresses shows good agreement with the analytical result, which indicates that the model is valid. The variation in the bending stress is less for the selected materials, whereas the variation of flank and root safety factors is observed. The minimum flank safety factor is 0.873 for EN24 steel, and the minimum root safety factor is 5.07 and 5.19 for Al$_{80}$Li$_5$Mg$_5$Zn$_5$Cu$_5$ and Al7075-T6, respectively. Thus, the capacity of load carrying NCR spur gear is increased by less weight high entropy alloys and Al7075-T6 alloy.

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