The Prediction of Stress and Strain Behaviors in Composite Gears using FEM

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ABSTRACT

Metal matrix composite (MMC) gears are used as a major component in the industry and are responsible for providing high-quality power transfer at high speeds. High quality, including high strength and impact-resistance, low brittleness, and long lifetime, is very important and needed in the industry. Gears are made of different materials, and, nowadays, researchers and industrialists have turned to designing, manufacturing, and using composite gears more than other gears due to their low weight, high hardness and strength, and better mechanical properties. In this research, the stress and strain behaviors are predicted in the composite gears made of aluminum silicon carbide with 3 different SiC volume fractions, namely 55 vol.%, 40 vol.%, and 30 vol.%, and with specifications of (Al45/SiC55, Al60/SiC40, and Al70/SiC30) and gears made of aluminum oxide with 3 different alumina weight fractions, namely 94 wt.%, 96 wt.%, and 99.5 wt.% to evaluate and compare the stress behavior due to different forces exerted on a single gear tooth in MMC gears. The Al45/SiC55 composite experienced the largest stress compared to other composites such as Al60/SiC40 and Al70/SiC30. The strain values (unlike the stress values) reduced with increasing in the volume fraction of the SiC reinforcement. Moreover, 94% aluminum oxide composite showed larger stress compared to 96% aluminum oxide and 99.5% aluminum oxide. The spur gear is designed and analyzed using SOLID WORKS and ANSYS Workbench softwares.

doi: 10.5829/ije.2021.34.02b.29

1. INTRODUCTION

Gears are different in terms of type (spur, helical, bevel, worm, and rack and pinion) and material (gray cast iron, alloy cast iron, steel, brass, bronze, plastic, etc.). One of the simplest types of gears is spur gears, which have straight teeth that are parallel to the gear axis. For example, one of the important industrial applications of the composite “Al-SiC” is in internal combustion engine, like piston crown, cylinder liners where alumina and carbon fiber reinforced aluminum have shown a suitable substitute for cast iron. Also, the composite of “Al/SiC” has many applications in structural and industrial aims, where suitable weight and high strength-to-weight is required. In addition, the obtained results show and prove that the composite “Al/SiC” considerably increased the mechanical properties. So, it can be concluded that the mentioned composite can be the best-suited engineering material with characteristics in the application of the engine cylinder liner to get the modern demands of the automotive industries in the world. The teeth are tasked with transferring force between two parallel shafts. These gears are easy to design and manufacture and are used in a wide range of applications, such as trains, agricultural machinery, motorcycles, automobiles, aircraft, and similar applications [1, 2]. Nowadays, MMC gears have drawn the interest of researchers and industrialists due to their features such as improved hardness, low weight, and high tensile strength [3, 4]. Composites consist of a matrix and reinforcement. They can be divided into several categories in terms of the types of the matrix and reinforcement. Metal Matrix Composites (MMC’s) are lightweight materials composed of a metal matrix and hard reinforcement particles that provide suitable strength and stiffness. Recently, researchers and manufacturers have shown interest in using MMCs in automotive, airplane, helicopter, and spacecraft industries due to their good physical and mechanical properties. MMCs have better characteristics such as resistance to high heat, high thermal conductivity, high

Keywords:
Alloys
Composites
Metal Matrix Composite Gears
Strain
Stress

Paper history:
Received 03 October 2020
Received in revised form 31 October 2020
Accepted 05 November 2020

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Please cite this article as: M. Bigdeli, V. Monfared, The Prediction of Stress and Strain Behaviors in Composite Gears using FEM, International Journal of Engineering, B: Applications Vol. 34, No. 02, (2021) 556-563
strength and stiffness, resistance against erosion, and high strength to weight ratio. Composites with aluminum alloy matrices have attracted most research and development programs and commercial applications. Reinforcements used for aluminum composites include alumina, aluminosilicate, silicon carbide, and graphite. Reinforcements can be in the form of particles, continuous and discontinuous fibers, and whiskers and constitute 10% to 60% of the volume of the composite. Continuous fibers MMCs include carbon, silicon carbide, boron, alumina, and refractory metals [5–7]. In this research, the aim is to examine the stress and strain behaviors in an aluminum silicon carbide composite gear with different SiC volume fractions (55 vol.%, 40 vol.%, 30 vol.%) and an aluminum oxide composite gear with weight fractions of 94 wt.%, 96 wt.% and 99.5 wt.%. Among the available research works published in this field, one can name the paper by Singla et al. [8] in which the authors made a silicon aluminum part by casting and concluded from the test that hardness and impact-resistance increase with an increase in the SiC weight fraction [8]. MMCs have been used in power transmission gear applications, and the results show that aluminum oxide gears are also noteworthy for power transmission [9, 10]. In other cases, aluminum oxide has been used in dentistry to replace teeth and dental implants, and in various fields such as artificial joints, artificial bones, and the electronic industry due to such features as high mechanical strength, high hardness and resistance, high thermal conductivity, and high erosion-resistance [11, 12], and other types of composites particularly Al/SiC’s composites in many industries [13–21].

2. MATERIALS AND METHODS

2.1. Composite Materials

Composites consist of matrix and reinforcement. They can be divided into several categories in terms of the types of matrix and reinforcement. In terms of the matrix type, they are classified into metal, polymer, ceramic, and intermetallic matrix composites. Metal matrix composites have drawn the most attention among the various types. Methods of manufacturing metal matrix composites include powder metallurgy, spray deposition, mechanical alloying, and various casting techniques such as squeeze casting, slip casting, and compo casting. All of these techniques are based on the addition of reinforcement particles, in powder or molten form, to the matrix [7, 13].

2.2. Aluminum Silicon Carbide

Most metal matrix metals have commercial and industrial applications with an aluminum matrix, i.e., most of them are focused on an aluminum matrix. Aluminum matrix metals feature low weight, high strength, and very good mechanical properties, which have made the alloys of this metal popular. It is easy to fabricate this composite due to the low melting point of aluminum. Examples of reinforcements used in aluminum composites are alumina, aluminosilicate, silicon carbide, and graphite. Similar to silicon carbide (SiC) reinforcement particles, MMCs are a famous group of composites due to their characteristics such as stiffness, hardness, strength, erosion-resistance, and availability. Casting is a common method of producing these MMCs [14–16]. Here, three different SiC volume fractions, namely 55 vol.%, 40 vol.%, and 30 vol.%, are used to analyze three types of Al-SiC MMC. The mechanical properties of aluminum silicon carbide composites (Al45/SiC55, Al60/SiC40, Al70/SiC30) composites are shown in Table 1.

2.3. Aluminum Oxide

Aluminum oxide has the chemical formula Al₂O₃ and is commonly known as alumina. Alumina has strong ionic inter-atomic bonds. Moreover, it represents a family of engineering ceramics that feature availability and a low price. Among the different and prominent properties of alumina are such mechanical properties as high compressive strength, hardness, and refractoriness. Due to the high hardness and erosion-resistance of alumina, it is used in various applications such as erosion-resistant coatings for pipes and conduits, pumps, and valves. Also, due to its high hardness at high temperatures, it is utilized as a tooltip material in metal cutting [17–19]. Three different weight fractions of alumina oxide, namely 94 wt.%, 96 wt.%, and 99.5 wt% have been used here for analysis. For high-temperature use, a purity of 94% to 99.5% is available. The mechanical properties corresponding to each purity level of alumina are provided in Tables 2-4.

2.4. Gear Design

Gears are among the most common power and motion transmission tools. A gear mechanism is a system composed of at least two gears working as a pair. Gears have various types, such as spur, helical, bevel, worm, and rack and pinion [1, 20]. Since the goal of this research is comparing and analyzing
### TABLE 1. Mechanical Properties of Al70/SiC30, Al60/SiC40, Al45/SiC55

| Property                      | SI         | Al70/SiC30 | Al60/SiC40 | Al45/SiC55 |
|-------------------------------|------------|------------|------------|------------|
| Composition (vol. %)          |            |            |            |            |
| Density, ρ (g/cm³)            | 2.78       | 2.87       | 2.96       |
| Poisson’s Ratio, ν            | -          | 0.29       | 0.28       | 0.25       |
| Young’s Modulus, E (GPa)      |            | 125        | 150        | 200        |
| Thermal Conductivity, k (W/m.K)| 160        | 160        | 160        |
| Specific Heat                 |            |            |            |            |
| Ultimate Tensile Strength (MPa) | 370        | 370        | 340        |
| Flexural Strength (MPa)       | NA         | NA         | NA         |
| Fracture Toughness (MPa·m²/n) | 15         | 14         | 13         |
| Damping Factor (%Zeta)        | 0.26       | ---        | 0.58       |
| Specific Stiffness, (E/ρ) (GPa/g/cm³) | 45         | 52         | 68         |
| Thermal Stability, (k/ο)      | J/K·m³     | 11         | 13         | 14         |

* Adapted from http://www.mmmt.com/resources/standard-material-properties.html

### TABLE 2. Mechanical Properties of 94% aluminum oxide

| Mechanical Property            | Units of measure | SI/Metric | Imperial |
|--------------------------------|-----------------|-----------|----------|
| Density                        | g/m³ (lb/ft³)   | 3.69      | 230.4    |
| Flexural Strength              | MPa (lb/in² × 10⁹) | 330      | 47       |
| Elastic Modulus                | GPa (lb/in² × 10⁹) | 300      | 43.5     |
| Shear Modulus                  | GPa (lb/in² × 10⁹) | 124      | 18       |
| Bulk Modulus                   | GPa (lb/in² × 10⁹) | 165      | 24       |
| Poisson’s Ratio                | ---              | 0.21      | 0.21     |
| Compressive Strength           | MPa (lb/in² × 10⁹) | 2100    | 304.5    |
| Hardness                       | Kg/mm²           | 1175     | ---      |
| Fracture Toughness kₘₑ         | MPa·m¹/²         | 3.5      | ---      |
| Maximum Use Temperature (no load) | °C (°F)      | 1700      | 3090     |
| Specific Heat                  | J/kg·K (Btu/lb·°F) | 880     | 0.21     |
| Thermal Conductivity           | W/m·°K (BTU.in/ft²·hr·°F) | 18     | 125     |
| Coefficient of Thermal Expansion | 10⁻⁶/°C (10⁻⁶/F) | 8.1   | 4.5      |

* Adapted from http://www.matweb.com/

### TABLE 3. Mechanical Properties of 96% aluminum oxide

| Mechanical Property            | Units of measure | SI/Metric | Imperial |
|--------------------------------|-----------------|-----------|----------|
| Density                        | g/m³ (lb/ft³)   | 3.89      | 242.8    |
| Flexural Strength              | MPa (lb/in² × 10⁹) | 379     | 55       |
| Elastic Modulus                | GPa (lb/in² × 10⁹) | 375      | 54.4     |
| Shear Modulus                  | GPa (lb/in² × 10⁹) | 152      | 22       |
| Bulk Modulus                   | GPa (lb/in² × 10⁹) | 228      | 33       |
| Poisson’s Ratio                | ---              | 0.22      | 0.22     |
| Compressive Strength           | MPa (lb/in² × 10⁹) | 2600    | 377      |
| Hardness                       | Kg/mm²           | 1440     | ---      |
| Fracture Toughness kₘₑ         | MPa·m¹/²         | 4        | ---      |
| Maximum Use Temperature (no load) | °C (°F)      | 1750      | 3180     |
| Specific Heat                  | J/kg·K (Btu/lb·°F) | 880     | 0.21     |
| Thermal Conductivity           | W/m·°K (BTU.in/ft²·hr·°F) | 35     | 243     |
| Coefficient of Thermal Expansion | 10⁻⁶/°C (10⁻⁶/F) | 8.4   | 4.7      |

* Adapted from http://www.matweb.com/
MMCs, the spur gear has been used for the analysis. Spur gears have a simple design and are widely used in the industry due to their ease of manufacture. The methods of manufacturing gears include machining, forging, casting, stamping, powder metallurgy, and plastic injection molding. The most common gear manufacturing method is machining, which is divided into gear hobbing and form milling [20, 21].

In this study, the spur gear along with its shaft was designed in the SOLIDWORKS 2016 software. The design procedure can be seen in the figures below. Figure 1 shows the design of a single gear tooth.

As shown in Figure 2, the number of teeth was increased to 20 using the Circular Pattern command.

Finally, the 3D model of the gear was completed by adding the shaft, as shown in Figure 3.

2.5. Analysis using ANSYS Workbench

After designing the gear, the mechanical properties of aluminum silicon carbide and aluminum oxide composites with the specifications [Al45/SiC55, Al60/SiC40, and Al70/SiC30] and [94% aluminum oxide, 96% aluminum oxide, and 99.5% aluminum oxide] were defined in the Engineering Data Sources of ANSYS Workbench software. Then, fine meshing was performed on the gear geometry for stress and strain analyses, as shown in Figure 4.

After the meshing, a gear tooth is selected, and [100 N, 200 N, 300 N, 400 N, 500 N] forces are applied to a (Al45/SiC55, Al60/SiC40, Al70/SiC30) aluminum silicon carbide tooth. Moreover, [100 N, 350 N, 600 N, 800 N, 1000 N] forces are exerted on a (94% Aluminum Oxide, 96% Aluminum Oxide, 99.5% Aluminum Oxide) aluminum oxide tooth. An example of a force (350 N) applied to a gear tooth is shown in Figure 5.

In the final part of modeling, the stress and strain results of the composite gears in terms of the exerted forces are derived so that they could be analyzed and compared. An example of this stress computation process for the Al45/SiC55 with Force=400 N is displayed in Figure 6.

Also, the stress analysis for the 94% aluminum oxide composite gear with Force = 350 N is presented in Figure 7.
3. RESULTS AND DISCUSSIONS

After applying force on a single gear tooth, the stress and strain results for aluminum silicon carbide gears with 3 different SiC volume fractions, i.e., 30 vol.%, 40 vol.%, and 55 vol.% and with the specifications (Al45/SiC55, Al60/SiC40, Al70/SiC30) and aluminum oxide gears with 3 different alumina weight fractions, i.e., 94 wt.%, 96 wt.%, and 99.5 wt.%, were analyzed and compared. The stress and strain results of each gear in terms of the exerted forces have been shown in Figures 5-12, and the stresses of the gears relative to each other are displayed in Figures 8 and 9. These tables and figures show good results for aluminum silicon carbide and aluminum oxide metal matrix composites. According to the results, the gears made of aluminum silicon carbide of the type Al45/SiC55 exhibited less stress compared to 2 other gears made of Al60/SiC40 and Al70/SiC30 under forces of [100 N, 200 N, 300 N, 400 N, 500 N]. Hence, the Al45/SiC55 gears can be used in sensitive applications in the industry where gears must bear larger pressures.

The stress (strength) and strain (elongation and deformation) values increase with an increase in the applied forces (Table 5). The combination of “SiC” (reinforcement) and Al (matrix) significantly increases the stress values, such as the yield strength, compressive strength, ultimate tensile strength, Young’s modulus, yield and fracture stresses, hardness, and wear properties and decreases the elongation, strain (ductility and strain rate), and toughness of the composites in comparison with those of the matrix alloy. Moreover, the “SiC” reinforcement particles are the most effective strengthening particulates for higher strength, hardness, and grain size reduction. Also, Table 6 indicates the maximum stress and strain results for the Al60/SiC40 gear.

According to the obtained results for the “Al/SiC” composite, it is concluded that the strain values decrease with an increase in the volume fraction of the “SiC” reinforcement particles (unlike the stress values). Table 7 shows the maximum stress and strain results for the Al70/SiC30 gear.

The stress results for each of the aluminum silicon carbide composite gears with SiC volume fractions of (55 vol.%, 40 vol.%, 30 vol.%) are shown in Figure 8. The results of Figure 8 and the following table show that the stress has increased with an increase in the volume fraction of the SiC reinforcement. In other words, the strength of the gear increases with an increase in the volume fraction of SiC.

Given the obtained stress values, the results of Figure 8 indicate that the Al45/SiC55 composite gear has experienced higher stress compared to Al70/SiC30 and

| TABLE 5. Stress and strain results for Al45/SiC55 gear |
|---------------------------------|-----------------|-----------------|
| Number | Force (K) | Stress maximum (MPa) | Strain maximum (m/m) |
|--------|-----------|---------------------|---------------------|
| 1      | 0.1       | 1.0701              | 5.66 x 10^-6        |
| 2      | 0.2       | 2.1402              | 1.13 x 10^-5        |
| 3      | 0.3       | 3.2103              | 1.70 x 10^-5        |
| 4      | 0.4       | 4.2804              | 2.27 x 10^-5        |
| 5      | 0.5       | 5.3506              | 2.83 x 10^-5        |

| TABLE 6. Stress and strain results for Al60/SiC40 gear |
|---------------------------------|-----------------|-----------------|
| Number | Force (K) | Stress maximum (MPa) | Strain maximum (m/m) |
|--------|-----------|---------------------|---------------------|
| 1      | 0.1       | 1.0653              | 7.52 x 10^-6        |
| 2      | 0.2       | 2.1305              | 1.50 x 10^-5        |
| 3      | 0.3       | 3.1958              | 2.26 x 10^-5        |
| 4      | 0.4       | 4.2611              | 3.01 x 10^-5        |
| 5      | 0.5       | 5.3263              | 3.76 x 10^-5        |

| TABLE 7. Stress and strain results for Al70/SiC30 gear |
|---------------------------------|-----------------|-----------------|
| Number | Force (K) | Stress maximum (MPa) | Strain maximum (m/m) |
|--------|-----------|---------------------|---------------------|
| 1      | 0.1       | 1.0637              | 9.01 x 10^-6        |
| 2      | 0.2       | 2.1274              | 1.80 x 10^-5        |
| 3      | 0.3       | 3.1911              | 2.70 x 10^-5        |
| 4      | 0.4       | 4.2548              | 3.61 x 10^-5        |
| 5      | 0.5       | 5.3185              | 4.51 x 10^-5        |

| TABLE 8. Results for Al45/SiC55, Al60/SiC40, Al70/SiC30 |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Stres maximum (MPa) | Number | Force (K) | Al45/SiC55 | Al60/SiC40 | Al70/SiC30 |
|---------------------|--------|-----------|------------|------------|------------|
| 1                   | 0.1    | 1.0701    | 1.0653     | 1.0637     |
| 2                   | 0.2    | 2.1402    | 2.1305     | 2.1274     |
| 3                   | 0.3    | 3.2103    | 3.1958     | 3.1911     |
| 4                   | 0.4    | 4.2804    | 4.2611     | 4.2548     |
| 5                   | 0.5    | 5.3506    | 5.3263     | 5.3185     |
Al60/SiC40 composite gears. Hence, Al45/SiC55 can be employed to manufacture gears with good mechanical properties and high impact-resistance.

The stress and strain results for the 94% aluminum oxide composite gear are shown in Figure 9. The strain results in Tables 9-11 indicate that the stress under different forces has decreased with a decrease in the weight fraction of alumina. For example, for Force = 1 KN, the stress in the composite gear with a weight fraction of 94 wt.% is 12.727, which is larger than those corresponding to composite gears with weight fractions of 99.5 wt.% and 96 wt.%

The stress and strain results for the 96% aluminum oxide composite gear are shown in Table 10.

![Figure 8. Stress results for Al45/SiC55, Al60/SiC40, Al70/SiC30 composite gears](image)

**TABLE 9.** Stress and strain results for 94% Aluminum Oxide composite material

| Number | Force (KN) | Stress maximum (MPa) | Strain maximum (m/m) |
|--------|------------|----------------------|----------------------|
| 1      | 0.1        | 1.2727               | 4.51 × 10^{-6}       |
| 2      | 0.35       | 4.4543               | 1.58 × 10^{-5}       |
| 3      | 0.6        | 7.636                | 2.71 × 10^{-5}       |
| 4      | 0.8        | 10.181               | 3.61 × 10^{-5}       |
| 5      | 1          | 12.727               | 4.51 × 10^{-5}       |

**TABLE 10.** Stress and strain results for 96% Aluminum Oxide composite material

| Number | Force (KN) | Stress maximum (MPa) | Strain maximum (m/m) |
|--------|------------|----------------------|----------------------|
| 1      | 0.1        | 1.266                | 4.29 × 10^{-6}       |
| 2      | 0.35       | 4.431                | 1.50 × 10^{-5}       |
| 3      | 0.6        | 7.5959               | 2.57 × 10^{-5}       |
| 4      | 0.8        | 10.128               | 3.43 × 10^{-5}       |
| 5      | 1          | 12.66                | 4.29 × 10^{-5}       |

The stress and strain results for the 99.5% aluminum oxide composite gear are shown in Table 11. The results show smaller stress for the composite gear with a weight fraction of 99.5 wt.% compared to those for weight fractions of 94 wt.% and 96 wt.%.

The stress results for 94% Aluminum Oxide, 96% Aluminum Oxide, 99.5% Aluminum Oxide are shown in Table 12 and Figure 9. According to Figure 9 and the obtained results, the composite gear made of 99.5% aluminum oxide has the lowest stress and the composite gear made of 94% aluminum oxide has the highest stress under different forces. In other words, the 94% aluminum oxide composite gear has the highest stress.

**TABLE 11.** Stress and strain results for 99.5% Aluminum Oxide composite material

| Number | Force (KN) | Stress maximum (MPa) | Strain maximum (m/m) |
|--------|------------|----------------------|----------------------|
| 1      | 0.1        | 1.2592               | 3.33 × 10^{-6}       |
| 2      | 0.35       | 4.4072               | 1.17 × 10^{-5}       |
| 3      | 0.6        | 7.5552               | 2.00 × 10^{-5}       |
| 4      | 0.8        | 10.074               | 2.67 × 10^{-5}       |
| 5      | 1          | 12.592               | 3.33 × 10^{-5}       |

**TABLE 12.** Stress results (MPa) for 94% aluminum oxide, 96% aluminum oxide, and 99.5% aluminum oxide composite material gears

| Number | Force (KN) | 94% aluminum oxide | 96% aluminum oxide | 99.5% aluminum oxide |
|--------|------------|---------------------|---------------------|----------------------|
| 1      | 0.1        | 1.2727              | 1.266               | 1.2592               |
| 2      | 0.35       | 4.4543              | 4.431               | 4.4072               |
| 3      | 0.6        | 7.636               | 7.5959              | 7.5552               |
| 4      | 0.8        | 10.181              | 10.128              | 10.074               |
| 5      | 1          | 12.727              | 12.66               | 12.592               |
oxide composite gear can be employed where the teeth are required to carry larger loads.

According to Figure 10, the teeth can fracture or fail under forces greater than the load capacities of the gears. Therefore, reinforcing the regions of the teeth under the highest pressure can reduce the probability of failure or fracture.

**Figure 10.** Strengthening specified areas to reduce the failure probability

4. CONCLUSION

The (Al45/SiC55, Al60/SiC40, Al70/SiC30) aluminum silicon carbide composite with (55 vol.%, 40 vol.%, 30 vol.%) SiC volume fractions and aluminum oxide composite with (94 wt.%, 96 wt.%, 99.5 wt.%) weight fractions were analyzed and compared, and the following results were obtained,

- The Al45/SiC55 composite material experiences higher and larger stresses compared to Al60/SiC40 and Al70/SiC30 composite materials.
- An increase in the volume fraction of SiC reinforcement particles in the aluminum silicon carbide composite gear, increases stress under different forces, thus improving the strength of the gear is resulted.
- The results of the investigation on the aluminum oxide composite gears showed that the 94% aluminum oxide experienced higher and larger stress values under different forces compared to 95% aluminum oxide and 99.5% aluminum oxide composite materials. In other words, the stress has increased with a decrease in the weight fraction of alumina.
- The higher stresses in the Al45/SiC55 and 94% aluminum oxide gears under different forces compared to the composite gears studied in this research are remarkable and can satisfy the needs of industrialists in many industries for gears with high fracture-resistance.
- The strain values decrease with an increase in the volume fraction of SiC reinforcement particles.
- Reinforcing the tooth areas under can reduce the probability of fracture and failure. Finally, the engineers and researchers can trust to the ANSYS results for predicting the composite gear behaviors in the practical and academic fields.

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