Finite Element and Taguchi Response Analysis of the Application of Graphite Aluminium MMC in Automotive Leaf Spring

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Abstract

The leaf spring is one of the vital components of an automobile which absorbs vibration from shocks generated due to uneven road surface. It is made up of conventional materials like plain carbon steel are heavy and add weight to vehicle which reduces mileage. This necessitates new material which is light in weight and could provide adequate strength to leaf spring along with higher strain energy absorption to absorb shocks. The current research investigates the application of Graphite Aluminium MMC on leaf spring for mass reduction using Finite Element Method. The CAD model is developed in ANSYS design modeler and analyzed in workbench. The design is then optimized using Taguchi Response Surface method using Central Composite Design scheme. The RSM optimization generated specific set values for optimization variables (inner radius and outer radius) along with sensitivity plot and goodness of fit curve. The application of Graphite Aluminium MMC resulted in 56.1% of mass reduction without increase in stress as compared to conventional steel material.

Keywords: Graphite Aluminium MMC, FEA, Response Surface, Leaf Spring, stress

I. Introduction

The suspension system is used to absorb the vibrations from shocks due to irregularities of the road surface [XII]. The passenger comfort in an automobile is determined by its suspension system which separates chassis and vehicle axle and therefore obstructs any vibration from reaching to passenger [III]. Therefore, the suspension system performance of the vehicles should be maximized to reduce the damage and vibration. The main functions of suspension systems in vehicles are to isolate the structure and the occupants from shocks and vibrations generated by the road surface. The suspension system requires elastic resistance to absorb the road vibrations.
shocks. Most of the suspensions are made from carbon steel (1 % carbon) which are heat treated.

The competition in automobile industry demands for lighter and economical materials in manufacturing of components. The feasible methods included application of MMC composites in manufacturing of leaf springs. Carbon and glass fibers are widely used material for composite leaf springs. Considering the Fig. 1, in dynamic loading the HT-carbon/epoxy is capable of storing the greatest amount of energy. The material has high strength and less weight. The limitations are galvanic corrosion, low impact strength and high cost.

![Fig. 1: Leaf spring material strain energies](image)

The composites are better material than steel for leaf spring applications due to lower stress generation [XVI], [I], [XX] and natural frequency, reliability of composite leaf springs are higher than steel leaf spring [XXII], [XVII], [X]. Another advantage is considerable weight reduction using composite leaf springs [XIX], [IX], [VIII], [XIII], [IV], [VI]. The biggest disadvantage of composite materials is higher cost [VII]. Yinhuan Z et al. [XX] analyze the stress distribution a deformation of a composite leaf spring made from glass fiber reinforced plastics using the ANSYS software. Deshmukh BB and Jaju SB [V] conducted experimental and numerical analysis of mono composite leaf spring. The UTM testing results was validated with ANSYS FEA results and results have shown 74% lower stress using composite as compared to steel leaf springs.

II. **Application of Graphite Aluminum MMC using FEM**

The objective of this research is to investigate the application of Graphite Aluminum MMC (Metal Matrix Composite) in automotive leaf spring using Finite Element Method. The design of leaf spring is further optimized using Taguchi Response Surface optimization method. The variables selected for optimization are inner radius and outer radius.
III. Modelling & Specification

The CAD model of mono leaf spring is modelled using dimensions mentioned in table 1. The model is developed in ANSYS design modeler using sketch and extrude tools as shown in fig.2 below.

![CAD model of mono leaf spring](image)

**Fig. 2: CAD model of mono leaf spring**

The inner radius value for base design is 993.72mm and outer radius value of base design is 1023.7mm.

**Table 1: Specifications of leaf spring [XI]**

| S No. | Specification               | Value |
|-------|----------------------------|-------|
| 1     | Length of leaves (mm)      | 965   |
| 2     | Number of full-length leaves| 01    |
| 3     | Width of all leaves (mm)   | 45    |
| 4     | Thickness of all leaves (mm)| 30     |
| 5     | Inner radius of the eye(mm) | 23    |
| 6     | Outer radius of the eye(mm)| 50    |
| 7     | Camber (mm)                | 125   |

The CAD model is developed in ANSYS design modeler using sketch and extrude tools. In next stage the model is meshed using hexahedral elements with fine sizing as shown in fig.3 below. The transition is set to smooth, span angle center coarse.
The total number of elements generated is 474 and number of nodes generated is 3268. After meshing the CAD model is applied with appropriated loads and boundary conditions as shown in fig.4 below. The material used for analysis is Graphite-Al MMC, the properties are given below.

**Table 2: Graphite Al MMC properties [XVIII]**

| Property                  | Value |
|---------------------------|-------|
| Density (g/cm$^3$)        | 2.45  |
| Young’s Modulus (GPa)     | 88.7  |

The left end is applied with displacement support and right end of mono leaf spring is applied with remote displacement keeping Rot$_z$ degree of freedom free and other degree of freedom restricted. The load is applied in mid face of mono leaf spring.

The next step is solution stage in which software formulates element stiffness matrix which is assembled to form global stiffness matrix. The further process involves matrix inversions and multiplications to determine deformation and stresses at nodes and these results are interpolated for entire element edge length.

**IV. Results and Discussion**

Static structural analysis is performed using ANSYS software using appropriate boundary conditions. Equivalent stress and deformation contours are generated as shown in fig.5 below and fig.6 below respectively.

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*Agarwal A. et al*
The equivalent stress plot generated is shown in fig. 5 above. The stress plot shows maximum values of equivalent stress near remote displacement support portion of leaf spring with magnitude of 141.78MPa and maximum value of deformation is seen near displacement support with magnitude of 14.67mm as shown in fig. 6 below.

The analytical calculation of stress is made using below given formula.

For “n” number of leaves, the stress can be written as,

\[ \sigma = \frac{M}{z} = \frac{6 \times w \times L}{n \times b \times t^2} \]

Applying \( w = 2000 \), \( b = 45 \), \( t = 30 \) we get stress as

\[ \sigma = \frac{M}{z} = \frac{6 \times 2000 \times 965/2}{1 \times 45 \times 30^2} = 142.96 MPa \]

It’s evident that the theoretical value of stress is in close agreement to FEA simulation results which is 142.21MPa for 2000N load.

V. Response Surface Optimization of Leaf Spring

The dimensions of mono leaf spring are optimized using Taguchi response surface optimization [II]. The RSM technique involves controllable independent variables that can be denoted by \( X_1, X_2, X_3, X_4 \ldots \ldots X_n \) and captured responses denoted by \( y \). The relationship between the dependent variable and independent variables can be represented as

\[ y = f(X_1, X_2, X_3, X_4 \ldots \ldots X_n) + \epsilon \]
Where, $\varepsilon$ represents the noise or error observed in the response ‘y’. If we denote the expected response by $E(y) = f(X_1, X_2, X_3, X_4 \ldots X_n) = \eta$. Then, the surface represented by $f(X_1, X_2, X_3, X_4 \ldots X_n) = \eta$ is called the response surface. The optimization variable used for analysis is inner radius and outer radius as shown in table 3 & fig.7 respectively.

**Table 3: Input variables for optimization**

| $X_1$ (H12) | Inner radius |
| $X_2$ (H14) | Outer radius |

![Fig. 7: Optimization parameters are inner radius and outer radius](image)

The goodness of fit curve shown in fig.8 shows close proximity between observed values and predicted values of equivalent stress, strain energy, total deformation and mass. These design points are generated from combination of optimization parameters i.e. inner radius and outer radius.

![Fig. 8: Goodness of fit curve](image)

The software carries out analysis at these design points and generates equivalent stress, strain energy, deformation and mass as shown below in table 4.

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Table 4: Design points generated using DOE

| Name       | P8- Inner radius (mm) | P9- Outer Radius (mm) | P5-Equivalent Stress Max (MPa) | P6-Strain Energy max (mJ) | P7-Total Deformation Max (mm) | P10 Solid Mass (Kg) |
|------------|-----------------------|-----------------------|--------------------------------|--------------------------|------------------------------|---------------------|
| 1          | 995.83                | 1021.7                | 185.38                         | 226.04                   | 22.085                       | 3.5044              |
| 2          | 999.17                | 1023.9                | 201.59                         | 252.88                   | 25.166                       | 3.3839              |
| 3          | 989.17                | 1027.2                | 93.444                         | 88.349                   | 7.8716                       | 4.9U1               |
| 4          | 994.17                | 1026.1                | U6.96                          | 133.04                   | U.444                        | 4.2144              |
| 5          | 987.5                 | 1020.6                | 118.82                         | U0.47                    | 11.168                       | 4.3203              |
| 6          | 990.83                | 1022.8                | U6.55                          | 131.79                   | U.324                        | 4.2026              |
| 7          | 992.5                 | 1029.4                | 98.464                         | 94.965                   | 8.5472                       | 4.7954              |
| 8          | 997.5                 | 1028.3                | 135.54                         | 146.17                   | 13.789                       | 4.0955              |
| 9          | 985.83                | 1025                  | 88.557                         | 82.309                   | 7.2699                       | 5.0281              |

After response surface optimization the maximum and minimum values of output parameters are generated as shown in Table 5.

Table 5: Maximum and minimum values of Output Parameters

| A | B                                      | C                                      | D                                      |
|---|----------------------------------------|----------------------------------------|----------------------------------------|
| Name                               | Calculated Minimum | Calculated Maximum | Maximum Error | Predicted |
| PS - Equivalent Stress Maximum (MPa) | 67.325               | 276.04           | 0.031353     |           |
| P6 - Strain Energy Maximum (MJ)     | 68.788               | 39.113           | 0.024686     |           |
| P7 – Total Deformation Maximum (mm) | 6.4371               | 38.967           | 4.8569E-07   |           |
| P10 - Solid Mass (kg)               | 2.8342               | 5.7093           | 2.3499E-14   |           |

The mass minimization is achieved with magnitude of 2.8342Kg and maximization is 5.7093 Kg under specified limit of inner radius and outer radius. The minimum strain energy achieved is with magnitude of 68.788mJ and maximum strain energy is 391.13mJ.

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Agarwal A. et al
The sensitivity plots of different variables are shown in fig.9 above. The sensitivity plot shows positive sensitivity of inner radius for equivalent stress, strain energy and total deformation while shows negative sensitivity for solid mass. The sensitivity of inner radius is 54.18% positive for equivalent stress and outer radius shows 32.64% negative for equivalent stress. The sensitivity of inner radius is 52.086% positive for strain energy and outer radius shows 30.8% negative.

The sensitivity of inner radius is 54.253% positive for deformation and outer radius shows 30.996% negative for deformation. The sensitivity of inner radius is 59.24% negative for mass and outer radius shows 40.75% positive for deformation. The 3D response surfaces are generated for different output variables i.e. equivalent stress, deformation and mass and input variables for analysis are inner radius and outer radius as shown in fig.10.

The response of equivalent stress shows highest magnitude of 270 MPa for outer radius range from 1020 mm to 1025 mm and inner radius above 995 mm. The minimum equivalent stress with magnitude of 70Mpa is attained at outer radius range of 1103 mm to 1025mm and inner radius range from 985 mm to 990 mm.
Fig. 11: Response chart of strain energy

The response of strain energy in fig.11 shows highest magnitude of 390mJ for outer radius range from 1020 mm to 1025mm and inner radius above 995mm. The minimum strain energy with magnitude of 70Mpa is attained at outer radius range of 1103mm to 1025mm and inner radius range from 985mm to 990mm.

Fig. 12: Response chart of total deformation

The response of total deformation in fig.12 shows highest magnitude of 37mm for outer radius range from 1020 mm to 1025mm and inner radius above 995mm. The minimum deformation with magnitude of 7mm is attained at outer radius range of 1103mm to 1025mm and inner radius range from 985mm to 990mm.
The response of solid mass in fig. 13 shows lowest magnitude of 2.9Kg and below for outer radius range from 1020 mm to 1025mm and inner radius above 995mm. The maximum solid mass with magnitude 5.7kg and more is attained at outer radius range of 1103mm to 1025mm and inner radius range. The mass of conventional steel leaf spring is 13kg as discussed in literature [XIX]. The above results clearly show significant reduction in weight using Graphite Aluminum composite for leaf spring applications.

VI. Conclusion

As experimental testing of components has become costly and requires manpower and support therefore numerical method of analysis involving use of computer programmes has become viable option. From the structural analysis of rectangular plate conducted using ANSYS software stresses and strain energy are determined. The model is optimized using central composite design (CCD) scheme. The detailed conclusion points are as follows:

1. The sensitivity plot shows positive sensitivity of inner radius for equivalent stress, strain energy and total deformation while shows negative sensitivity for solid mass.
2. The effect of inner radius dimensions are higher for all the evaluated parameters i.e. equivalent stress, deformation, strain energy and mass.
3. The optimized dimensions for minimum mass are determined i.e. the outer radius ranging from 1020 mm to 1025mm and inner radius above 995mm.
4. The mass reduction of leaf spring achieved using Graphite Aluminium MMC is 56.1% which is significant.
5. The deformation developed in leaf spring is higher than that of conventional steel material.

The efficacy of other optimization models like optimal space filling design, box Behnken design and sparse grid initialization require investigation. Other MMC
materials like Boron aluminium, aluminium Silicon Carbide can be investigated for application in leaf spring.

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