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Comparative Evaluation and Optimization of 4-Cylinder CI Engine Camshaft Material Using Finite Element Analysis: A Hybrid MOORA Technique and Taguchi based Desirability Function Analysis Approach

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Abstract*— Camshaft is one of the vital parts in the I.C. engines of automobiles. The cam shaft and its allied parts i.e. push rods, rocker arms, valve springs and tappets regulates the opening and closing of intake and exhaust valves. It acts as a timing device that governs the setting the valve overlap that arises at TDC (Top Dead Centre) of the exhaust stroke. The shaft is made with some journals that ride on bearings inside the engine. The camshaft is certain to crankshaft rotation by a timing chain, timing belt or timing gears. Any failure in the camshaft drive can cause the valves to make contact with the piston crowns, leading to extensive internal damage. In this paper, optimization of existing automobile camshaft material using different composition of metal matrix composite is studied. This study focuses on optimizing the camshaft by selection of the best material along with the loading condition by employing MOORA technique and Taguchi based Desirability Function Analysis approach to minimize the maximum stress, maximum deformation and maximum strain obtained. Analysis has been conducted using the Taguchi's design of experiment; L16 orthogonal array in ANSYS 17.2. The developed predictive model is used to search for an optimal setting. It will not only help in designing it faster, but also help in developing more specific camshaft which would be beneficial in larger displacement engines.

***Keywords*— Camshaft, FEA, MOORA, Metal-matrix composite, Taguchi, Desirability Function Analysis**

I. INTRODUCTION

Camshaft acts as a timing device for transfers motion to inlet & exhaust valve. The shaft is made with some journals that drive on bearings inside the engine. A camshaft has an egg-shaped lobe known as cam which actuate the valve train, either by pushing directly on the valve stems, or by moving lifters and pushrods. *The camshaft is certain to crankshaft rotation by a timing chain, timing belt or timing gears. Any failure in the camshaft drive can cause the valves to make contact with the piston crowns, leading to extensive internal damage.* It is generally used in all internal combustion engines. In older IC engines, Camshafts have gears machined into them which operated the distributor and the oil pump. In modern IC engines, the camshaft may have a position sensor mounted on the end which sends data to the Engine Control Unit which contains Powertrain control module which will properly time the fuel injection pulses and ignition. This is also known as VVT (Variable Valve Timing) [1].

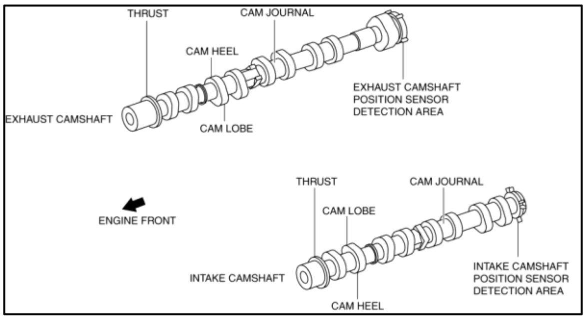

Fig. 1: Camshaft Terminology

II. CAD MODELLING

The Input to the design of the camshaft is taken 4-cylinder compression ignition engine. The model was then developed in CATIA V5 R21 uses various operations for designing and generating of the camshaft. Fig. 2 shows the CAD model of the camshaft.

TABLE I.
CAMSHAFT DIMENSIONS

Camwidth	18 mm
Camshaft Diameter	27 mm
Journal Diameter	35 mm
Cam Height	42.6 mm
Base Circle Diameter	34.2 mm
Total lift of cam	8.4 mm
Length of Camshaft	436 mm

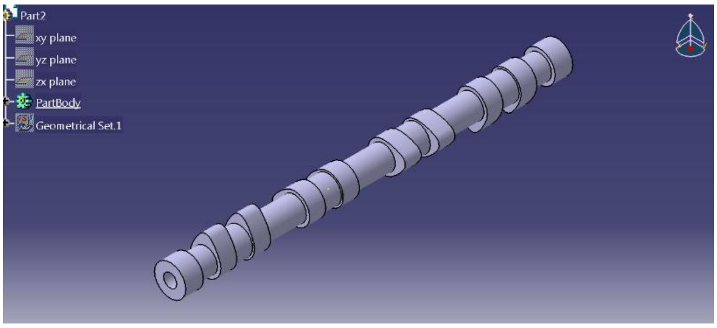

Fig. 2: CAD model of the camshaft

III. MATERIALS FOR CAMSHAFT

The material choice for the manufacturing of camshaft relies on the strength and operating conditions like wear, noise, load, etc. It includes the cost and in addition the material execution. The camshaft might be fabricated from metallic or non-metallic materials. Cast steel is generally utilized for the manufacturing of camshaft because of its great wearing properties, magnificent machinability and simplicity of creating muddled shapes by machining. Alloy steels are additionally used in a few spots for substantial working conditions like high speed engines [3].

A. Cast Iron

At present Camshaft is widely made of chilled cast iron material. In chilled cast iron, iron-carbon alloy with low graphitization factor, so that chill arises forming a graphite-free structure. In order to attain chilling, the silicon content is fixed to a low level subjected on the wall thickness of the casting; The carbon content in this is approx. 2.5 to 3.8%. Some Carbide-stabilizing additives such as chrome helps in increasing chill. It is shock resistance and less tensile strength than steel, but its compressive strength is comparable to low carbon steel and medium-carbon steel [3].

B. Metal Matrix Composite (AlSiC)

AlSiC is a metal matrix composite consisting of an aluminium matrix with silicon carbide particles. AlSiC composites can be produced relatively inexpensively the dedicated tooling, however, causes large up-front expenses, making AlSiC more suitable for mature designs. Resistant to corrosion, salt water, light weight, etc. makes AlSiC useful in many fields like construction of aircraft, marine construction, automotive parts etc. [5].

TABLE II.
MECHANICAL PROPERTIES OF MATERIALS

Properties	**Cast Iron**	**AlSiC 20%**	**AlSiC 30%**	**AlSiC 40%**
Young’s Modulus, E	110 GPa	100 GPa	120 GPa	140 GPa
Poisson’s Ratio ,ν	0.3	0.30	0.29	0.29
Density, ρ	7200 kg/m^3	2700 kg/m^3	2800 kg/m^3	2810 kg/m^3
Yield Stress, σ_{yield}	98 MPa	305 MPa	210 MPa	200 MPa
Ultimate Tensile Stress, σ_{uts}	150 MPa	360 MPa	216 MPa	226 MPa

IV. FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) is an on-screen method for predicting how a product responds to real-world forces. It demonstrates whether a product will break, wear out or work the way it is designed. In product development process, FEA is used to predict what will happen when the product is used [5]. Here, Static Analysis is done by using ANSYS 17.2 and boundary conditions are fed to get desired solution.

A. Meshing

For meshing, CATPART file of the CAD model of camshaft is imported to ANSYS 17.2. Since all the dimensions of the camshaft are measurable, the best element for meshing is the tetrahedral element. Meshing tool in ANSYS workbench was used to create a very fine mesh with element size 2 mm. Fig. 3 shows the meshed model of camshaft in ANSYS [5].

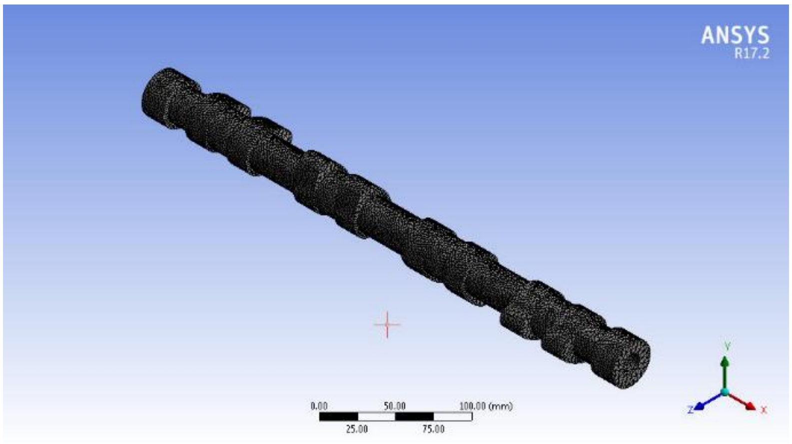

Fig. 3: Meshed models of camshaft

B. Boundary Conditions

Subsequently meshing is accomplished, boundary conditions were applied. These boundary conditions are the reference points for calculating the results of the analysis.

Forces acting on the camshaft:

- Load on the cam nose
- Gravitational force which is neglected in this case.

The load on the cam nose = 5000N, 5500N, 6000N, 6500N (variable loads has been used to carry out the optimization process in later stage). The camshaft has been constrained at the bearings and variable loads has been applied on the cam nose [5] shown in Fig 9.

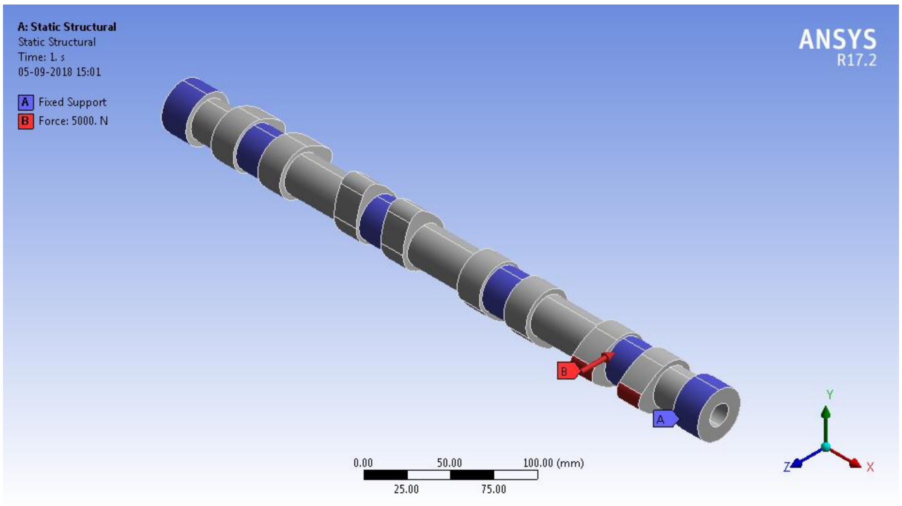

Fig. 4: Boundary conditions applied on camshaft

C. Solution

After meshing and boundary condition applied to the model, analysis process was done in ANSYS 17.2. The software first computed the deflection with respect to the boundary conditions applied. Then on the basis of deflection it calculated the stress and strain. The results were observed in different material under different loads. The calculation of stress depends upon the failure theory suitable for the analysis [5].

V. MULTI OBJECTIVE OPTIMIZATION ON THE BASIS OF THE RATIO ANALYSIS METHOD (MOORA)

The MOORA method (Multi objective optimization on the basis of the ratio analysis) has been used to disregard unsuitable substitutions by selecting the most appropriates an also by collation the selection parameter. It is a decision making method, where the objectives were restrained for every pronouncement of outcomes from a set of available alternatives. The MOORA method can be functional in numerous forms of complex multi objective optimization problems. In MOORA method the recital of the diverse output responses is arranged in a decision matrix as specified in Equation (i) [6,7,8].

$$X = \begin{bmatrix} x_{11} & x_{12} & .. & .. & x_{1n} \\ x_{21} & x_{22} & .. & .. & x_{2n} \\ :: & :: & :: & :: & :: \\ x_{m1} & x_{m1} & .. & .. & x_{mn} \end{bmatrix} \quad \text{(i)}$$

Where, x_{ij} is the performance measure of the i^{th} alternative on j^{th} attribute, m is the number of alternatives, and n is the number of attributes.

A ratio system will be formed by normalizing the data of decision matrix which can be calculated by using the equation (ii).

$$x_{ij}^{*} = x_{ij} / \left[\sum_{i=1}^{m} x_{ij}^{2}\right]^{\frac{1}{2}} \qquad (j = 1, 2, \ldots\ldots n) \qquad \text{(ii)}$$

Where, x_{ij}^{*} represents the normalized value x which is a dimensionless number which lies between 0 and 1 i^{th} alternative on j^{th} attribute.

After that, the normalized value will be added for maximization problem or subtracted in case of minimization problems. In some cases, some of the attributes have more importance than others, and to deliver even more importance to these attributes, they are multiplied by their corresponding weight. After the consideration of weight, the equation will be:

$$y_i = \sum_{j=1}^{g} w_j x_{ij}^{*} - \sum_{j=g+1}^{g} w_j x_{ij}^{*} \qquad \text{(iii)}$$

where, g is the maximized number of attribute, (n-g) is the attributes to be minimized and w_j is the weight of j^{th} attribute. y_i is the normalized assessment value of the i^{th} alternative relating to all the attributes. After calculation of normalized assessment value, ranking of y_i is done from highest to lowest value to know the best alternate among the entire attributes. Thus, highest y_i value is the best alternative among all since ranking of the y_i is the final preference. [6,7,8].

VI. DESIRABILITY FUNCTION ANALYSIS

In this approach, the first step is to convert each response into the corresponding desirability value. The desirability value varies within zero to unity which be subject to the preferred range of the responses and the target value to be achieved. If the response touches its target value, which is the most desired condition, its desirability is consigned as unity. If the value of the response falls outside the prescribed tolerance rage, which is not desired, its desirability value is implicit as zero. Consequently, desirability value may vary within zero to unity. Derringer and Suich in 1980 proposed the formulae to calculate the desirability of each response depending upon the requirement of the target value. To calculate the individual desirability index (d_i) for the corresponding responses using two forms of the desirability functions according to the response characteristics [9,10].

A. *Smaller-the better*

Smaller the better characteristic is functional to regulate the individual desirability values when the objective is to minimize the response. The value of $\hat{y}$ is predictable to be the smaller the better. When the $\hat{y}$ is less than a precise criteria value, the desirability value equals to 1; if the $\hat{y}$ surpasses a certain criteria value, the desirability value equals to 0. The desirability function of the-smaller-the-better can be defined as specified in Equation (iv) [9,10]:

$$d_i = \begin{cases} 1 & \hat{y} \le y_{min} \\ \left(\frac{\hat{y} - y_{max}}{y_{min} - y_{max}}\right)^{r}, y_{min} \le y \le y_{max}, r \ge 0 & r \ge 0 \\ 0 & \hat{y} \ge y_{max} \end{cases} \qquad \text{(iv)}$$

Where the y_{min} signifies the lower tolerance limit of $\hat{y}$, the y_{max} signifies the upper tolerance limit of $\hat{y}$, and r denotes the weight. If the corresponding response is predictable to be closer to the target, the weight can be set to the larger value; otherwise, the weight can be set to the smaller value.

B. *Larger-the better*

Larger the better characteristic is applied to determine the individual desirability values for tool life since objective is to maximize the tool life. The value of $\hat{y}$ is predictable to be the larger the better. When the $\hat{y}$ outdoes a particular criteria value, which can be viewed as the obligation, the desirability value equals to 1; if the $\hat{y}$ is less than a particular criteria value, which is deplorable, the desirability value equals to 0. The desirability function of the larger-the better can be written as given in Equation (v) [9,10]:

di ¼

$$d_i = \begin{cases} 0 & \hat{y} \le y_{min} \\ \left(\frac{\hat{y}-y_{min}}{y_{max}-y_{min}}\right)^r, & y_{min} \le \hat{y} \le y_{max}, r \ge 0 \\ 1 & \hat{y} \ge y_{min} \end{cases} \qquad \text{(v)}$$

where the y_{min} represents the lower tolerance limit of $\hat{y}$, the y_{max} represents the upper tolerance limit of $\hat{y}$ and r represents the weight.

In the next step, calculate the overall desirability value D_0. The individual desirability index of all the responses can be combined to form a single value called composite desirability D_0 by the following Equation (vi):

$$D_0 = (d_1^{w1} d_2^{w2} \dots d_n^{wn})^{\frac{1}{W}} \qquad \text{(vi)}$$

where d_i is the individual desirability of the property y_i, w_i is the weight of the property y_i in the composite desirability and W is the sum of the individual weights [9,10].

VII. ANALYTICAL PROCEDURES FOR DESIGN OPTIMIZATION

In this study, the camshaft made of Cast Iron and AlSiC MMC was used. The analytical studies were carried out ANSYS 17.2 software. The analysis was conducted under static loading conditions. The analysis was carried out using materials and load as input parameters. These input parameters are shown in Table 1. After applying the parameters, stress, deformation and strain of the camshaft was obtained for different run of analysis.

TABLE III.
INPUT PARAMETERS

Factors	Symbol	Level 1	Level 2	Level 3	Level 4
Material	A	Cast Iron	AlSiC 20%	AlSiC 30%	AlSiC 40%
Load (N)	B	5000	5500	6000	6500

VIII. RESULTS AND DISCUSSION

The analysis of the camshaft has been done for all four materials, i.e. cast iron, AlSiC 20% MMC, AlSiC 30% MMC and AlSiC 40% MMC.

A. Best experimental run

The experimental results for the maximum stress, deformation and strain are listed in Table 2. Typically, small values of all the responses are required for optimizing in the camshaft designing.

TABLE IV.
ORTHOGONAL ARRAY L_{16} OF THE EXPERIMENTAL RUNS AND RESULTS

Run No.	A	B	Max. Stress (MPa)	Max. Deformation (mm)	Max. Strain
1	Cast Iron	5000	22.155	0.003993	0.00026082
2	Cast Iron	5500	24.17	0.0043923	0.00028691
3	Cast Iron	6000	25.184	0.0047916	0.00031299
4	Cast Iron	6500	20.141	0.0051909	0.00033907
5	AlSiC 20%	5000	22.155	0.0044367	0.0002898
6	AlSiC 20%	5500	24.17	0.0048803	0.00031878
7	AlSiC 20%	6000	25.08	0.005324	0.00034776
8	AlSiC 20%	6500	20.21	0.0055677	0.00037675
9	AlSiC 30%	5000	22.23	0.003652	0.00024138
10	AlSiC 30%	5500	24.251	0.0040172	0.00026552
11	AlSiC 30%	6000	26.272	0.0043824	0.00028965
12	AlSiC 30%	6500	20.11	0.0047476	0.00031379
13	AlSiC 40%	5000	22.23	0.0029812	0.00019704
14	AlSiC 40%	5500	24.251	0.0032793	0.00021675
15	AlSiC 40%	6000	26.272	0.0035775	0.00023645
16	AlSiC 40%	6500	26.272	0.0038756	0.00025616

B. Optimization using MOORA Technique

Now, MOORA optimization method is applied to find out the optimal parameters for camshaft. The normalization of the output responses is done conferring to Equation (ii). After that the normalized assessment values were calculated.

Equal percentage of weight is considered for max. stress, max. deformation, max. strain and the sum of all the weights will be 1. Table V shows the normalized assessment values of the responses.

TABLE V.
NORMALIZED INDIVIDUAL ASSESSMENT VALUES

Run No.	**Max. Stress**	**Max. Deformation**	**Max. Strain**
1	0.2353	0.2280	0.2262
2	0.2567	0.2508	0.2488
3	0.2674	0.2736	0.2715
4	0.2139	0.2964	0.2941
5	0.2353	0.2534	0.2513
6	0.2567	0.2787	0.2765
7	0.2663	0.3040	0.3016
8	0.2146	0.3179	0.3268
9	0.2361	0.2085	0.2093
10	0.2575	0.2294	0.2303
11	0.2790	0.2503	0.2512
12	0.2136	0.2711	0.2722
13	0.2361	0.1702	0.1709
14	0.2575	0.1873	0.1880
15	0.2790	0.2043	0.2051
16	0.2790	0.2213	0.2222

The MOORA overall assessment value is calculated using equation (iii) and ranked according to the highest value of the overall assessment value. Table VI shows the value overall assessment value and their ranking according to the highest value.

TABLE VI.
OVERALL ASSESSMENT VALUE

Run no.	y_i	**Rank**
1	-0.0745	7
2	-0.0827	9
3	-0.0943	11
4	-0.1272	15
5	-0.0914	10
6	-0.1013	12
7	-0.1150	14
8	-0.1452	16
9	-0.0621	5
10	-0.0690	6
11	-0.0759	8
12	-0.1115	13
13	-0.0364	1
14	-0.0407	2
15	-0.0451	3
16	-0.0565	4

In the above table, it can be seen that by using the MOORA method for a particular values of input parameter in experiment no. 13 is an optimal parameter combination for camshaft. Hence, AlSiC 40% can be recommended for replacement of cast iron for designing camshaft according to MOORA technique optimization.

C. Optimization using Desirability Function Analysis

In this study, the smaller-the-better characteristic is applied to determine the individual desirability values (d_i) for max. stress, max. deformation, max. strain using equation (iv) since all are to be minimized. After calculating individual desirability, the composite desirability (d_0) is calculated using equation (vi).

TABLE VII.
EVALUATED INDIVIDUAL DESIRABILITY AND COMPOSITE DESIRABILITY

Sl No.	**Individual Desirability (d_i)**			**Composite Desirability (d_0)**
	Max. Stress	**Max. Deformation**	**Max. Strain**	
1.	0.6681	0.6088	0.6451	0.6403
2.	0.3411	0.4544	0.4999	0.4270
3.	0.1766	0.3001	0.3548	0.2667
4.	0.9950	0.1457	0.2097	0.3108
5.	0.6681	0.4373	0.4838	0.5205
6.	0.3411	0.2658	0.3226	0.3082
7.	0.1934	0.0942	0.1613	0.1434
8.	0.9838	0.0000	0.0000	0.0000
9.	0.6560	0.7407	0.7533	0.7157
10.	0.3280	0.5995	0.6189	0.4966
11.	0.0000	0.4583	0.4847	0.0000
12.	1.0000	0.3171	0.3503	0.4792
13.	0.6560	1.0000	1.0000	0.8701
14.	0.3280	0.8847	0.8903	0.6390
15.	0.0000	0.7695	0.7807	0.0000
16.	0.0000	0.6542	0.6710	0.0000

Figure 5 shows the SN-ratio plot for the composite desirability value for the levels of the max. stress, max. deformation and max. strain. Essentially, the larger the composite desirability, the better is the multiple performance characteristics. In Table VII and Fig. 5, the combination of A_4 and B_1 shows the smallest value of the SN ratio for the factors A and B respectively. Therefore, A_4B_1 i.e. AlSiC 40% and Load of 5000N is the optimal parameter combination.

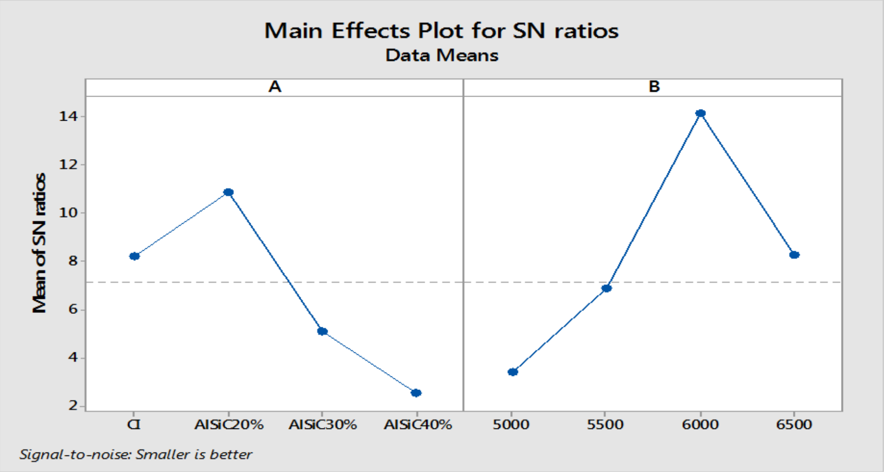

Fig. 5: SN-ratio graph with factors and their levels

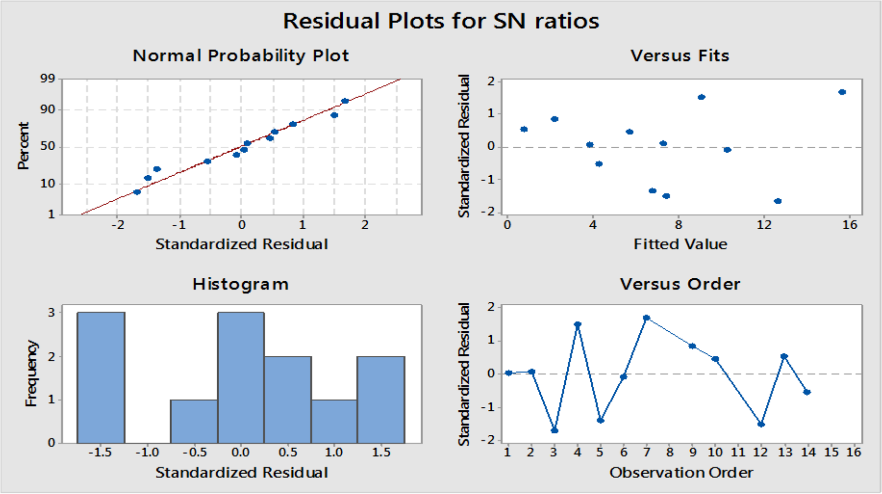

Fig. 6: Residual Plots for SN ratio

TABLE VIII.
THE RESPONSE TABLE FOR COMPOSITE DESIRABILITY

Level	A	B
1	8.224	3.415
2	10.920	6.895
3	5.125	14.174
4	2.549	8.270
Delta	8.371	10.759
Rank	2	1

D. *Most influential factor*

Table IX gives the results of the analysis of variance (ANOVA) for the max. stress, deformation and strain using the calculated values from the Composite Desirability of Table VII and the response table of Table VIII. According to Table IX, factor B, the load induced with 48% of contribution, is the most significant controlled parameters for the camshaft followed by factor A, the material with 21.67% of contribution if the minimization of max. stress, deformation and strain simultaneously considered.

S = 1.221   R-Sq = 96.5%   R-Sq(adj) = 92.2%

TABLE IX.
ANOVA RESULT FOR COMPOSITE DESIRABILITY

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Contribution**
A	3	45.567	15.189	10.20	0.014	21.67
B	3	100.928	33.643	22.58	0.002	48
Error	5	7.449	1.490			3.54
Total	11	210.263				

E. *Confirmation experiment*

After obtaining the best level of parameters, in order to verify the improvement of output quality characteristics, a confirmation test is performed. The Composite Desirability estimated is expressed from the output of confirmation experiment. using the formulae given in Equation (vii) [5].

$$\mu_{predicted} = a_{2m} + b_{1m} - 3\mu_{mean} \quad \text{(vii)}$$

where a_{2m} and b_{1m} are the individual mean values of the Composite Desirability with optimum level values of each parameters and μ_{mean} is the overall mean of Composite Desirability [5]. The predicted mean ($\mu_{predicted}$) at optimal setting is found to be 0.864018. From the confirmation experiment performed with the same experimental setup, maximum stress increases from 22.155 to 22.23 MPa, Maximum deformation reduces to 0.0029812 from 0.003993 mm and maximum strain decreases from 0.0026082 to 0.00019704. Thus the experimental Composite Desirability is 0.8701, which shows an improvement by 35.88 %.

TABLE X.
INITIAL AND OPTIMAL LEVEL PERFORMANCE

	Initial parameter	Optimal parameter	
		Predicted	Experimental
Level Setting	A_1B_1	A_4B_1	A_4B_1
Max. Stress	22.155	*	22.23
Max. Deformation	0.003993	*	0.0029812
Max. Strain	0.00026082	*	0.00019704
Composite desirability value	0.6403	0.864018	0.8701
%Improvement		34.93956	35.88943

TABLE XI.
OPTIMAL PARAMETERS USING TWO OPTIMIZATION METHODS

Algorithm	**A**	**B**
MOORA Technique	AlSiC 40%	5000 MPa
Desirability Function Analysis	AlSiC 40%	5000 MPa

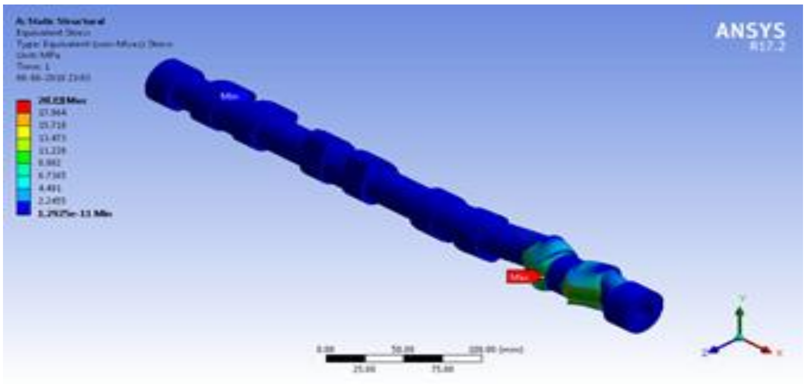

Fig. 7: Von-Misses stress plot of camshaft (AlSiC 40%)

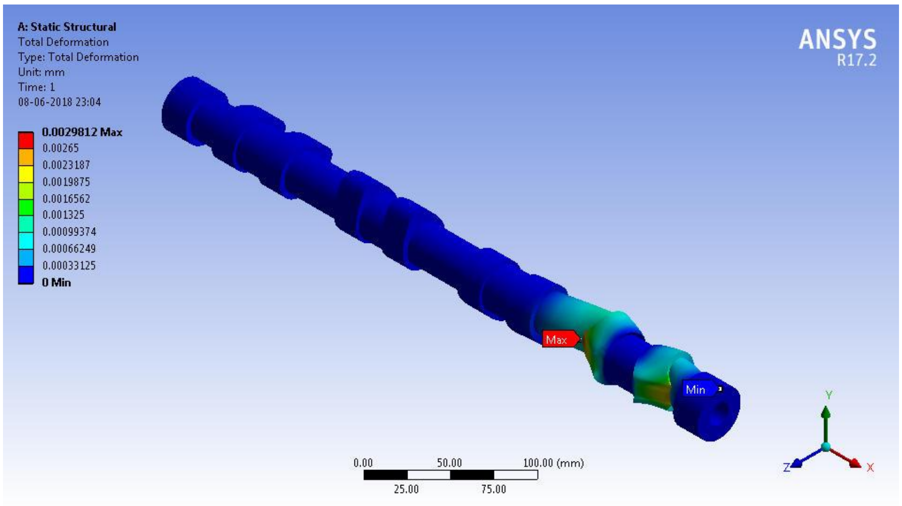

Fig. 8: Total Deformation plot of camshaft (AlSiC 40%)

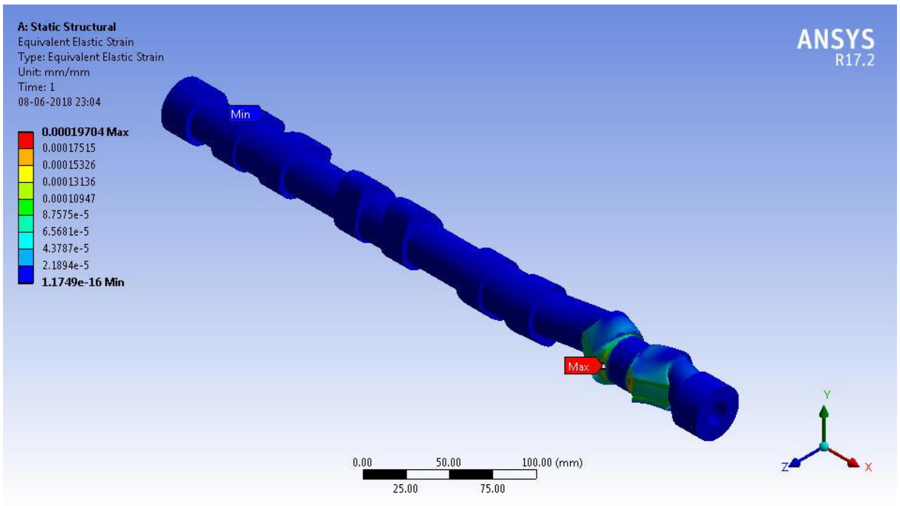

Fig. 9: Equivalent Elastic Strain plot of camshaft (AlSiC 40%)

Fig. 7, 8, 9 shows the Von-Mises stress, Total Deformation and Equivalent Elastic Strain Plot of camshaft made of AlSiC 40% Metal Matrix Composite when subjected to loading of 5000 MPa respectively.

IX. CONCLUSIONS

This paper presents prediction and optimization of designing parameters leading to a minimization of stress, deformation and strain induced during static loading of the camshaft. The predictive values determined using Desirability function analysis is close to the experimental values. The significance of the developed model has been tested by using ANOVA and an examination of residuals. The optimal values will be useful for the industry during selection of material to get the desired design of a camshaft. It has been shown that the MOORA technique approach can be used as an effective and alternative approach for costly and time consuming experimental studies and can contribute to economic optimization of material selection. According to both the optimization technique, AlSiC 40% metal matrix composite can be recommended as an alternative to traditional Cast iron camshaft. This will help in subsequent weight reduction of camshaft during its designing. The results have also proven that the load induced is the main influencing parameter for the camshaft followed by the material. This work can be extended to measure, predict and optimize the material selection for designing a camshaft. More reliable prediction of unit process will enable industry to develop more optimized camshaft design and more efficiency can be achieved during power transmission.

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