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Thermal Design Analysis of Piston Using RSM Method

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***Abstract*- A piston is a component of reciprocating IC-engines. Piston is the component which is moving that is contained by a cylinder and was made gas-tight by piston rings. A mathematical model is formulated based on the simulation result values of total deformation, stress and first ring groove temperature. The Piston during the working condition exposed to the high gas pressure and high temperature gas because of combustion. At the same time it is supported by the small end of the connecting rod with the help of piston pin (Gudgeon pin). The gas pressure given 20 Mpa is applied uniformly over top surface of piston (crown) and arrested all degrees of freedom for nodes at upper half of piston pin boss in which piston pin is going to fix. The statistical ''Design-Expert 8.0.7.1" software has been used to study the regression analysis of simulation data and to draw the response surface plot. The statistical parameters were estimated by using ANOVA. The objective of the study is to minimize the mass. The optimum combination of the influencing parameters for the mass can be found using Response Surface Method. It is found that Height of top land and crown thickness has a dominant effect on total deformation, stress, mass and first ring temperature and The optimal piston mass is determined at height of top land = 2 mm and Crown thickness= 10 mm is 174.43 g.**

***Keywords*- Piston , reciprocating IC-engines, mathematical model, temperature, gas, combustion, piston pin , connecting rod , gas pressure, crown, ring temperature.**

I. INTRODUCTION

A piston is a component of reciprocating IC-engines. Piston is the component which is moving that is contained by a cylinder and was made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod. Nowadays Piston mainly endures the cyclic gas pressure and the inertial forces at working and this working condition may cause the fatigue damage of piston. Piston in an IC engine must possess the good mechanical and thermal characteristics.

Generally pistons are made of Al alloy and cast iron. But the Al alloy is more preferable in comparison of cast iron because of its light weight which suitable for the reciprocating part. There are some drawbacks of Al alloys in comparison to cast iron that are the Al alloys are less in strength and in wearing qualities. The heat conductivity of Al is about of thrice of the cast iron. Al pistons are made thicker which is necessary for strength in order to give proper cooling.

Pistons are designed with features which perform specific functions during engine operation. The piston head or crown receives the majority of the initial pressure and force caused by the combustion process. The piston pin area is exposed to a significant amount of force due to rapid directional changes. It is also subjected to thermal expansion caused by the transfer of heat from the head to the body of the piston. The piston pin area is subject to more thermal expansion than other areas of the piston. This occurs from the thermal expansion properties of cast aluminum alloy and the mass in the piston pin area.

Some pistons are cast and machined at the factory into a cam ground (elliptical shape). An elliptical shape is an oval shape in which one-half is a mirror image of the other half. These piston shapes provide an advantage in conforming to the ever-changing dimensions of the cylinder bore. The piston is designed to be an elliptical shape when cold. As the engine reaches operating temperature, the piston pin bore area expands more than other thinner areas of the piston. At operating temperature, the piston shape becomes a circular shape, which matches the cylinder bore for improved sealing and combustion efficiency.

II. LITERATURE REVIEW

Zhaoju et. al. (2019) calculated the temperature field distribution of the highly intensified diesel engine piston in static compression state and the thermo-mechanical coupling stress and compared with only consider the mechanical load, the results showed that the mechanical load is the major stress.

Mishra (2019) evaluated the strength of reciprocating piston, the simultaneous effect of all these forces should be considered, while simulating through finite element method. With effect of all these forces, the currently considered piston of Gray Cast Iron, aluminum alloy and Metal-Metric-Composite (Si-C) are given four different crown shapes for optimization of material and crown geometry for better strength.

Krishnan et al. (2017) they studied approximately using light-weight materials, which include advanced ultra-high tensile strength steels, aluminum and magnesium alloys, polymers, and carbon-fiber strengthened composite materials.

Sinha et. al. (2017) analyzed piston numerically with FEA software named ANSYS Workbench to assess its thermo mechanical capability under a predefined thermal and structural load.

Gopal et. al. (2017) studied a mechanism of the Piston, Connecting rod and Crank shaft of a four wheeler petrol engine. The components of the assembly have to be inflexible and the assembly has to move as a mechanism.

Shehanaz et. al. (2017) investigated thermal analyses on a piston, made of Cast Aluminum alloy and titanium alloy. Then, structural analyses are performed on piston of titanium alloy &Aluminum alloy material by means of using ANSYS workbench.

Sathish (2016) evaluated the stress distribution on the four stroke engine piston by using FEA. The finite element analysis is performed by using FEA software. The couple field analysis is carried out to calculate stresses and deflection dueto thermal loads and gas pressure.

Pandey et. al. (2016) investigated design, evaluation and optimization of 4 strokes S.I. Engine piston, which is strong and lightweight the usage of finite element analysis with the help of ANSYS Software. Solid Model of piston has been made the use of ANSYS 16.2

Geometric module and Thermo-Mechanical (Static Structural Analysis + Steady-State Thermal Analysis) analysis is achieved to analyze stresses, general deformation and factor of safety distribution in numerous parts of the piston to understand the impact due to gasoline strain and thermal versions using ANSYS 16.2.

Rao et. al. (2016) analyzed the piston model by the use of unigraphics and outcomes are proven by fabricating piston by way of vortex approach the usage of aluminum primarily based mmc containing 5, 10, 15, wt. % and fly ash particulates of 53micro meter.

Here we used stir casting method to get appropriate form and complexity. And after casting suitable machining is completed to the component to get the desired form.

Srinadh et. al. (2015) designed a piston for 1300cc diesel engine vehicle and brought three exclusive profile rings. A 2D drawing is constituted of the calculations. The piston and piston rings have modeled the use of Pro/Engineer software program. The pressure and displacement are analyzed for the piston and piston rings by making use of stress on it in the Structural analysis.

3. RESEARCH METHODOLOGY

1. Methodology of Piston Analysis:

The Piston during the working condition exposed to the high gas pressure and high temperature gas because of combustion. At the same time it is supported by the small end of the connecting rod with the help of piston pin (Gudgeon pin). So the methodology for analyzing the piston is considered as; the gas pressure given 20 Mpa is applied uniformly over top surface of piston (crown) and arrested all degrees of freedom for nodes at upper half of piston pin boss in which piston pin is going to fix. Considering the type of fit between piston pin and piston is clearance fit, only the upper half of piston pin boss is considered to be fixing during the analysis.

2. Selection of Objectives:

The first step of optimization by RSM method is to select proper objectives to be optimized (minimized or maximized). As one of the most important heated parts of internal combustion engine, the piston moves in high speed under high thermal load and mechanical load for a long time.

At present, the calculation and analysis of the piston generally adopt the method of separately analyzing the thermal stress or mechanical stress, and master the stress and deformation of each of them, so as to complete the optimization and design of the whole piston. Piston mass, maximum temperature, maximum mechanical stress and maximum thermo-mechanical coupling stress are the output parameters.

Table 1. Levels of each factor.

Parameters/Factors		Level		
		1	2	3
A	Height of top land	7.2	8.0	8.8
B	Crown thickness	4	7	10

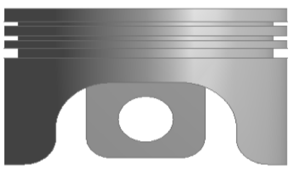

Fig 1. Piston Model.

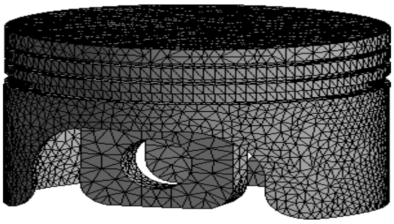

Fig 2. Meshed model of piston.

The element selected for meshing the piston model is solid187 tetrahedron type of element which is higher order tetrahedral element. The mesh count for the model contains 71910 numbers of nodes and 41587 numbers of elements. Figure 4 shows the meshed model of piston.

The main parameters and material characteristics of the piston are: elastic modulus 7200 MPa; Poisson ratio 0.3; Specific heat 902 J/(kgK); Linear expansion coefficient 2.3 x 10-5 K-1;Thermal conductivity 163W/(mK); Density of 2730 kg/m3; The maximum tensile strength 250 MPa (Zhaoju et. al., 2019).

Figure 3.3 shows the loading and boundary conditions considered for the analysis. The uniform pressure of 3.3Mpa is applied on crown of piston which is indicated by red colour and the model is constrained on upper half of piston pin hole as shown by violet colour.

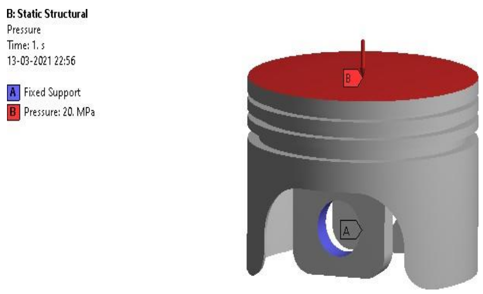

Fig 3. Boundary condition.

IV. RESULTS AND DISCUSSION

Table 2. Total deformation results.

Case no.	Control factors		Total deformation (mm)
	Height of top land	Crown thickness	
1	2	7	0.597
2	2	8	0.566
3	2	10	0.660
4	3	7	0.692
5	3	8	0.818
6	3	10	0.755
7	4	7	0.881
8	4	8	0.849
9	4	10	0.943

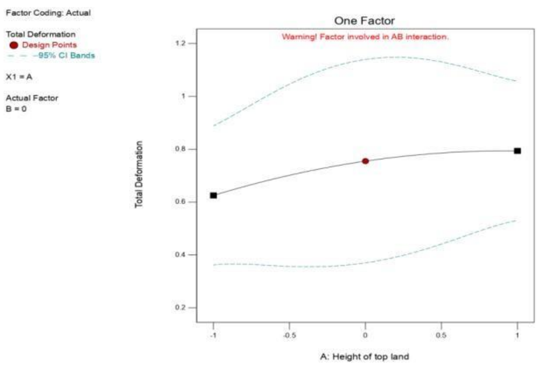

Fig 4. Variation of total deformation with height of top land.

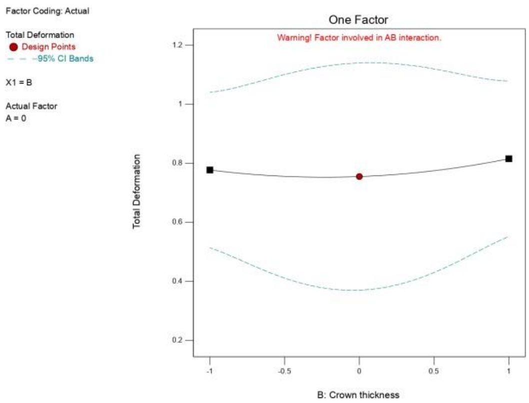

Fig 5. Variation of total deformation with crown thickness.

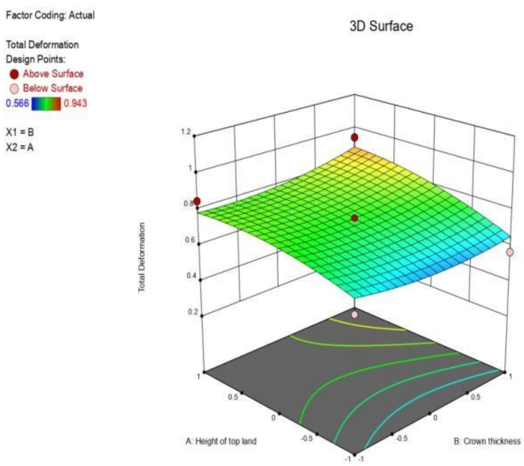

Fig 6. RSM plot of total deformation.

In RSM method, intuitive analysis is usually selected to study factorial effects and contribution ratios of every control factor on the target. It is very important and helpful to know the influence of every factor on them when designing and optimizing piston geometric parameters. Based on the Table 4.2 and above-mentioned formula, factorial effects and RSM plot are further presented in Fig.

From Fig. 4.4, it can be seen that the with increase in height of top land and crown thickness, total deformation increases.

Table 3. Equivalent stress results.

Case no.	Control factors		Equivalent stress(MPa)
	Height of top land	Crown thickness	
1	2	7	858.48
2	2	8	813.3
3	2	10	948.85
4	3	7	994.03
5	3	8	1174.8
6	3	10	1084.4
7	4	7	1265.1
8	4	8	1219.9
9	4	10	1355.5

1. Piston Mass:

Table 4. Piston mass results.

Case no.	Control factors		Mass(g)
	Height of top land	Crown thickness	
1	2	7	167.7
2	2	8	174.2
3	2	10	182.3
4	3	7	168.4
5	3	8	174.9
6	3	10	187.6
7	4	7	168.7
8	4	8	175.2
9	4	10	188.2

Table 5. First ring groove temperature results.

Case no.	Control factors		First ring groove temperature (°C)
	Height of top land	Crown thickness	
1	2	7	137.29
2	2	8	136.34
3	2	10	138.45
4	3	7	139.41
5	3	8	140.23
6	3	10	140.92
7	4	7	140.23
8	4	8	139.41
9	4	10	138.45

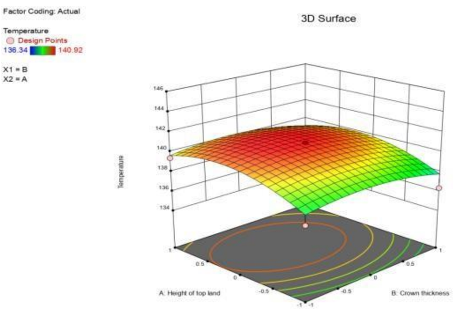

Fig 7. RSM plot of first ring groove temperature.

A mathematical model is formulated based on the simulation result values of total deformation, stress and first ring groove temperature.

Total deformation is given by

Total Deformation =

+0.755000	
+0.084282	Height of top land
+0.019012	Crown thickness
+0.031250	Height of top land * Crown thickness
-0.045500	Height of top land²
+0.041250	Crown thickness²

Where the negative sign indicates the antagonistic effects whereas the positive sign indicates the synergistic effects.

Table 6. ANOVA table for total deformation .

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	214.43	9	64.56	82.17	<0.0001	significant
A-Height of top land	113.61	1	113.61	138.40	<0.0001	
B-Crown thickness	2.27	1	2.27	5.16	0.5370	
AB	88.04	1	88.04	97.41	<0.0001	
A²	225.73	1	225.73	364.24	<0.0001	
B²	8.47	1	8.47	10.33	0.0336	
Residual	9.27	7	0.134			
Lack of fit	0.58	5	0.1675	0.7479	0.6822	Not significant
Pure Error	5.71	2	0.148			
Cor Total	667.49	19				

The Model F-value of 82.17 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

The objective of the study is to minimize the total deformation. The optimum combination of the influencing parameters for the total deformation can be found using Response Surface Method. A list of optimal solutions is got from which the solution with the maximum desirability is chosen. Desirability table has been plotted as graph through which desirability of the total deformation easily identified as shown in Fig 4.12.

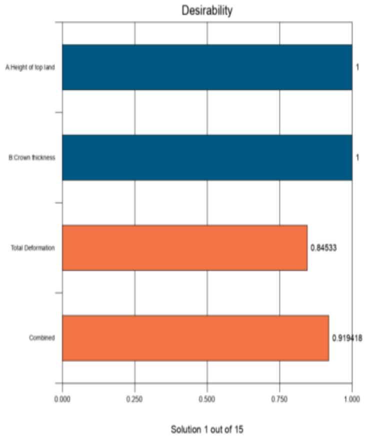

Fig 8. Desirability plot for total deformation.

Table 7. Desirability table for total deformation.

Case no.	Control factors		Total deformation (mm)	Desirability
	Height of top land	Crown thickness		
1	2	7	0.624	0.919
2	2	8	0.624	0.919
3	2	10	0.624	0.919
4	3	7	0.624	0.919
5	3	8	0.624	0.919
6	3	10	0.624	0.919
7	4	7	0.626	0.917
8	4	8	0.626	0.917
9	4	10	0.626	0.917

Table 8. Optimum combination for total deformation.

Control factors		Total deformation (mm)
Height of top land	Crown thickness	
2	7	0.624

The statistical ''Design-Expert 8.0.7.1" software has been used to study the regression analysis of simulation data and to draw the response surface plot. The statistical parameters were estimated by using ANOVA. As the output proposed by the Design-Expert software, the quadratic model was not aliased.

The final empirical model in terms of a coded factor for ash reduction (Y, %) is shown below:

Stress is given by:

Stress =

+1084.40000	
+120.93927	Height of top land
+27.26544	Crown thickness
+45.19500	Height of top land * Crown thickness
-64.95500	Height of top land²
+59.30000	Crown thickness²

The fitness of the model is checked through Analysis of Variance. The model is found to be significant and is presented through the ANOVA table shown in Table no 4.9.

Table 9. ANOVA table for stress.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	334.53	9	77.16	110.67	<0.0001	significant
A-Height of top land	133.72	1	133.72	148.55	<0.0001	
B-Crown thickness	7.47	1	7.47	6.26	0.8812	
AB	89.74	1	89.74	94.81	<0.0001	
A²	275.63	1	275.63	344.84	<0.0001	
B²	9.17	1	9.17	11.23	0.2436	
Residual	8.47	7	0.1049			
Lack of fit	0.68	5	0.1413	10.21	0.0916	Not significant
Pure Error	6.61	2	0.2316			
Cor Total	601.59	19				

The Model F-value of 110.67 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

P-values less than 0.05 indicate model terms are significant. In this case A, AB, and A2 are significant model terms. Values greater than 0.1 indicate the model terms are significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The objective of the study is to minimize the stress. The optimum combination of the influencing parameters for the stress can be found using Response Surface Method. A list of optimal solutions is got from which the solution with the maximum desirability is chosen.

Desirability table has been plotted as graph through which desirability of the stress easily identified as shown in Fig 4.16.

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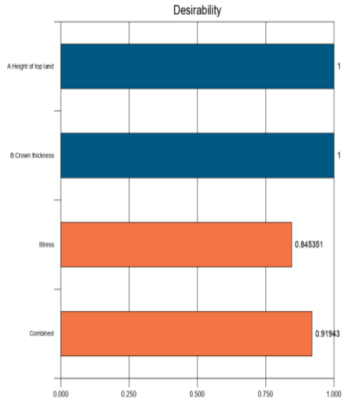

Fig 9. Desirability plot for stress.

Table 10. Desirability table for stress.

Case no.	Control factors		Stress (MPa)	Desirability
	Height of top land	Crown thickness		
1	2	7	897.150	0.919
2	2	8	897.154	0.919
3	2	10	897.156	0.919
4	3	7	897.186	0.919
5	3	8	897.378	0.919
6	3	10	897.634	0.919
7	4	7	898.204	0.918
8	4	8	899.495	0.917
9	4	10	902.520	0.914

The statistical ''Design-Expert 8.0.7.1'' software has been used to study the regression analysis of simulation data and to draw the response surface plot. The statistical parameters were estimated by using ANOVA. As the output proposed by the Design-Expert software, the quadratic model was not aliased. The final empirical model in terms of a coded factor for ash reduction (Y, %) is shown below:

Table 11. Optimum combination for stress.

Control factors		Stress (MPa)
Height of top land	Crown thickness	
2	7	897.15

Mass is given by:

Mass =

+187.60000

+0.230304 Height of top land

+1.34148 Crown thickness

+1.62500 Height of top land * Crown thickness

-5.43750 Height of top land²

-7.21250 Crown thickness²

The fitness of the model is checked through Analysis of Variance. The model is found to be significant and is presented through the ANOVA table shown in Table no 4.11.

Table 12. ANOVA table for mass.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	334.53	9	77.16	80.67	<0.0001	significant
A-Height of top land	133.72	1	133.72	148.55	<0.0001	
B-Crown thickness	7.47	1	7.47	6.26	0.8812	
AB	89.74	1	89.74	94.81	<0.0001	
A²	275.63	1	275.63	344.84	<0.0001	
B²	9.17	1	9.17	11.23	0.2436	
Residual	8.47	7	0.1049			
Lack of fit	0.68	5	0.1413	10.21	0.0916	Not significant
Pure Error	6.61	2	0.2316			
Cor Total	601.59	19				

The Model F-value of 80.67 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.05 indicate model terms are significant. In this case A, AB, and A2 are significant model terms. Values greater than 0.1 indicate the model terms are significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The objective of the study is to minimize the mass. The optimum combination of the influencing parameters for the mass can be found using Response Surface Method. A list of optimal solutions is got from which the solution with the maximum desirability is chosen. Desirability table has been plotted as graph through which desirability of the mass easily identified as shown in Fig 4.17.

Table 13. Desirability table for mass.

Case no.	Control factors		Mass (g)	Desirability
	Height of top land	Crown thickness		

1	2	7	174.436	0.819
2	2	8	174.617	0.814
3	2	10	174.727	0.811
4	3	7	174.848	0.807
5	3	8	175.003	0.802
6	3	10	175.085	0.798
7	4	7	175.190	0.797
8	4	8	175.203	0.796
9	4	10	175.577	0.785

Table 14. Optimum combination for mass.

Control factors		Mass (g)
Height of top land	Crown thickness	
2	7	174.43

The statistical ‘‘Design-Expert 8.0.7.1” software has been used to study the regression analysis of simulation data and to draw the response surface plot. The statistical parameters were estimated by using ANOVA. As the output proposed by the Design-Expert software, the quadratic model was not aliased. The final empirical model in terms of a coded factor for ash reduction (Y, %) is shown below:

First ring temperature is given by:

Temperature =

+140.92000

+0.698456 Height of top land

-0.238750 Crown thickness

-0.002500 Height of top land * Crown thickness

-1.42187 Height of top land^2

-0.771875 Crown thickness^2

The fitness of the model is checked through Analysis of Variance. The model is found to be significant and is presented through the ANOVA table shown in Table no 4.14.

Table 15. ANOVA table for first ring temperature .

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	858.18	9	115.43	137.52	<0.0001	significant
A-Height of top land	253.62	1	253.62	221.11	<0.0001	
B-Crown thickness	43.81	1	43.81	44.38	0.0044	
AB	158.22	1	158.22	135.16	<0.0001	
A^2	338.01	1	338.01	404.44	<0.0001	
B^2	21.17	1	21.17	29.13	0.0063	
Residual	5.47	7	0.98			
Lack of fit	4.16	5	1.06	5.08	0.0778	Not significant
Pure Error	3.11	2	0.39			
Cor Total	942.19	19				

The Model F-value of 137.52 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.05 indicate model terms are significant. In this case A, AB, and A2 are significant model terms. Values greater than 0.1 indicate the model terms are significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The objective of the study is to minimize the mass. The optimum combination of the influencing parameters for the first ring temperature can be found using Response Surface Method. A list of optimal solutions is got from which the solution with the maximum desirability is chosen. Desirability table has been plotted as graph through which desirability of the mass easily identified as shown in Fig 4.18.

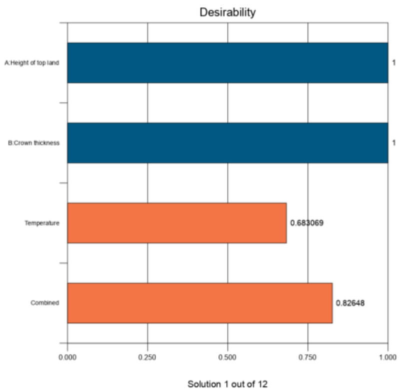

Fig 10. Desirability plot for temperature.

Table 16. Desirability table for temperature.

Case no.	Control factors		Temperature	Desirability
	Height of top land	Crown thickness		
1	2	7	137.792	0.826
2	2	8	137.830	0.821

3	2	10	137.827	0.820
4	3	7	137.847	0.819
5	3	8	137.862	0.813
6	3	10	137.898	0.812
7	4	7	138.041	0.793
8	4	8	138.173	0.775
9	4	10	138.264	0.762

Table 17. Optimum combination for temperature.

Control factors		Temperature
Height of top land	Crown thickness	
2	7	137.792

V. CONCLUSION

From the present study following conclusions can be done:-

Height of top land and crown thickness has a dominant effect on total deformation, stress, mass and first ring temperature.

The optimal total deformation is determined as height of top land = 7.2 mm and Crown thickness= 7 mm is 0.624 mm.

The optimal equivalent stress is determined at height of top land = 2 mm and crown thickness= 4 mm is 897.5 MPa.

The optimal piston mass is determined at height of top land = 2 mm and Crown thickness= 10 mm is 174.43 g.

The optimal first ring groove temperature is determined at height of top land = 2 mm and Crown thickness= 7 mm is 137.9ºC.

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