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FEM ANALYSIS AND DESIGN OPTIMISATION OF PISTON

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Abstract: In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. As an important part in an engine, piston endures the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of piston, such as piston side wear, piston head/crown cracks and so on. The investigations indicate that the greatest stress appears on the upper end of the piston and stress concentration is one of the mainly reason for fatigue failure. This work describes the stress distribution on piston of internal combustion engine by using FEA. The FEA is performed by CAD and CAE software. The main objectives are to investigate and analyze the thermal stress and mechanical stress distribution of piston at the real engine condition during combustion process. The work also describes the FEA technique to predict the higher stress and critical region on the component. With using CATIA software the structural model of a piston was developed. Using ANSYS V14.5 software, simulation and stress analysis was performed.

Keywords: crankshaft, piston, connecting rod, CATIA, FEA, thermal stress, mechanical stress distribution, combustion, structural model, simulation.

1. INTRODUCTION

Piston is a reciprocating component in an engine which converts the chemical energy after the burning of fuel into mechanical energy. The purpose of the piston is to transfer the energy to crankshaft via connecting rod. The piston ring is used to provide seal between the cylinder and piston. It must able to work with low friction, high explosive forces and high temperature around 2000℃ to 2800℃.The piston is to be strong but its weight should be less to prevent inertia forces due to reciprocating motion.

It is the moving component that is contained by a cylinder and is made gas tight by piston rings. In an engine, its transfer force from expanding gas in the cylinder to the crankshaft via a piston rod or connecting rod. As a main part in an engine, piston endures the cyclic gas pressure and the inertial forces at work, and this real working condition may cause the fatigue damage of piston, such as piston skirt wear, piston head or crown cracks and so on. The investigations denote that the greatest stress appears on the upper end of the piston and stress concentration is one of the mainly reason for fatigue failure. On the other hand piston over heating-seizure can only occur when something burns or scrapes away the oil film that exists between the piston and the cylinder wall. Understanding this, it's not hard to visually why oils with exceptionally high film strengths are very desirable. Good quality oils will offer provide a film that stands up to the most intense heat and the pressure loads of a modern high output engine. Thermal analysis is a branch of materials science where the properties of materials are studied as they change with temperature. Finite element method (FEM) is commonly used for thermal Analysis. Due to the complicated working environment for the piston; on one hand, the finite element method (FEM) for the piston became more difficult, on the other hand, though there have many methods which are put forward to apply optimal design, the optimal parameters is not easy to determine. 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.

2. 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.

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 due to thermal loads and gas pressure.

Pandey et. Al. (2016) investigated design, evaluation and optimization of 4 stroke S.I. Engine piston, which is strong and lightweight the usage of finite element analysis with the help of ANSYS Software

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.

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.

Prasanth et. Al. (2015) they conducted a thermal evaluation of piston by way of the use of Hybrid steel matrix. In the prevailing work, a specimen is made to Al-Sic-graphite contained in particulate metal matrix composites by way of stir casting method.

Singh et. Al. (2015) they studied the stress variations and thermal stresses of three various aluminum alloys piston by using finite element method (FEM). The parameters used for the simulation are performing gas pressure, temperature and material behaviors of piston.

3. RESEARCH METHODOLOGY

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.

3.1 SELECTION OF OBJECTIVES

The first step of optimization by Taguchi 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. The stress generated by these loads affects its service life, which is directly related to the reliability and durability of internal combustion engine [1–3]. The overall design of piston involves flow field, temperature field, structure and other disciplines, and each discipline has strong interrelationship.

Table 3.1: 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

3.2 PISTON MODEL

Figure 3.1 show the piston created by CAD software for further analysis.

The following are the sequence of steps in which the piston is modelled.

- Drawing a half portion of piston
- Exiting the sketcher
- Developing the model
- Creating a hole

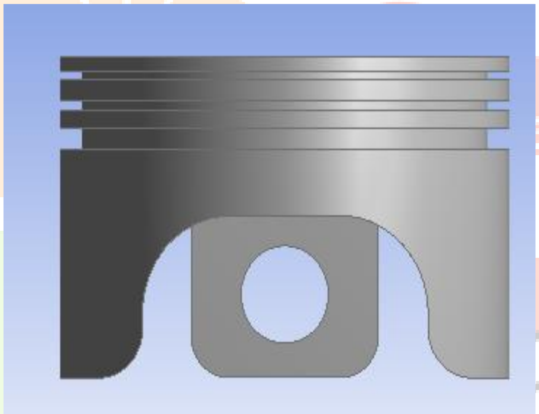

Fig. 3.1: Piston Model

3.3 PROPERTIES OF MATERIALS

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/m^3; The maximum tensile strength 250 MPa (Zhaoju et. al., 2019).

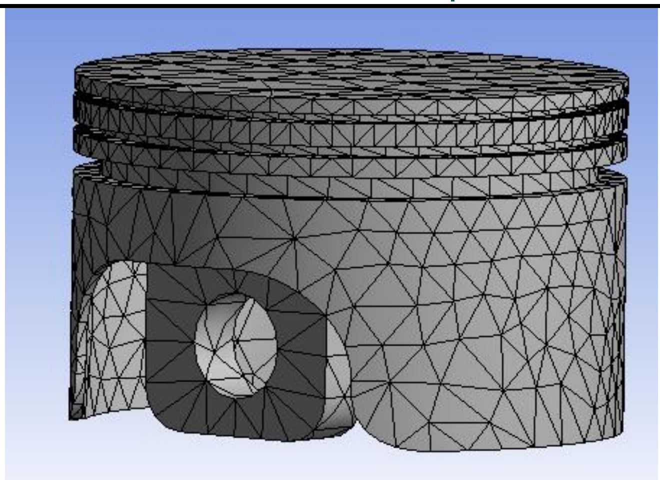

Fig. 3.2: Meshed model of piston

Figure 3.3 shows the loading and boundary conditions considered for the analysis. The uniform pressure of 3.3 Mpa 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.

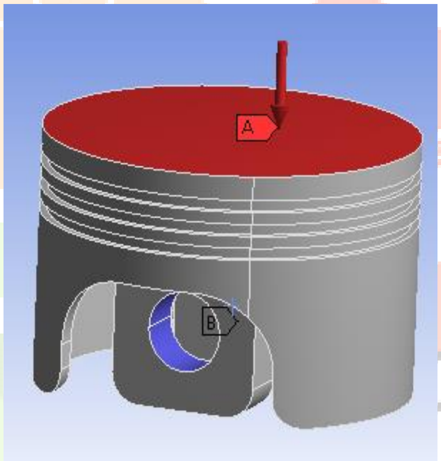

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Fig. 3.3: Boundary condition

4. RESULTS AND DISCUSSION

4.1 Total deformation

Table 4.1: Total deformation results

Case no.	Control factors		Total deformation (mm)
	Height of top land	Crown thickness	
1	2	7	1.014
2	2	8	0.848
3	2	10	0.597
4	3	7	1.050
5	3	8	0.876
6	3	10	0.615
7	4	7	1.076
8	4	8	0.897
9	4	10	0.629

Table 4.2: Factorial effects for SNR-total deformation

Level	Height of top land	Crown thickness
1	1.9306	-0.3936
2	1.6495	1.1754
3	1.4450	4.2433
Delta	0.4856	4.6369
Rank	2	1

$$\text{Contribution ratio}(i) = \frac{\text{SNR}_{\max,i} - \text{SNR}_{\min,i}}{\sum_{i=1}^{k}(\text{SNR}_{\max,i} - \text{SNR}_{\min,i})}$$

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 contribution ratios for height of top land and crown thickness are further presented in Fig. 4.2.

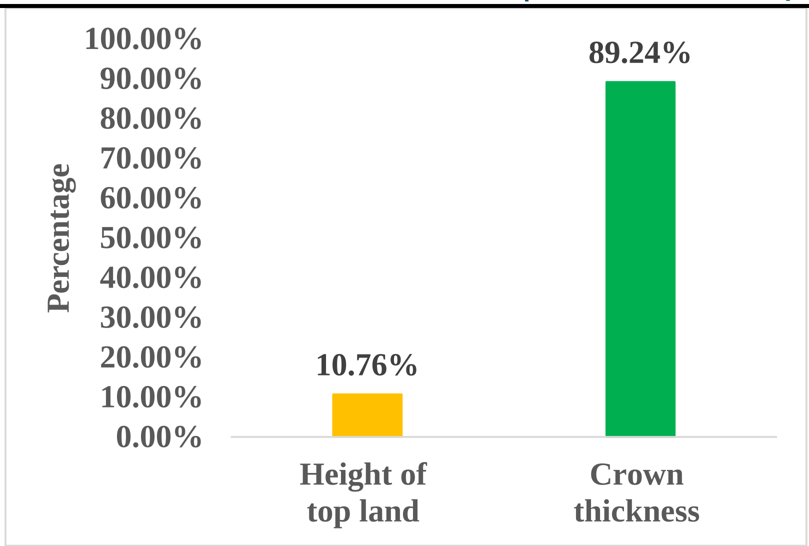

Fig. 4.2: Contribution ratio of each factor for SNR-total deformation

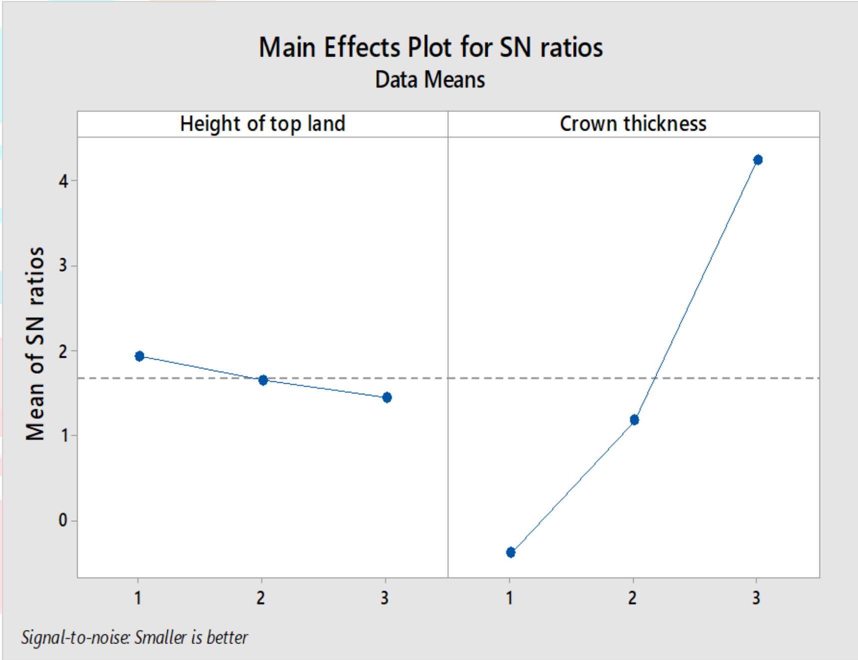

Fig. 4.3: Main effect plot for SNR-total deformation

It has been known that the level that has the smallest SNR is the optimal level for the factor. If interaction effects between all factors can be negligible, the combinations of levels showing the smallest SNR-total deformation for each factor are regarded as the optimal level combination respectively. From fig. 4.3, the optimal combination for SNR-total deformation is determined as A3B1.

4.2 EQUIVALENT STRESS

Table 4.3: Equivalent stress results

Case no.	Control factors		Equivalent stress(MPa)
	Height of top land	Crown thickness	
1	2	7	1216.3
2	2	8	1097.9
3	2	10	954.9
4	3	7	1409.6
5	3	8	1209.2
6	3	10	907.07
7	4	7	1343.4
8	4	8	1048.5
9	4	10	903.67

Table 4.4: Factorial effects for SNR-Equivalent stress

Level	Height of top land	Crown thickness
1	-60.70	-62.42
2	-61.26	-60.96
3	-60.70	-59.29
Delta	0.56	3.12
Rank	2	1

Main-effect plots for SNR-equivalent stress is shown in Fig. 4.6.From Fig. 4.5, it can be seen that the order of the parametric effectiveness for equivalent stress is crown thickness>height of top land. Crown thickness has a dominant effect on equivalent stress with contribution ratio of 84.78%

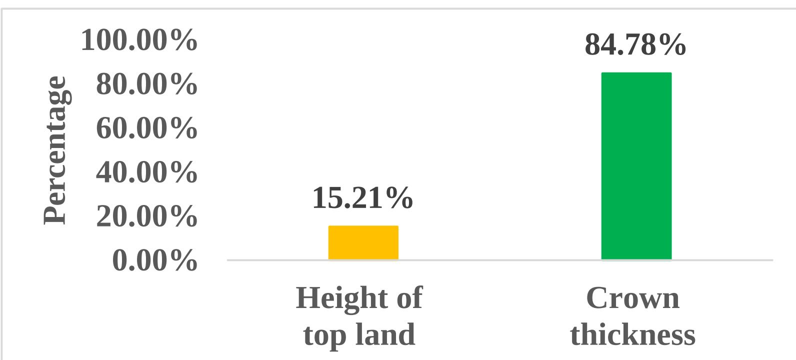

Fig. 4.5: Contribution ratio of each factor for SNR-Equivalent stress

It has been known that the level that has the smallest SNR is the optimal level for the factor. If interaction effects between all factors can be negligible, the combinations of levels showing the smallest SNR-equivalent stress for each factor are regarded as the optimal level combination respectively. From fig. 4.6, the optimal combination for SNR-Equivalent stress is determined as A2B1.

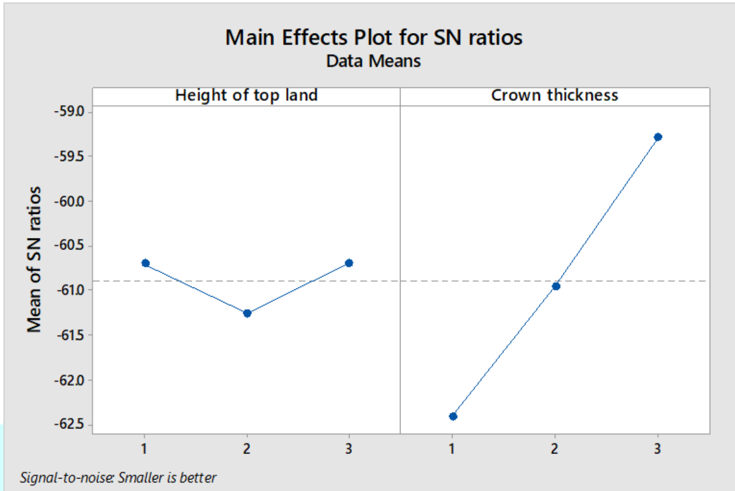

Fig. 4.6: Main effect plot for SNR-Equivalent stress

4.3 PISTON MASS

In this work the main consideration is to optimize the piston with reduction of piston weight. The material of the piston becomes reduced. Then the optimized result of the piston obtained.

Table 4.5: 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 4.6: Factorial effects for SNR-Piston mass

Level	Height of top land	Crown thickness
1	-44.84	-44.52
2	-44.95	-44.85
3	-44.97	-45.39
Delta	0.13	0.87
Rank	2	1

.From Fig. 4.5, it can be seen that the order of the parametric effectiveness for piston mass is crown thickness>height of top land. Crown thickness has a dominant effect on piston mass with contribution ratio of 84.78%

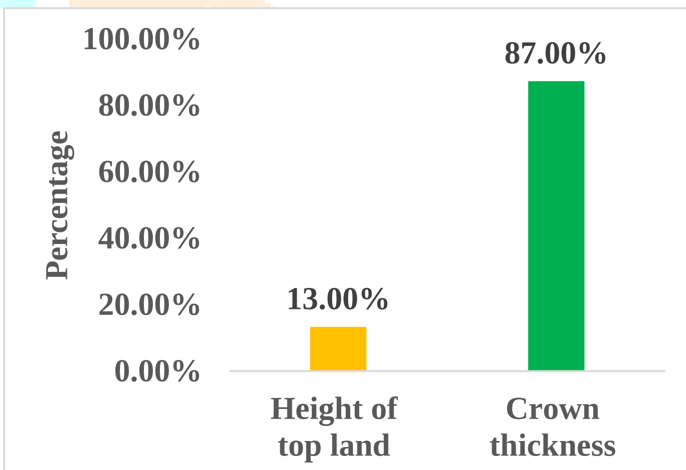

Fig. 4.7: Contribution ratio of each factor for SNR-Equivalent stress

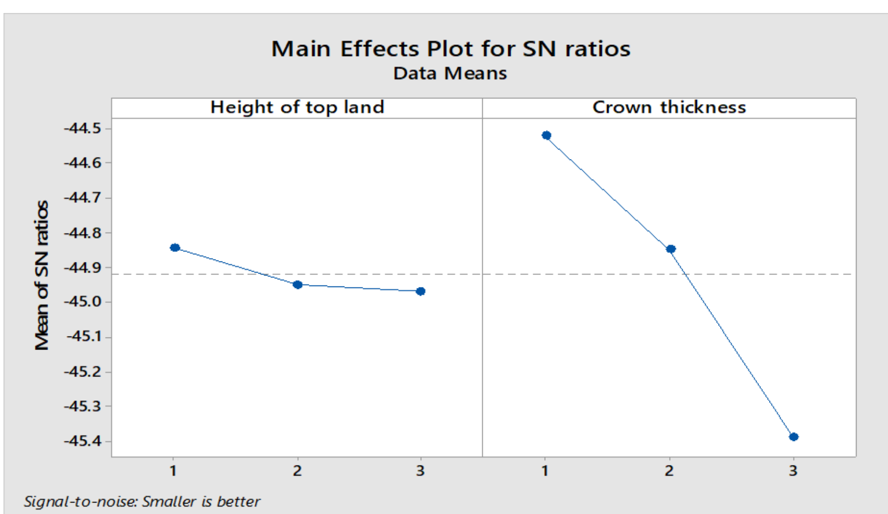

Fig. 4.8: Main effect plot for SNR-Piston mass

It has been known that the level that has the smallest SNR is the optimal level for the factor. If interaction effects between all factors can be negligible, the combinations of levels showing the smallest SNR-piston mass for each factor are regarded as the optimal level combination respectively. From fig. 4.8, the optimal combination for SNR-Piston mass is determined as A3B3.

4.4 FIRST RING GROOVE TEMPERATURE

Table 4.7: First ring groove temperature results

Case no.	Control factors		Firstring groove temperature(°C)
	Height of top land	Crown thickness	
1	2	7	135.9
2	2	8	137.3
3	2	10	138.41
4	3	7	137.2
5	3	8	138.45
6	3	10	137.32
7	4	7	137.27
8	4	8	138.44
9	4	10	137.29

Table 4.8: Factorial effects for SNR-First ring groove temperature

Level	Height of top land	Crown thickness
1	-42.75	-42.72
2	-42.78	-42.80
3	-42.78	-42.78
Delta	0.03	0.08
Rank	2	1

Main-effect plots for SNR-First ring groove temperature is shown in Fig. 4.11.From Fig. 4.10, it can be seen that the order of the parametric effectiveness for first ring groove temperature is crown thickness>height of top land. Crown thickness has a dominant effect on first ring groove temperature with contribution ratio of 72.72%

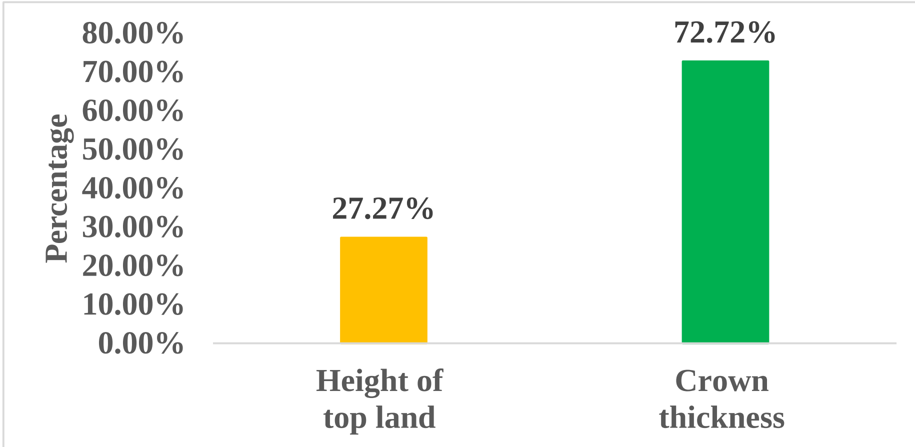

Fig. 4.10: Contribution ratio of each factor for SNR-First ring groove temperature

It has been known that the level that has the smallest SNR is the optimal level for the factor. If interaction effects between all factors can be negligible, the combinations of levels showing the smallest SNR-equivalent stress for each factor are regarded as the optimal level combination respectively. From fig. 4.11, the optimal combination for SNR-First ring groove temperature is determined as A3B2.

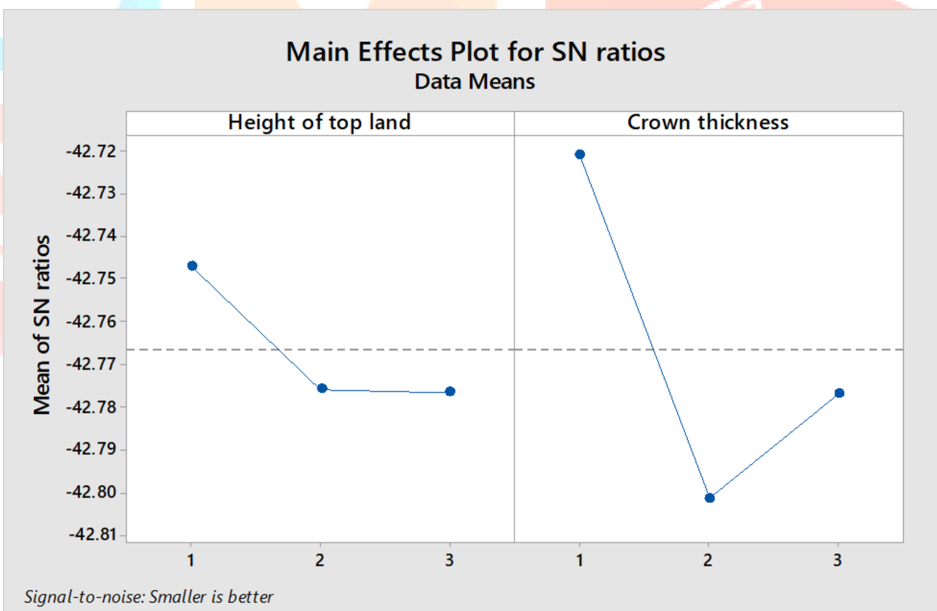

Fig. 4.11: Main effect plot for SNR-First ring groove temperature

5. CONCLUSION

From the present study following conclusions can be done:-

1. It can be seen that the order of the parametric effectiveness for total deformation is crown thickness >height of top land. Crown thickness has a dominant effect on total deformation with contribution ratio of 89.24%
2. It can be seen that the order of the parametric effectiveness for equivalent stress is crown thickness >height of top land. Crown thickness has a dominant effect on equivalent stress with contribution ratio of 84.78%
3. It can be seen that the order of the parametric effectiveness for total deformation is crown thickness >height of top land. Crown thickness has a dominant effect on total deformation with contribution ratio of 84.78%
4. It can be seen that the order of the parametric effectiveness for first ring groove temperature is crown thickness >height of top land. Crown thickness has a dominant effect on first ring groove temperature with contribution ratio of 72.72%.
5. The optimal combination for SNR-total deformation is determined as Height of top land = 7.2 mm and Crown thickness= 7 mm.
6. The optimal combination for SNR-Equivalent stress is determined as Height of top land = 8 mm and Crown thickness= 4 mm.
7. The optimal combination for SNR-Piston mass is determined as Height of top land = 8.8 mm and Crown thickness= 10 mm.
8. The optimal combination for SNR-First ring groove temperature is determined as Height of top land = 8.8 mm and Crown thickness= 7 mm.

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