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PAGES:6-18
5/1/24
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FEM Analysis And Design Optimization Of The Piston

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ABSTRACT

The workings of an engine rely on the piston rod and/or connecting rod to transmit the force of the expanding gas in the cylinder to the crankshaft. Because of its critical role in engines, the piston is subject to inertial stresses and cyclic gas pressure, which may lead to fatigue damage in the form of side wear, fractures in the piston head or crown, and other issues. According to the research, the top of the piston experiences the highest level of stress, which is a major contributor to fatigue failure. This study uses finite element analysis to illustrate the stress distribution on an internal combustion engine's piston. It is the CAD and CAE programs that carry out the FEA. Examining and analyzing the distribution of thermal and mechanical stresses on the piston under real-world engine conditions during combustion is the primary focus. Predicting the component's critical area and greater stress using finite element analysis is also detailed in the paper. Created a structural model of a piston using CATIA software. We ran simulations and stress analyses with the help of ANSYS V14.5.

Keywords: Piston, CATIA, FEA, mechanical stress distribution, combustion, simulation.

1. INTRODUCTION

In order to transform the chemical energy that results from burning fuel into mechanical energy, an engine's piston must reciprocate. The piston's job, via the connecting rod, is to transmit power to the crankshaft. The piston ring acts as a sealant between the piston and the cylinder. Its operating temperature range should be 2000–2800 degrees Celsius, and it should be able to withstand strong explosive forces and little friction.A lightweight, robust piston is required to avoid inertia forces caused by reciprocating action.

The piston rings seal the cylinder, allowing the moving part within to remain gas tight. The piston rod or connecting rod in an engine transfers the force from the expanding gas in the cylinder to the crankshaft. Because of its central role in engines, the piston is subject to the cyclic gas pressure and inertial forces that are always at work, which may lead to fatigue damage in the form of wear on the piston skirt, cracks in the piston head or crown, and other similar issues. The studies show that the top of the piston experiences the most stress, and that this concentration of stress is a major cause of fatigue failure. But, anything that scrapes or burns away the oil coating that separates the piston from the cylinder wall is the only item that may cause a piston overheating seizure. After you know this, it's easy to see why oils with extremely high film strengths are so desired. The film that high-quality oils provide can withstand the extreme temperatures and pressure loads seen by today's high-output engines. The study of how material characteristics alter with changes in temperature is known as thermal analysis, and it is a subfield of materials science. It is usual practice to conduct heat analyses using the finite element technique (FEM). The piston's complex working environment has two effects: first, it has made finite element method (FEM) applications more difficult; and second, despite several approaches to optimum design, determining the ideal parameters remains a challenging task. The design of pistons is such that they carry out certain tasks while the engine is running. The combustion process applies a great deal of initial pressure and force on the piston head or crown.

2. LITERATURE REVIEW

Zhaoju et. Al. (2019) examined the thermo-mechanical coupling stress with the temperature field distribution of the highly intensified diesel engine piston in a static compression condition, and found that mechanical load is the most significant stress.

Mishra (2019) Considering the reciprocating piston's strength, it is important to take into account the combined impact of all these forces while running the simulation using the finite element approach.

Krishnan et al. (2017) Lightweight materials, such as polymers, carbon-fiber reinforced composites, improved ultra-high tensile strength steels, aluminum and magnesium alloys, and so on, were the subject of their study.

Sinha et. Al. (2017) assessed the thermomechanical capabilities of the piston numerically using ANSYS Workbench, a finite element analysis program, under a set of predetermined thermal and structural loads.

Gopal et. Al. (2017) examined the workings of a gasoline four-wheeler engine's piston, connecting rod, and crank shaft. All of the parts must be rigid, and the whole must be able to move in unison.

Shehanaz et. Al. (2017) performed thermal studies on a titanium and cast-aluminum alloy piston. Then, we use the ANSYS workbench to conduct structural analysis on pistons made of titanium alloy and aluminum alloy.

Pandey et. Al. (2016) used ANSYS software for finite element analysis to study the design, assessment, and optimization of a strong and lightweight piston for a four-stroke S.I. engine.

3. RESEARCH METHODOLOGY

Byproducts of combustion expose the piston to very hot and pressurized gas as it works. Concurrently, the piston pin (also known as a Gudgeon pin) and the tiny end of the connecting rod provide support. The procedure for evaluating the piston is as follows: a gas pressure of 20 MPa is evenly distributed throughout the piston's top surface (the crown), and all of the nodes at the top half of the pin boss, where the pin will be fixed, have their degrees of freedom halted. The study only takes into account the top half of the piston pin boss as a fixing point since the fit between the piston and pin is a clearance fit.

3.1 SELECTION OF OBJECTIVES

Choosing the right goals to optimize (minimized or maximized) is the first stage in the Taguchi technique of optimization.The piston, a critical component of internal combustion engines, travels at high speeds while subjected to significant mechanical and thermal loads for extended periods of time. The amount of time an internal combustion engine can withstand these stresses is proportional to its dependability and longevity [1-3]. Each of the several disciplines involved in the design of a piston—structure, flow field, temperature field, and others—has a close link with the others.

Table 3.1: Levels of each factor

Constraints/Aspects		Level		
		1	**2**	**3**
A	Top land height	7.1	8.6	8.9
B	Thickness of crown	5	7	11

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3.2 PISTON MODEL

The computer-aided design (CAD) piston used in this investigation is shown in Figure 3.1. Here is the process flow diagram for modeling the piston.

- Sketching out the lower section of the piston
- Leaving the sketching tool
- Building the prototype
- Forming a hole

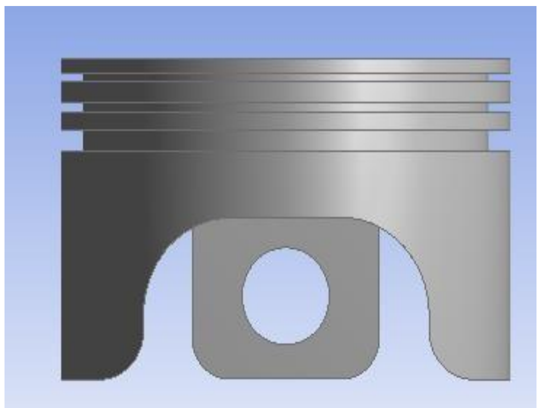

Fig. 3.1: Piston Model

3.3 PROPERTIES OF MATERIALS

Elastic modulus 7200 MPa, Poisson ratio 0.3, specific heat 902 J/(kgK), linear expansion coefficient 2.3 x 10^4 K-1, thermal conductivity 163 W/(mK), density 2730 kg/m^3, and maximum tensile strength 250 MPa are the primary parameters and material properties of the piston. (Zhaoju et. al., 2019).

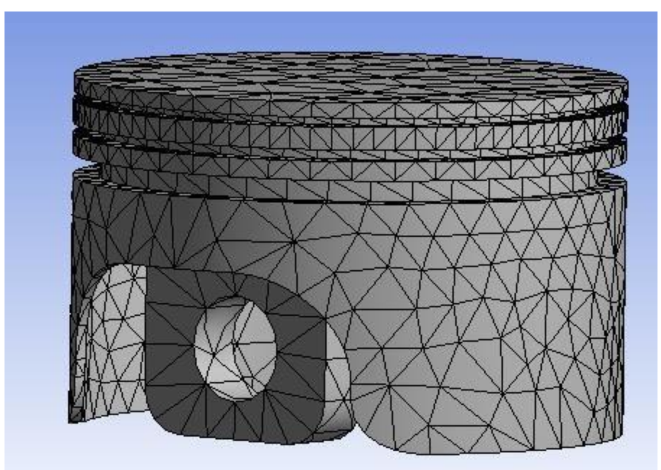

Fig. 3.2: Meshed model of piston

The loading and boundary conditions that were taken into account for the study are shown in Figure 3.3. The red area represents the piston crown, where a uniform pressure of 3.3 MPa is applied, and the violet area represents the top half of the piston pin hole, where the model is limited.

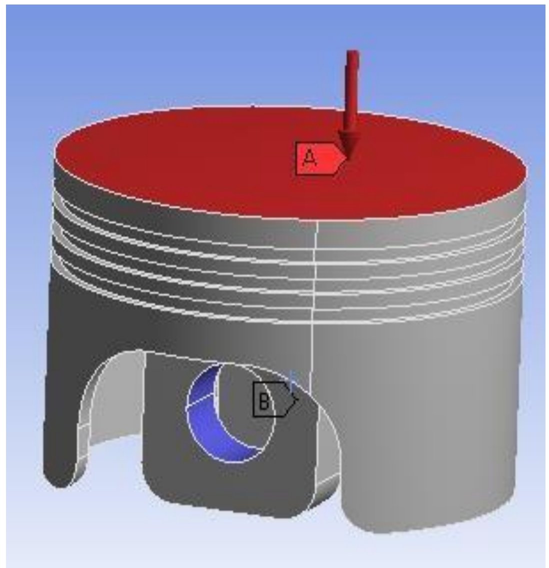

Fig. 3.3: Boundary condition

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	1.015
2	2	8	0.856
3	2	10	0.589
4	3	7	1.049
5	3	8	0.882
6	3	10	0.599
7	4	7	1.074
8	4	8	0.889
9	4	10	0.638

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

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

When optimizing the geometric characteristics of a piston, it is crucial to know how each element affects them. In addition to the formula and Table 4.2, Fig. 4.2 displays the factorial effects and contribution ratios for top land height and crown thickness.

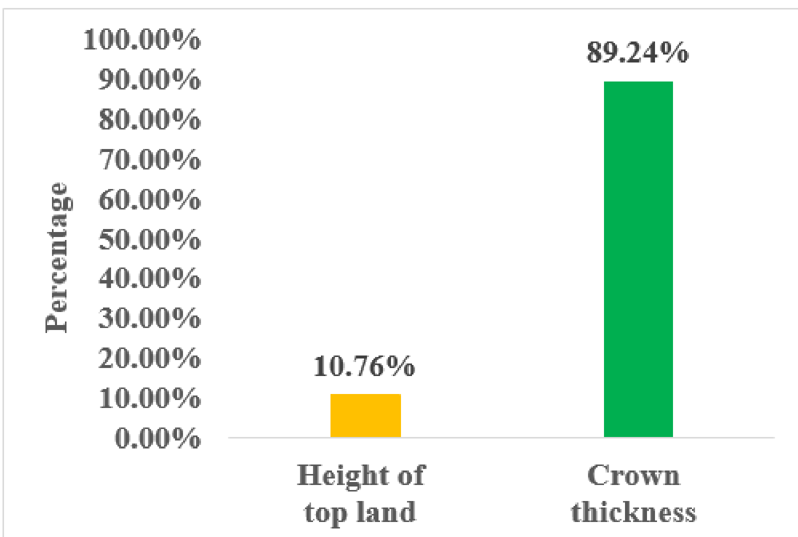

Fig. 4.2: Contribution ratio of each factor for SNR-total deformation

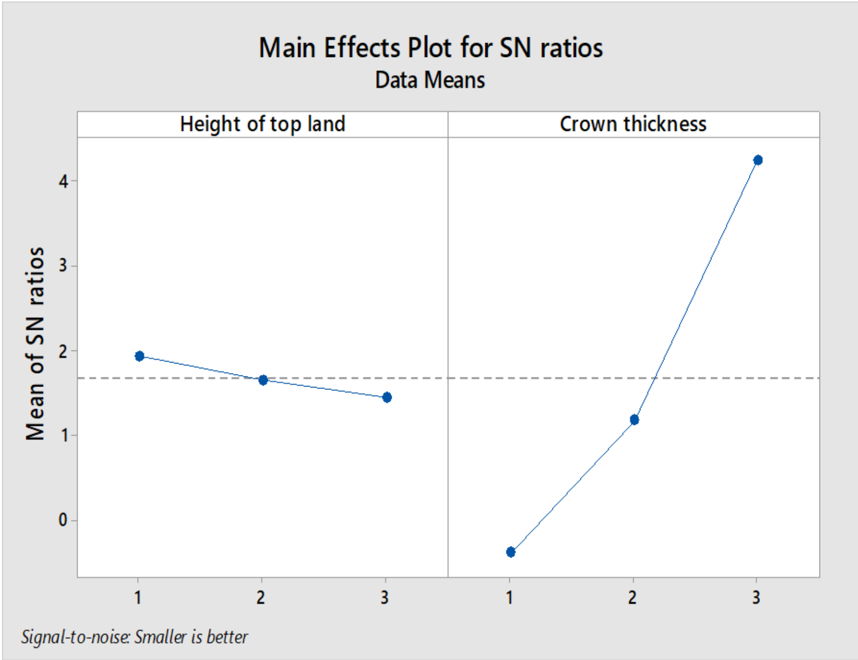

Fig. 4.3: Main effect plot for SNR-total deformation

It is well-established that the factor works best at the level with the lowest signal-to-noise ratio (SNR). The ideal level combinations for each component are those that demonstrate the least SNR-total deformation, assuming that the interaction effects between all elements may be minimal. Figure 4.3 shows that A3B1 is the best combination for SNR-total deformation.

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	12224.6
2	2	8	1098.8
3	2	10	960.2
4	3	7	1411.5
5	3	8	1214.8
6	3	10	906.02
7	4	7	1336.5
8	4	8	1039.9
9	4	10	904.55

Table 4.4: Factorial effects for SNR-Equivalent stress

Level	**Height of top land**	**Thicknes s of Crown**
1	-60.80	-63.10
2	-61.18	-60.87
3	-60.80	-58.98
Delta	0.58	3.22
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%

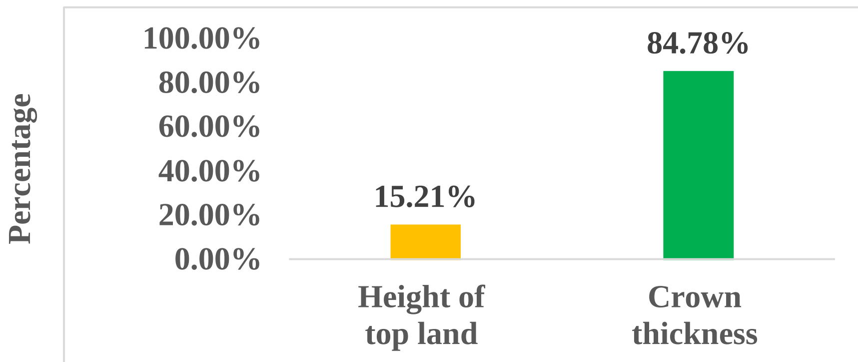

Fig. 4.5: Weighted average of all components for SNR-equivalent stress

It is well-established that the factor works best at the level with the lowest signal-to-noise ratio (SNR). The ideal level combinations for each element are those that demonstrate the minimum SNR-equivalent stress, assuming that the interaction effects between all variables may be insignificant. Figure 4.6 shows that A2B1 is the best combination for SNR-Equivalent stress.

PAGES:6-18
5/1/24
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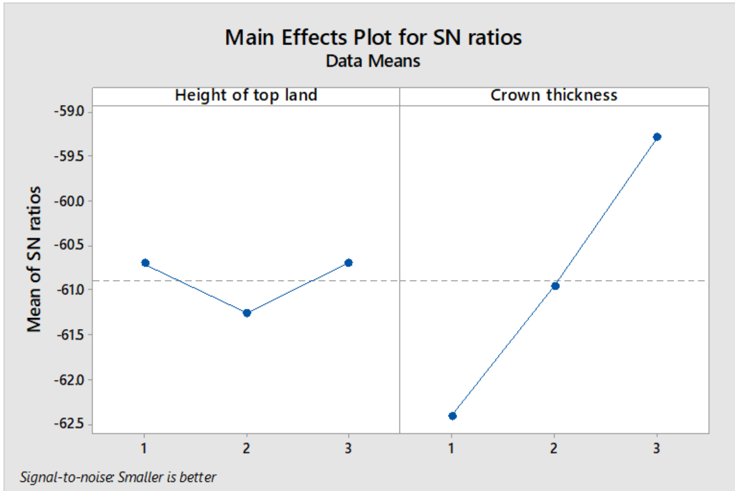

Fig. 4.6: Main effect plot for SNR-Equivalent stress

4.3 PISTON MASS

Optimizing the piston by reducing piston weight is the primary focus of this effort. There is a decrease in the piston's substance. Afterwards, we got the piston's optimal result.

Table 4.5: Piston mass results

Case no.	Control factors		Mass(g)
	Top land height	Thickness of Crown	
1	2	8	168.6
2	2	8	175.3
3	2	10	183.2
4	3	7	165.9
5	3	7	175.8
6	3	10	188.1
7	4	7	166.9
8	4	8	176.1
9	4	10	189.0

Table 4.6: Factorial effects for SNR-Piston mass

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

Crown thickness>height of top land is the order of the parametric efficacy for piston mass, as shown in Fig. 4.5. The crown thickness is the most important factor affecting the piston mass, accounting for 84.78% of the total.

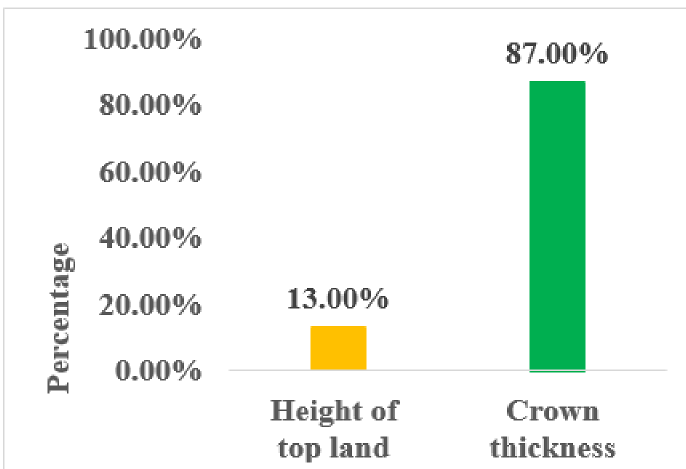

Fig. 4.7: Weighted average of all components for SNR-equivalent stress

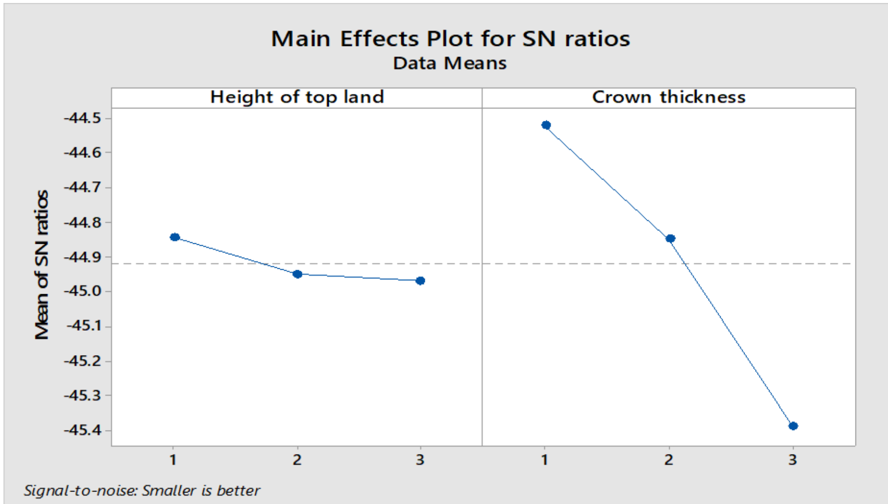

Fig. 4.8: Graph showing the main influence of SNR-Piston mass

The best value for the factor is the one with the lowest signal-to-noise ratio (SNR), as is well known. The ideal level combinations for each element are those that display the minimum SNR-piston mass, assuming that the interaction effects between all variables may be insignificant. See figure for reference. 4.8, A3B3 is the best SNR-Piston mass combo.

4.4 FIRST RING GROOVE TEMPERATURE

Table 4.7: First ring groove temperature results

Case no.	Controlling factors		Fir string groove temp(°C)
	Top land Height	Thickness of Crown	
1	2	7	136.1
2	2	8	138.0
3	2	10	138.41
4	3	7	137.2
5	3	8	138.45
6	3	10	138.21
7	4	7	135.98
8	4	8	139.10
9	4	10	136.33

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

Level	Top land Height	Thicknes s of Crown
1	-42.75	-42.65
2	-42.78	-42.77
3	-42.78	-42.81
Delta	0.03	0.08
Rank	2	1

Figure shows the main effect charts for SNR-First ring groove temperature. 4.11.From Fig. The order of the parametric efficacy for the temperature of the first ring groove is crown thickness>height of top land, as shown in 4.10. The temperature in the first ring groove is most affected by the thickness of the crown (72.72% contribution ratio).

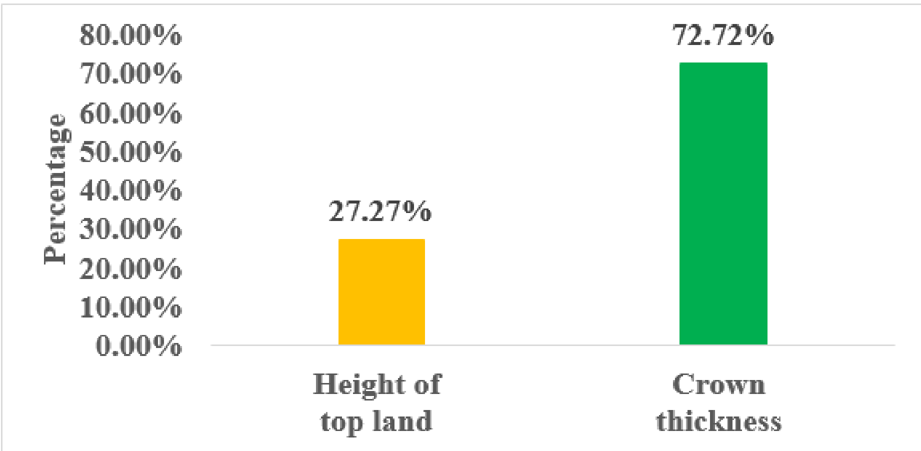

Fig. 4.10: Contribution ratio of each factor for SNR-First ring groove temperature

It is well-established that the factor works best at the level with the lowest signal-to-noise ratio (SNR). The ideal level combinations for each element are those that demonstrate the minimum SNR-equivalent stress, assuming that the interaction effects between all variables may be insignificant. See figure for reference. We find that A3B2 is the best combination for SNR-First ring groove temperature in 4.11..

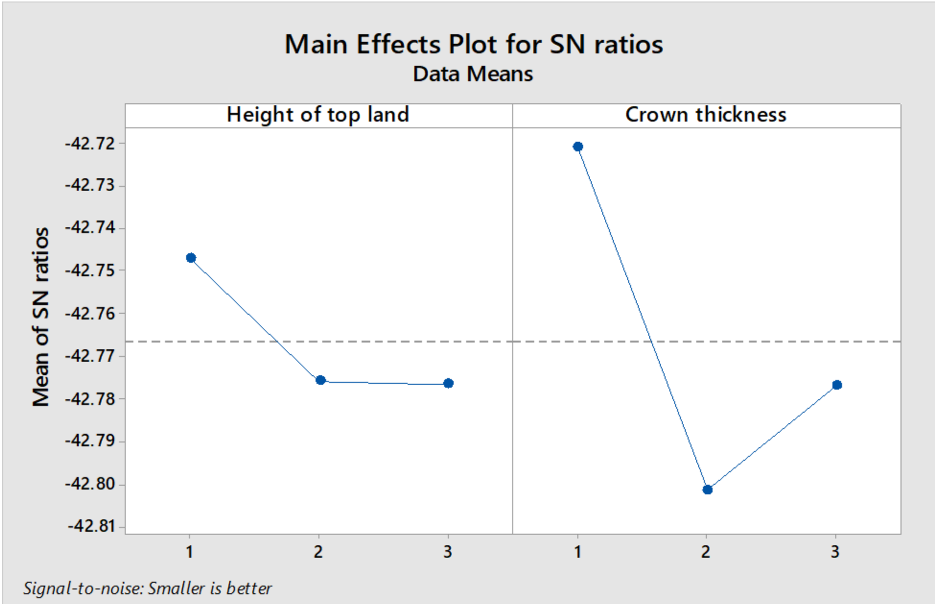

Fig. 4.11: First ring groove temperature main effect graphic for signal-to-noise ratio

5. CONCLUSION

The current investigation allows us to draw the following conclusions:-

- Crown thickness is clearly the most important parameter when considering overall deformation.
- >upper land height. Crown thickness is the most important factor influencing overall deformation, accounting for 89.24% of the total.
- It is clear that crown thickness is the most important parameter for determining equivalent stress.
- >upper land height. A significant 84.78% of the variation in equivalent stress is attributable to crown thickness.
- Crown thickness is clearly the most important parameter when considering overall deformation.
- >upper land height. With a contribution ratio of 84.78%, crown thickness is the most influential factor in overall deformation.
- Clearly, crown thickness > height of top land is the order of the parametric efficacy for first ring groove temperature. With a contribution ratio of 72.72%, crown thickness is the most important factor influencing the temperature of the first ring groove.
- When the height of the top land is 7.2 mm and the crown thickness is 7 mm, the SNR-total deformation is ideal.
- To get the best SNR-Equivalent stress, set the top land height to 8 mm and the crown thickness to 4 mm.
- The ideal height of the top land is 8.8 mm, and the crown is the mass of the SNR piston.
- Using the formula: Crown thickness= 7 mm and Height of top land= 8.8 mm, we can get the ideal combination for SNR-First ring groove temperature.

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