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# Thermal-static analysis and design optimization of piston using Taguchi method

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**Abstract:** There is a growing demand in components' performance that have low cost. To reduce the time it takes to manufacture new goods, R&D and testing engineers must build crucial components as quickly as feasible. It needs a thorough grasp of emerging technology as well as rapid incorporation into product development. In reciprocating IC engines, a piston seems to be a component which is a moving part of a cylinder which is sealed by piston rings. The piston's upper end experiences the most stress, so stress concentration is one of the leading reasons of fatigue failure. FEA is frequently used in the characterisationof stress distribution on an internal combustion engine's piston. FEA is performed with the help of CAD and CAE software. Its major goals are to explore and analyse the thermal and mechanical stress distribution of the piston throughout the combustion process in an actual engine. The paper also explains how to use FEA to examine the stress. The structural model of a piston is created utilizing CATIA software. Simulation and stress analysis were carried out using the ANSYS V14.5.

**Keywords:** Piston, thermal, static, Taguchi

## 1. Introduction

In an automobile Industry piston is found to be most important part of the engine which is subjected to high mechanical and thermal stresses. Due to very large temperature difference between the piston crown and cooling galleries induces much thermal stresses in the piston. Besides the gas pressure, piston acceleration and piston skirt side force can develop cycle of mechanical stresses which are superimposed on the thermal stresses. Due to this reason thermo-mechanical stresses are one of the main causes of the failure of the piston.

Thus it has become very important to discuss the thermal and mechanical stresses to improve the quality and performance of the piston. In spite of all the improvements and advancements in the technologies there exists large number of defective or damaged pistons.

Thermal and mechanical fatigue plays a prominent role in the designing of pistons. Large numbers of complex fatigue tests are carried out by piston manufacturers but this involves very high cost and time

A piston is a component of an engine. It is also the moving component within a cylinder & sealed using piston rings. A piston rod or connecting rod transfers force from expanding gas in cylinder towards the crankshaft inside of an engine. As it is a key component in an engine, the piston was subjected to cyclic gas pressure and inertial stresses during work, which can result in fatigue damage towards the piston, causing piston skirt wear, piston head or crown fractures, and so on. Higher stress develops on the upper end of a piston, according to the research, and stress concentration has been one of the primary causes of fatigue failure. A piston overheating seizure, on the other hand, can happen if anything burns or scrapes off the oil coating that lies between the piston and the cylinder wall. With it in mind, it's easy see why oils with extraordinarily high film strengths are so coveted. Good grade oils can produce a film which can withstand the most extreme heat and pressure loads encountered in today's high-output engines. Thermal analysis is a discipline of materials science that studies how materials' characteristics vary when temperature changes. For thermal analysis, the finite element technique (FEM) is often utilised. Various approaches for applying optimum design have been proposed, while determining the optimum parameters.

## 2. Literature review

Subbaiah (2021) investigated Internal combustion engines (IC engines) were widely used nowadays across the world. Due to stringent pollution regulations, most engineers have already been looking towards improved engine architectures that emit the least amount of pollutants. Subramani (2021) investigated the pressure and knocking phenomena. The butterworth bandpass filter was utilised to obtain the pressure readings, and the potential for knocking were determined utilizing peak-to-peak pressure values as well as the species concentration. Yadav (2021) confirmed that largest stress acted here on upper region of both the piston, according to experimental research, and stress concentration also is the major cause of fatigue failure. The article explains how to increase the piston's ability to withstand significant structural and thermal loads while also reducing stress concentration in the piston's upper part.

Zeng (2021) studied the impact of squish on the piston bowl in such a single cylinder 4 S compression ignition engine fed by jojoba biodiesel on performance, emission, and combustion parameters seems to be the subject of this study. Lin & Hong (2020) A two-dimensional axisymmetric CFD model is built to explore the operating mechanism of a beta-type free piston Stirling engine. Experiments are then used to verify the model's dependability. The model may be used to determine the periodic fluctuation of the temperature field and flow field in the expansion and compression chambers. Panicker (2020) Heat rejects a large percentage of the energy produced by combustion within an engine. Though this is difficult to completely eliminate heat rejection, lowering the quantity of heat rejected can assist to enhance useable energy. Low heat rejection engines, which provide designers with insulating features, are a solution to these issues.

Zhaojuet. al. (2019) demonstrated that mechanical load is the predominant stress when comparing the temperature field distribution of the highly intensified diesel engine piston in static compression condition and the thermo-mechanical coupling stress. Dhakar (2018) discussed the findings of a prior literature review which revealed information about the inner combustion engine's parts, such as pistons. The piston converts mechanical energy into the energy of the burned gases. Inside the cylinder liner or sleeve, a piston moves. Mereuta (2018) Utilizing computer-aided design tools, this paper describes both static and thermal stress distribution of a combustion engine piston. The solid model of a piston will be built utilizing computer assisted design programme Autodesk Inventor, while static & thermal analyses would be explored utilizing SolidWorks for two variations of a diesel piston made of distinct types of materials, Aluminum 6061 Alloy and Gray Cast Iron material.

Since of their superior mechanical and thermal capabilities, lightweight constructions, environmental and other desirable qualities, Al–Si based alloys have been widely employed in automobile piston and other thermal applications, as per a survey of literature by various authors. However, basic Al-Si alloys are unsuitable for making automobile pistons and it may not meet the fundamental criteria of both the piston. It caused a variety of unwelcome stresses in components during the manufacturing process. Catalytic converter life can indeed be extended through regulating the temperature of the exhaust stream. Heat transmission with in exhaust system has a direct effect on the internal combustion engine's operations and discharge characteristics. Controlling the temperature inside the automobile exhaust system is crucial for improving an engine's performance. In order to quantify the temperature effect and heat transfer towards the engine piston crown, it was determined that even a space and temporal averaged combustion side boundary scenario is most advantageous and appropriate treatment approach within engineering approximations.

## 3. Research Methodology

### *Methodology Of Piston Analysis*

Since of combustion, the piston becomes subjected to high gas pressure and high temperature throughout operation. At the very same time, this is supported either by connecting rod's tiny end, which would be held in place with piston pins (Gudgeon pin). As both a result, the approach for assessing the piston was just as follows; The gas pressure of 20 MPa is delivered evenly throughout the top surface of the piston (crown), arresting all degrees of freedom for nodes inside the upper half of a piston pin boss, where the piston pin will be fixed. Only the upper part of the piston pin boss is done at this stage throughout the study since the kind of fit between piston pin & piston involves clearance fit.

### ***Selection Of Objectives***

The first stage in Taguchi optimization is to have the right objectives to optimise (minimized or maximized). A piston, and one of the most critical heated elements of an internal combustion engine, moves at quite a high speed for such a long period under significant thermal and mechanical loads. That stress created by all these loads has an impact on its service life, which would be directly tied to the internal combustion engine's dependability and durability. The flow field, temperature field, structure, as well as other disciplines all have a role in overall design of both the piston, but each discipline seems to have a strong interaction. Currently, the approach of individually analysing the thermal stress or mechanical stress, and mastering the stresses and deflections from each, is used in the computation and analysis of both the piston, so that the entire piston's optimization & design may be completed The output parameters include piston mass, maximum temperature, maximum mechanical stress, and maximum thermo-mechanical coupling stress.

### ***Factors and Levels***

Two geometric characteristics of both the piston, namely the height of top land and crown thickness, were investigated in this study as control elements. In Table 3.1, the levels of every component were listed. These values are chosen consistently within the logical ranges of control parameters provided by (Zhaoju et al. 2019). It should be emphasised that the Taguchi approach could only improve a piston's design parameter through discretely picking the best value for each control factor.Nevertheless, because of its cheap time cost and increased robustness, the Taguchi approach is essential & desirable for creating and optimising design parameters of pistons roughly in the first phase. The Taguchi method's discrete optimization creates the groundwork for more precise and specialised optimizations to be carried out repeatedly all around optimal values in order to enhance overall optimization outcome.

**Table 1: Levels of each factor**

| | **Parameters/Factors** | **Level** | | |
|---|---|---|---|---|
| | | **1** | | **3** |
| | Height of top land | 7<br>.2 | .0 | 8<br>.8 |
| | Crown thickness | 4 | | 1<br>0 |

***The Piston Model***

The geometry of both the piston is below, which was put into in the simulation programme for analysis. After importing a geometrical model of such a piston, which may be generated using modelling software using Catia softwrae, geometrical modeling can also be done using analytical software such as ANSYS. Figure 1 depicts a CAD-created piston for further investigation.

The following are examples of the processes involved in creating a model of a piston.

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

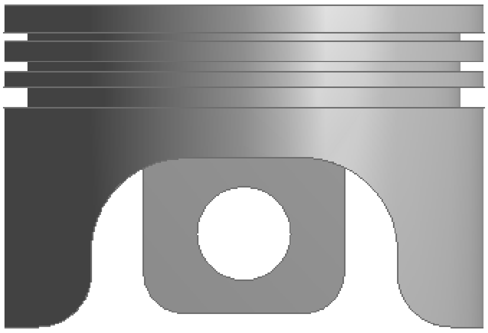

**Fig. 1: Piston Model**

### *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).

## 4. Results and Discussion

### *Total Deformation*

With ANSYS Workbench, deformation data should be shown as total deformation or directed deformation. They're used both to calculate displacements via stresses. It offers the square root of both the sum of squared of the x, y, and z directions in complete deformation.

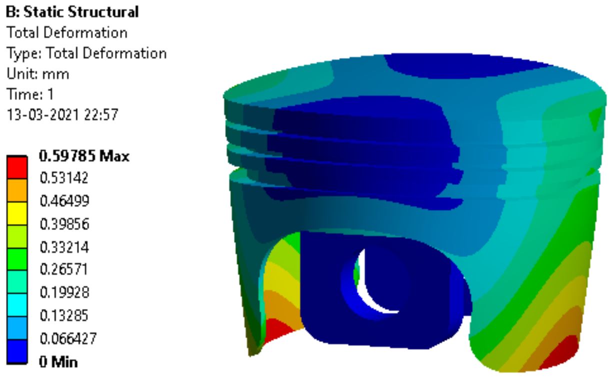

Fig. 2: Field distribution of Total deformation

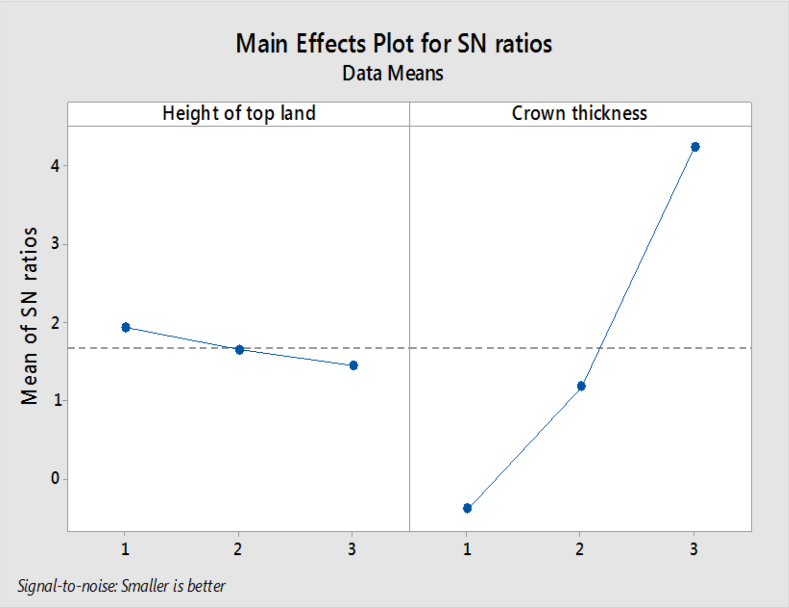

Fig. 3: Main effect plot for SNR-total deformation

These have long been assumed that now the factor's ideal level the one with the lowest SNR. When interaction effects among all components were insignificant, the level combinations with the minimum SNR-total deformation with each factor were considered the ideal level combination. An best combination for SNR-total deformation is A3B1, as seen in fig. 3.

### *Equivalent Stress*

Equivalent stress is included in the maximum equivalent stress failure hypothesis, which will be used to foresee yielding in ductile materials. The Von Mises stress seems to be a metric for determining whether a material may yield or fracture. It's most typically applied to ductile materials like as metals. A von Mises yield criteria states that such a fracture occurs when the von Mises stress under load equals equal to or greater than just the yield limit with much the same material in simple tension, which would be easy to test experimentally.

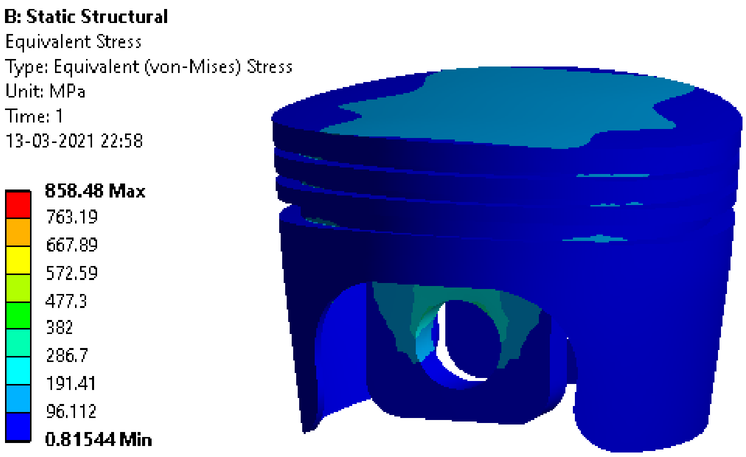

Fig. 4: Field distribution of equivalent stress

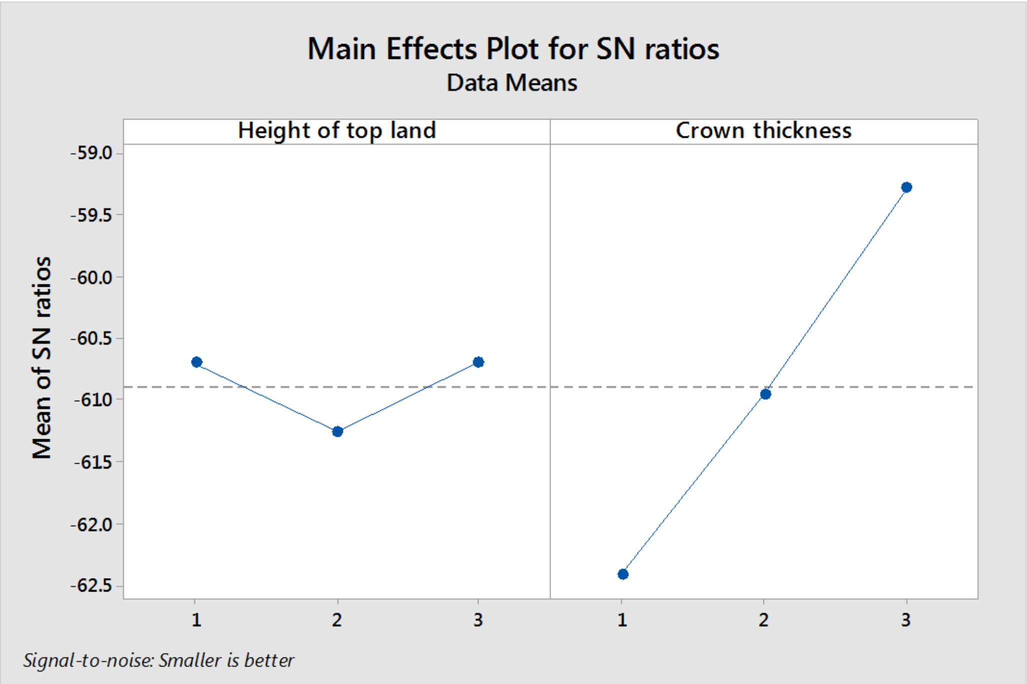

Fig. 5: Main effect plot for SNR-Equivalent stress

### *Piston Mass*

The major objectives of this work is to optimise the piston while lowering its weight. The piston's substance grows thinner. The piston's optimal result was then acquired.These have long been assumed that perhaps the factor's ideal level the one with the lowest SNR. If interrelations between all components are insignificant, the level combinations with the minimum SNR-piston mass for each factor is considered the ideal level combination. The best combination for SNR-Piston mass is A3B3 as shown in fig. 6.

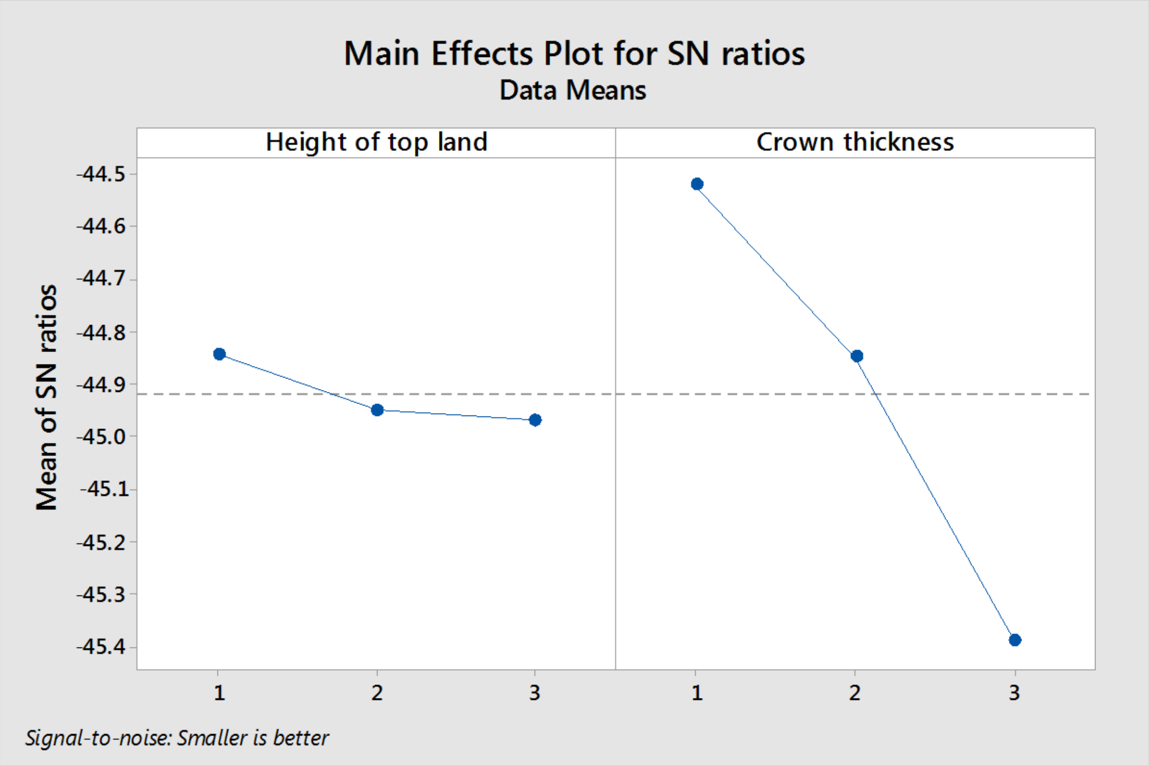

**Fig. 6: Main effect plot for SNR-Piston mass**

*First Ring Groove Temperature*

While planning and optimising piston geometric parameters, it is critical and beneficial to understand the impact of each aspect. Factorial impacts and contribution ratios for height of top land & crown thickness are further illustrated in Fig. 7, based on Table 4.4 and the above-mentioned formula. As per the estimated average SNRs of every component, the combines plots are also created to highlight the impacts of control variables. Figure 8 shows the main-effect charts for SNR-First ring groove temperature. In order of parametric efficacy for first ring groove temperature was crown thickness>height of top land, as shown in Fig. 4.10. With the a contribution ratio of 72.72 percent, crown thickness seems to have a major influence on first ring groove temperature.These have long been assumed that perhaps the factor's ideal level was the one with lowest SNR. Assuming interrelations among all components were insignificant, the level combinations with the lowest SNR-equivalent stress with each factor are considered the ideal level combination. The ideal combination with SNR-First ring groove temperature was A3B2 as shown in fig. 8.

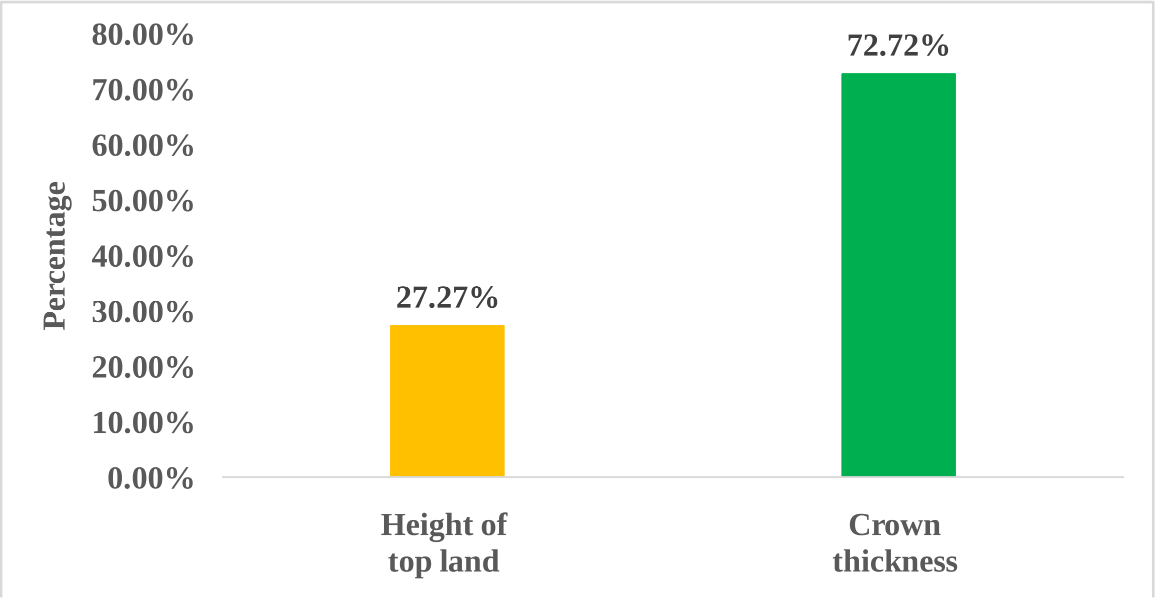

**Fig. 7: Contribution ratio of each factor for SNR-First ring groove temperature**

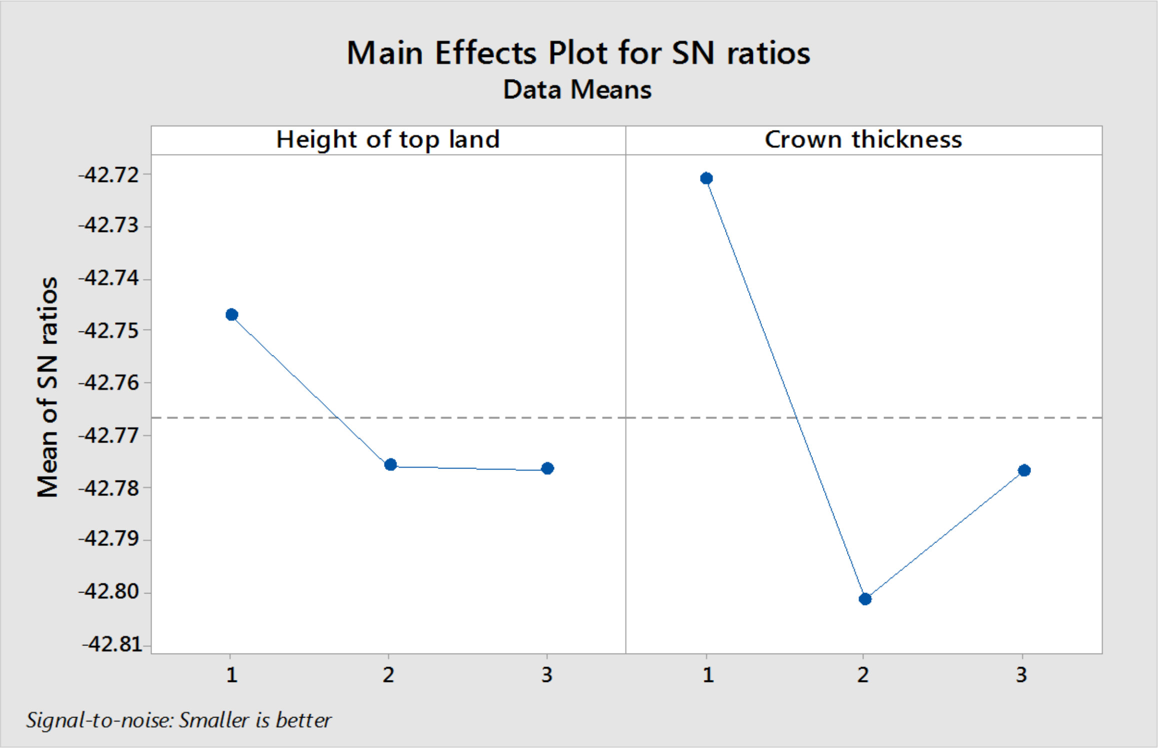

**Fig. 8: Main effect plot for SNR-First ring groove temperature**

## 5. Conclusion

The following findings may be drawn from the current research:-

1. It has been shown that crown thickness >height of top land is really the order of parametric efficacy on total deformation. With an 89.24 percent contribution ratio, crown thickness has a major influence on overall deformation.
2. It may be shown that crown thickness >height of top land seems to be the order of parametric efficacy with equivalent stress. With the a contribution ratio of 84.78 percent, crown thickness has a major influence on equivalent stress.
3. It has been shown that crown thickness >height of top land seems to be the order of parametric efficacy for overall deformation. With only an 84.78 percent contribution ratio, crown thickness seems to have a major influence on overall deformation.
4. It could be noticed that crown thickness >height of top land seems to be the order of parametric efficacy for first ring groove temperature. With such a contribution ratio of 72.72 percent, crown thickness seems to have a major influence on first ring groove temperature.
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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