TOPOLOGY OPTIMIZATION OF SEAT CLIP BY USING TAGUCHI DESIGN METHODOLOGY

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ABSTRACT

Topology optimization for a considerable time has been successfully applied in the field of design for the development of light-weight structures. Especially in the aerospace sector, topology / topography optimization techniques are gaining recognition as effective tools for improving structural efficiency of newly designed aerospace vehicles. In that context, a project has been done on aeroplane seat clip. Which is one of the most commonly used part for each seat in aeroplane. The aim of the project was to achieve at a light-weight design of the clip without compromising on its strength. Key objective of this project is applying Taguchi robust design Methodology for designing a clip in different combinations of process parameters. The general material used for clip is Aluminium. L09 orthogonal array is used to frame the experiments. Altair Inspire design software is used to design the clip and identify the best robost structure based on the von misses stress. Along the von misses, weight factor also observed in each condition. The von misses and weight results are taken for ANOVA to find the significance of each parameter and percentage contribution of each parameter on the result. This project reveals that optimized condition for von misess and weight.

Keyword: - *Topology Optimization, Taguchi, ANOVA, seat clip, von misess, weight reduction.*

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1. INTRODUCTION

Topology Optimization (TO) is a process that optimizes material layout and structure within a given 3D geometrical design space for a defined set of rules set by the designer. The goal is to maximize part performance by mathematically modelling and optimizing for factors such as external forces, load conditions, boundary conditions, constraints, and material properties within the design envelope. Although topology optimization has a broad range of applications across industries, in engineering product design, it is used at the design stage of new product design to optimize the form to increase stiffness to weight ratio. TO generated free form designs are often difficult to manufacture using traditional manufacturing methods. However, due to growth and technological advancement in additive manufacturing or so-called 3D printing, the design output by Topology optimization can feed directly to a 3D printer. Since the start of the 21st century, the topology optimization concept has been commonly used in CAD software applications such as Solidworks, Autodesk, Abaqus, Altair Insire etc. Conventional topology optimization uses finite element analysis to evaluate the design performance and produce structures to satisfy objectives such as the following:

- Reduced stiffness-to-weight ratio
- Better strain energy to weight ratio
- Reduced material volume to safety factor ratio,

Figure 1.1: Topology Transformation

1. 1: Topology optimization vs Generative design

Topology optimization is often misunderstood and mixed-up with Generative design. Both product design techniques have become popular in the last decade and are often incorrectly assumed to be the same. TO would require a design model from the user, along with inputs such as external forces, constraints, and material properties. The software then runs an FEA and removes the redundant material by analyzing the part to produce an optimized object. Hence topology optimization needs an engineering product designers' initial model, limiting the possibility of the engineers' knowledge to form part design. Generative design uses topology optimization but takes the process a step further by removing the need for an initial model. The generative design creates its model by taking the inputs such as design space, forces, and constraints. Then its uses shape optimization to analyze and create multiple designs for the engineer to evaluate. Advanced generative design software such as Creo and Autodesk can automatically generate and compare numerous designs against the predefined set of rules.

How does topology optimization work?

- First, the designer establishes the smallest allowed design space required for the part.
- Then user defines external loads, boundary conditions, constraints & material properties. At this stage, keep out areas or fixed locations are also specified.
- FEA then considers the minimum geometric design envelop and breaks down the design space into smaller areas such as applied load points, mounting locations, and constrained areas.
- TO creates a basic mesh of this smaller design space using finite elements. FEA then evaluates the mesh's stress distribution and strain energy to find the optimum load or stress each element can handle.
- The TO program then digitally places pressure on the design from various angles, evaluates its structural integrity, and finds unneeded material.
- Then the software tests each finite element for stiffness, compliance, stress, deflection against the defined requirement to find redundant material.
- Finally, the finite element analysis knits the pieces together to complete the pattern.

2. ALTAIR Inspire

Altair Engineering Inc. is an American multinational information technology company headquartered in Troy, Michigan. It provides software and cloud solutions for simulation, IoT, high performance computing (HPC), data analytics, and artificial intelligence (AI). Altair Engineering is the creator of the HyperWorks CAE software product, among numerous other software packages and suites. The company was founded in 1985 and went public in 2017. It is traded on the Nasdaq stock exchange under the stock ticker symbol ALTR.

Products

Altair develops and provides software and cloud services for product development, high-performance computing (HPC), simulation, artificial intelligence, and data intelligence. The company also offers its customers access to software applications from over 55 different software companies through its Altair Partner Alliance. Altair HyperWorks: A CAE program that enables finite element analysis, modeling, and simulation.
Altair OptiStruct: Topology optimization tool that provides structural analysis.
Altair SimSolid: A mesh-less structural analysis tool.
Altair PBS Works: Is a workload management tool that leverages high-performance computing.
Altair SmartWorks: An IoT product development solution.
Altair HyperMesh: A finite element pre-processor.
Altair Panopticon: A data visualization and monitoring software:
Altair One: A collaboration platform to access all Altair's simulation, HPC, and data analytics solutions.

2.1 Additional Changes and Enhancements for Sketching

The following changes and enhancements have also been added for version 2021.1:

- In the Polyline tool, you can now use the Shift key to toggle between creating a line and an arc.
- You can now purge parts and assemblies by selecting Delete Without History from the part context menu or the Model Browser context menu. A Remove History option is also available on the right-click context menu for the Delete Parts construction feature in the History Browser timeline. Selecting this option will purge the construction feature from the timeline.
- The Create Imprint on Face option is now available in the right-click context menu for sketching

3. EXPERIMENTAL DESIGN AND SETUP

Selection of control factors and levels:

The process parameter and their ranges are finalized using literature. The four control factors are Type of material (A), Force (B), Topology (C), Clip plate thickness (D) and their corresponding levels have been selected. The control factors and their levels are listed in Table

Table 3.1: Control factors and levels

Factors/ Levels	Material	Force (N)	Topology (%)	Clip plate thickness (mm)
1	AISI 316	1000	30	1.5
2	AISI 4142	1200	35	2
3	Ti- 6Al- 4V	1400	40	2.5

3.1. Selection of orthogonal array:

Selection of particular orthogonal array from the standard (O.A) depends on the number of factors, levels of each factor and the total degrees of freedom.

i) Number of control factors = 4
ii) Number of levels for each control factors = 3
iii) Over all mean =1
iv) Total degrees of freedom of factors = 4x(3-1)= 8
v) Number of experiments to be conducted (8+1) = 9.

Based on these values and the required minimum number of experiments to be conducted are 9, the nearest O.A fulfilling this condition is $\mathbf{L_{09}\,(3^4)}$. It can accommodate maximum of 4 number of control factors each at three levels with 9 numbers of experiments. Here the requirement is to accommodate four control factors at three levels, which can be easily done in this O.A.

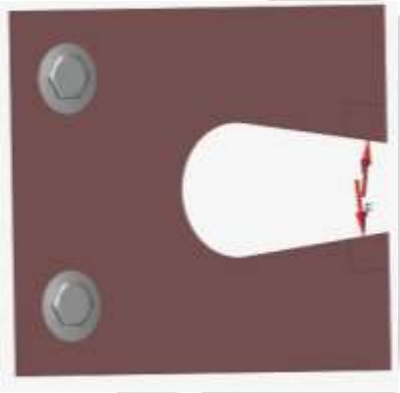
Table 3.2: L09 orthogonal array

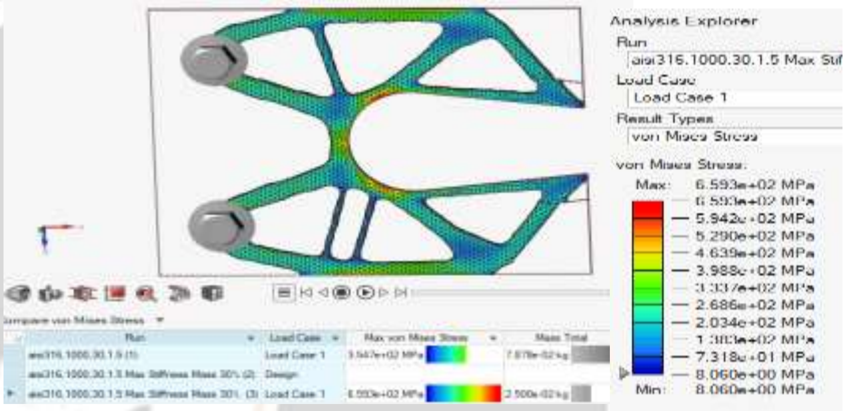
Exp. No.	Factor (A)	Factor (B)	Factor (C)	Factor (D)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 3.3: Experimental design

Exp. No.	**Column**			
	A	**B**	**C**	**D**
1	AISI 316	1000	30	1.5
2	AISI 316	1200	35	2
3	AISI 316	1400	40	2.5
4	AISI 4142	1000	35	2.5
5	AISI 4142	1200	40	1.5
6	AISI 4142	1400	30	2
7	Ti-6Al-4V	1000	40	2
8	Ti-6Al-4V	1200	30	2.5
9	Ti-6Al-4V	1400	35	1.5

3.2: Design and topology of Clip





Analysis Explorer

Run: aisi316.1000.30.1.5 Max Stif

Load Case: Load Case 1

Result Types: von Mises Stress

Table 3.4: Experimental results related to Von Mises stress and S/N ratio

S. No.	**Trial**		**Mean (MPa)**	**S/N ratio**
	1 (MPa)	**2 (MPa)**		
1	660.5	658.1	659.3	56.3816
2	497.5	495.1	496.3	53.9148
3	405.2	403.2	404.2	52.1318
4	360.7	358.3	359.5	51.1138
5	620.0	617.6	618.8	55.8310
6	638.4	636.0	637.2	56.0855
7	388.8	386.4	387.6	51.7676
8	444.0	441.6	442.8	52.9241
9	816.4	814.0	815.2	58.2253

3.3 Procedure of Analysis of Variance for Von Mises stress:

- The average response for each experiment:
- The overall experimental average
- The total sum of squares (SST)
- The total sum of squares due to mean:
- Total sum of squares due to factors:
    - Sum of squares of deviation from target for factor SS(material): 2527

- The same above procedure has been used to calculate the sum of squares due to factors force, topology percentage, clip thickness.
  - Sum of squares of deviation from target for factor “force”: (SS force) = 69968
  - Sum of squares of deviation from target for factor “topology percentage”: (SSTP) = 40115
  - Sum of squares of deviation from target for factor “clip thickness”: (SSCT) = 269511
  - The sum of squares due to error: SSe is 25

The mean sum of squares:

The mean sum of squares are calculated by dividing the sum of squares by the degree of freedom. In general, degree of freedom of a factor is number of levels minus one i.e.

- For factor material,----- MSS material = SS (material): ÷ DF material = 2527/ 2 = 1263

Similarly, the mean sums of squares of the remaining factors are calculated. These are force, topology percentage, clip thickness

- The mean sum of squares for factor “Force”: (MSS force) = 34984
- The mean sum of squares for factor “topology percent”: (MSSTP) = 20057
- The mean sum of squares for factor “clip thickness”: (MSS CT) = 134756
- The mean sum of squares for error, “Error”: (MSSer) = 3

The F-ratio (data): The F-ratio is calculated by dividing the mean sum of squares by the error sum of squares.

- For factor material: F material = (MSS material,÷ MSSer) = (1263÷3) = 454.08

Similarly the F-ratio is calculated for remaining factors force, topology percentage, clip thickness

F_{force} = 12574.04; F_{TP} = 7209.13; F_{CT}= 48434.51

The F-ratio (table): The F-ratio from the Table for combination of F (0.05, 2, 9) is extracted is 4.26

Table 3.5: Basic Analysis of Variance of Von mises stress

Factor	S.S	D.O.F	M.S.S	F-ratio (data)	F-ratio (Table)	Result
Material	2527	2	1263	454.08	4.26	Significant
Force	69968	2	34984	12574.04	4.26	Significant
Topology percentage	40115	2	20057	7209.13	4.26	Significant
clip thickness	269511	2	134756	48434.51	4.26	Significant
Error	25	9	3			
S_t	382145	17				

3.4: Weight of clip with corresponding S/N ratio:

The weight is observed for each experiment. The summary of average weight of clip and its S/N ratios are shown in Table

Table 3.6: Experimental results related to Clip weight and S/N ratio

S. No.	Trial		Mean (min)	S/N ratio
	1 (min)	2 (min)		
1	0.0270	0.0230	0.0250	32.0135
2	0.0120	0.0080	0.0100	39.8297
3	0.0530	0.0490	0.0510	25.8419
4	0.0490	0.0450	0.0470	26.5502
5	0.0340	0.0300	0.0320	29.8801
6	0.0349	0.0309	0.0329	29.6401
7	0.0280	0.0240	0.0260	31.6749
8	0.0260	0.0220	0.0240	32.3657
9	0.0190	0.0150	0.0170	35.3313

Procedure of Analysis of Variance for clip weight:
The average response for each experiment:

- The overall experimental average
- The total sum of squares (SST)
- The total sum of squares due to mean:
- Total sum of squares due to factors:
- Sum of squares of deviation from target for factor SS($_{material}$): 0.000677

The same above procedure has been used to calculate the sum of squares due to factors force, topology percentage, clip thickness.

- Sum of squares of deviation from target for factor "force": (SS force) = 0.000500
- Sum of squares of deviation from target for factor "topology": (SS_{TP}) = 0.000449
- Sum of squares of deviation from target for factor "clip thickness": (SS_{CT}) = 0.001144
- The sum of squares due to error: SS_e is 0.000072

The mean sum of squares:
The mean sum of squares is calculated by dividing the sum of squares by the degree of freedom. In general, degree of freedom of a factor is number of levels minus one i.e.

- For factor Material: $MSS_{material} = SS_{material} \div DF_{material}$ = 0.000677/ 2 = 0.000339

Similarly the mean sums of squares of the remaining factors are calculated. These are force, topology percentage, clip thickness.

- The mean sum of squares for factor "force": (MSS_{force}) = 0.000250
- The mean sum of squares for factor "topology": (MSS_{TP}) = 0.000225
- The mean sum of squares for factor "clip thickness": (MSS_{CT}) = 0.000572
- The mean sum of squares for error, "Error": (MSS_{er}) = 0.000008

The F-ratio (data): The F-ratio is calculated by dividing the mean sum of squares by the error sum of squares.

- For factor Material: $F_{material} = (MSS_{material} \div MSS_{er})$ = (0.000339 ÷ 0.000008) = 42.33

Similarly the F-ratio is calculated for remaining factors force, topology percentage, clip thickness.
F_{force} = 31.26; F_{TP} = 28.08; F_{CT}= 71.52
The F-ratio (table): The F-ratio from the Table for combination of F (0.05, 2, 9)
The F-ratio test:
Compare the values of F-ratio tabulated with calculated F- ratio. If Calculated F- ratio is greater than the tabulated, this concludes that, the selected factors and interactions are significant for the process. The consolidated calculations of ANOVA are given in the below Table.

Table 3.7: Basic Analysis of Variance of clip weight

Factor	S.S	D.O.F	M.S.S	F-ratio (data)	F-ratio (Table)	Result
Material	0.000677	2	0.000339	42.33	4.26	Significant
Force	0.0005	2	0.00025	31.26	4.26	Significant
Topology percentage	0.000449	2	0.000225	28.08	4.26	Significant
Clip thickness	0.001144	2	0.000572	71.52	4.26	Significant
Error	0.000072	9	0.000008			
total	0.002843	17				

3.5 Optimization of parameters for von mises:

Taguchi's robust design methodology has been successfully implemented to identify the optimum parameters from selected process parameter and their levels in order to increase the von mises stress for improved performance. After analysis of data from the robust design experiments the optimum process parameters are found. These optimum process parameters are validated by conducting confirmation test.

Table 3.7: Optimum Parameters for von mises stress

Material	AISI 4142
Force	1400 N
Topology percentage	30 %
clip thickness	1.5 mm

Factor response plot for performance characteristics:

The level of parameter with the highest S/N ratio is the optimal level. The individual factors effect on von mises found to be significant, clip thickness has major contribution (70.52%) followed by force (18.309%), Topology percentage (10.49%), material (0.661%). After selecting the optimal level of process parameters, the final step is to predict the performance characteristics and confirmation test has conducted using optimal condition. It is found that S/N ratio of predicted and confirmation test is within 95% confidence level and objective is fulfilled. Hence these suggested optimum conditions can be adopted.

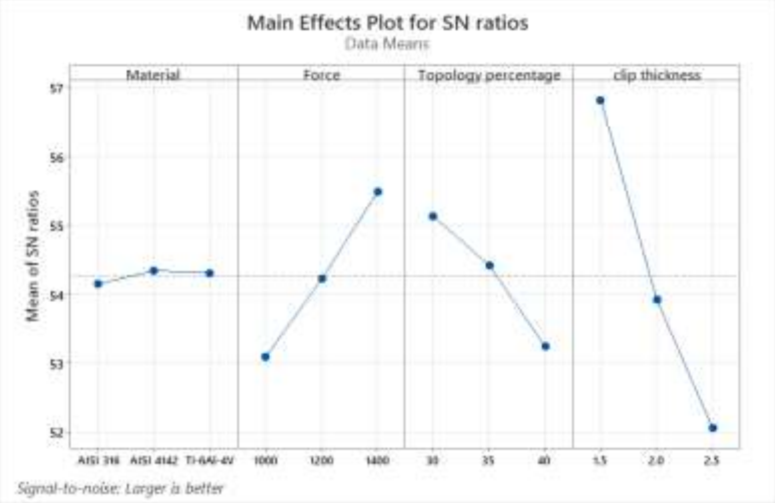


Fig. 3.1: Main effect plots for S/N ratio of von mises stress

All the factors selected for this experiment is significant. The parameter which is having major contribution is clip thickness. The clip thickness can change the result of von mises stress. Proper optimal clip thickness can give high von mises stress. High S/N ratio is observed in 2nd level of material, 3rd level of force, 1st level of topology percentage and 1st level of clip thickness for von mises stress. So, the levels will be considered for optimum condition.

3.6. Optimization of cutting parameters for clip weight:

Taguchi's robust design methodology has been successfully implemented to identify the optimum parameters from selected process parameter and their levels in order to decrease the weight of clip for improved performance. After analysis of data from the robust design experiments the optimum process parameters are found.

Table 6.2: Optimum Parameters for clip weight

Material	Ti- 6Al- 4V
Force	1200 N
Topology percentage	35 %
clip thickness	2 mm

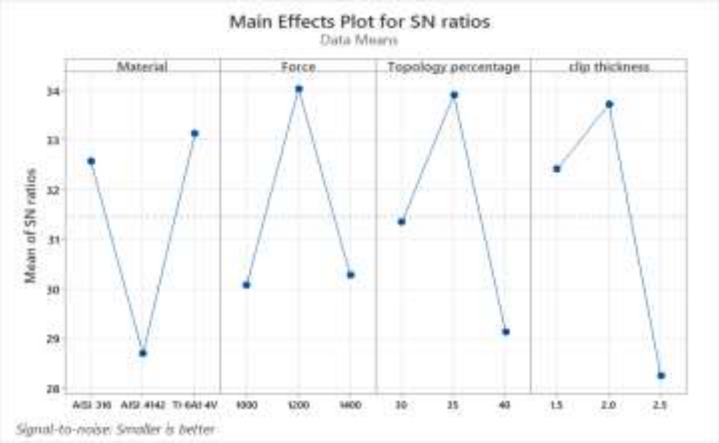


Fig. 3.2: Main effect plots for clip weight

The S/N ration is selected to smaller the better. From the above figure, it is observed that Signal to Noise ratio is very high in different cutting conditions. Those are Material is high at 3rd level, S/N ratio is high at 2nd level of force, 2nd level of Topology percentage and 2nd level of clip thickness are having highest S/N ratios. So, these levels are considered for optimum condition. The individual factors effect on clip weight reduction process found to be significant, clip thickness has major contribution (40.23%) followed by material (23.81%), force (17.58%), topology percentage (15.79%).

4. CONCLUSIONS

After the project the below conclusions are drawn

- The factors are selected for designing of clip to find optimum von mises stress. Those factors are identified significant. Which means that, all the factors are having countable impact on result (von mises stress)
- Each factor percentage contributions are calculated. The percentage contributions are Clip thickness has major contribution (70.52%) followed by force (18.309%), Topology percentage (10.49%), material (0.661%).
- The optimized condition for von mises stress in the clip design obtained as Material is AISI 4142, force 1400 N, Topology percentage 30% and clip thickness is 1.5 mm.
- The factors are selected for designing of clip to find optimum clip weight. Those factors are identified significant. Which means that, all the factors are having countable impact on result (clip weight)
- Each factor percentage contributions are calculated. The percentage contributions are Clip thickness has major contribution (70.52%) followed by force (18.309%), Topology percentage (10.49%), material (0.661%).
- The individual factors effect on clip weight reduction process found to be significant, clip thickness has major contribution (40.23%) followed by material (23.81%), force (17.58%), topology percentage (15.79%).
- The optimized condition for clip weight in the clip design obtained as material Ti-6Al-4V, force 1200 N, topology percentage 35%, clip thickness 2mm.

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