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Topography Optimization of Sheet Metal Bracket Using Taguchi's Design of Experiments for Varying Materials and Load Conditions

Madasu Prasad [a], A. Sai Kumar[b]

[a] *M. Tech Scholar, Department of Mechanical Engineering, J.B. Institute of Engineering and Technology, Moinabad, Hyderabad-75, Telangana, India.*
[b] *Assistant Professor, Department of Mechanical Engineering, J.B. Institute of Engineering and Technology, Moinabad, Hyderabad-75, Telangana, India.*

A B S T R A C T

This research investigates the topography optimization of sheet metal brackets with the objective of minimizing displacement while ensuring structural integrity. Utilizing the Taguchi Design of Experiments (DOE) methodology, an L09 orthogonal array was implemented to conduct a series of nine experiments. The study examines the effects of three distinct materials—steel, nickel, and Inconel—under varying loading conditions of 300N, 500N, and 700N, while maintaining uniform component sizes of 20mm, 30mm, and 40mm. The research aims to identify optimal design configurations that effectively reduce displacement. By systematically analyzing the influence of material properties, load conditions, and geometric dimensions, this study provides valuable insights for enhancing the performance of sheet metal designs and reducing material usage in engineering applications. The findings are expected to guide future innovations in design practices and contribute to more efficient and sustainable engineering solutions. Inconel demonstrated the best performance, achieving the lowest post-optimization displacement of 0.19mm at the condition of 300N and Uniform size 40mm.

Keywords: Topography Optimization, Hypermesh, sheet metal bracket, Taguchi's DOE.

1. INTRODUCTION

Sheet metal brackets are fundamental components used across multiple industries for supporting, connecting, and securing mechanical or structural elements. They are typically fabricated from flat sheets of metal that are cut, bent, and formed into specific shapes to provide the necessary support. The simplicity and versatility of sheet metal make it an ideal material for producing brackets that are lightweight yet durable and these features allow them to be used in a vast array of applications. Sheet metal brackets serve both structural and non-structural purposes in industries like aerospace, automotive, construction, electronics, and consumer goods manufacturing. Their primary role is to hold components together, provide support, and withstand various loads while being cost-effective and easy to produce in high volumes.

Figure 1.1: Sheet metal bracketsaa

Sheet metal brackets are essential components in modern engineering and manufacturing due to their versatility, durability, and relatively low production cost. They are frequently used in assembly processes to support or fix various components in place, making them indispensable in sectors like automotive, aerospace, construction, electronics, and even household goods. From small electronic devices to large industrial machines, brackets provide the structural support necessary to ensure stability and reliability. They act as joining elements, connecting parts of machines or structures, and distributing loads evenly to prevent failure under stress. The demand for reliable brackets has increased as modern engineering requires solutions that are both efficient and capable of handling high performance under varied conditions.

1.1: Topography optimization of sheet metal brackets

Topography optimization is a design process that adjusts the distribution of material within a structure to improve its performance, often with the aim of minimizing weight while maintaining strength and rigidity. When applied to sheet metal brackets, the goal is to create a lighter component that can still handle the stresses and loads it will encounter in service. This process is especially valuable in industries such as automotive, aerospace, and electronics, where reducing weight can improve efficiency and performance. Optimizing the topography of sheet metal brackets is a complex task that involves careful consideration of multiple factors, including material properties, load-bearing capacity, manufacturing feasibility, cost efficiency, and sustainability.

In any topography optimization process, the key issue is finding a balance between reducing material usage and maintaining the bracket's ability to withstand operational forces. This involves intricate simulations and calculations to determine the optimal geometry that can distribute stress evenly across the bracket without creating weak points. The results of these simulations can significantly improve the performance of a sheet metal bracket, but the path to achieving an optimized design is filled with technical considerations that must be carefully navigated.

1.2: Material Selection for Topography Optimization

The choice of material is critical in topography optimization because the mechanical properties of different metals can have a significant impact on the performance of the bracket. Each material, whether it is steel, aluminium, brass, or advanced alloys like Inconel, brings its own set of advantages and limitations that must be taken into account during the optimization process. For example, steel is often favoured for its strength and durability, making it suitable for applications where the bracket will be subjected to heavy loads. Its relatively high density means that using steel may not result in the lightweight design that many industries require. Aluminium offers an excellent strength-to-weight ratio, making it a popular choice in industries such as aerospace and automotive, where reducing the overall weight of the vehicle or component is critical for performance. Aluminium is also resistant to corrosion, which extends the lifespan of the bracket, especially in environments where moisture or chemicals are present. Aluminium's lower tensile strength compared to steel means that it may not be suitable for applications where the bracket will face significant mechanical stress.

Similarly, nickel-based alloys like Inconel offer superior strength at elevated temperatures, making them ideal for applications in extreme environments, such as in the aerospace and energy sectors. The high cost and difficulty of working with these materials may limit their use to specialized applications. Engineers must carefully evaluate these trade-offs when selecting a material for optimization, as the chosen material will dictate the bracket's final performance and manufacturability.

2. LITERATURE REVIEW

[1] Krishnan, P. & Yang, Z. (2023), Topography Optimization of a Sheet Metal Assembly of Repetitive Features. The authors focused on topography optimization of sheet metal assemblies, in this study, an assembly consisting of several identical sheet metal components is employed for demonstrating the effectiveness of topography optimization, in which various beads are to be derived with appropriate heights and widths, where needed, at the discretion of the algorithm to attempt to render the design variables within the constraints. The identical pieces are arranged around an axis of revolution such that the geometric shape is cyclic symmetric at a constant angular spacing. Despite the geometric symmetry, however, the entire 360-degree assembly has to be modelled in the finite element analysis, to account for the overall lateral stiffness. Thus, during the course of optimization, it is necessary to impose a constraint known as pattern repetition for the evolved shapes of the design such that each component has the identical features for the purpose of simplicity and cost-effectiveness in manufacturing. The responses from the finite element solution in the form of lateral and rotational stiffness as well as maximum stresses are used as the design constraints and objective function. It turns out that the topography algorithm used in this study seems smart enough to figure out a set of design variables to meet some seemingly contradictory constraints.

[2] Rajan R. Chakravarty (2019), Study of Topography Optimization on Automotive Body Structure., In this paper, Rajan R. Chakravarty from General Motors explores a methodology for improving the structural performance of automotive body structures through large-scale topography optimization. The study focuses on applying topography optimization to an entire automotive body structure, highlighting its effectiveness in identifying morphing locations that maintain or improve structural integrity. The paper emphasizes that the optimization can be mass-neutral or mass-efficient, meaning that it improves the structure without adding unnecessary weight. The results from this case study illustrate the potential of topography optimization to enhance performance while remaining cost-effective in automotive applications. Chakravarty's work demonstrated that topography optimization can significantly improve the structural performance of automotive body structures. By identifying optimal morphing locations, it was possible to enhance stiffness and performance without adding mass. This methodology is valuable for automotive engineers aiming to balance performance with weight constraints in vehicle design.

[3] Iacob-LiviuScurtu et. al. (2023), Topography Optimization of a Bracket Used for Car Bodywork Reinforcement. In this study, the authors present a comprehensive process for optimizing a bracket used for reinforcing car bodywork using topography optimization techniques. The goal of their work is to improve the structural integrity of the bracket while minimizing weight and maintaining the mechanical requirements needed for its role in the car body.

The bracket geometry was initially modelled in SolidWorks CAD, after which it was simplified to a midsurface and meshed into shell finite elements using HyperMesh. The study applied material properties and created a load case for the bracket after determining the design and non-design spaces. Using OptiStruct, the authors solved the finite element model and analyzed the six vibration modes between the original and optimized models. The study effectively demonstrated the use of topography optimization to enhance the stiffness of automotive body reinforcement brackets while reducing their weight. The authors concluded that the implementation of CAD and FEM tools in automotive design optimizations is essential for improving both design efficiency and performance in practical engineering applications.

This paper adds valuable insights into the practical application of topography optimization in automotive engineering, showing how integrated software tools can streamline the design process and improve component performance.

[4] Cheng Wang & Fang Liao (2010), Topography Optimization and Parametric Analysis of Bead Layout for Sheet Metal Bracket. In this paper, Cheng Wang from Key Safety System Inc. and Fang Liao from SAIC Motor Technical Center explore the reinforcement of sheet metal brackets using bead layouts, which allow for structural enhancement without increasing the material thickness. This technique effectively reduces material costs while maintaining the bracket's mechanical strength. The authors focus on determining the optimal bead parameters, such as bead height and width, by performing a parametric analysis of the geometric aspects of the bead section.

The paper applies topography optimization to determine the ideal bead layout for an automotive DVD bracket assembly. Through this process, the first natural frequency of the bracket assembly was improved by 30%. The method also shortens the design cycle, allowing for quicker development of beads and a more efficient design process overall. The optimization technique is implemented using specialized topography optimization software, which aids designers in achieving the best possible bead layout. The study showed that the topography optimization process is effective in improving the mechanical properties of sheet metal brackets, with a significant increase in the natural frequency of the optimized part. The authors conclude that using parametric analysis combined with topography optimization leads to a more efficient design process, which improves both performance and cost-effectiveness in automotive applications. This work highlights the importance of bead layout optimization as a cost-saving and performance-enhancing strategy for automotive components.

3. EXPERIMENTAL DESIGN AND SETUP

The Taguchi technique was employed in this work to examine the effects of crucial process variables, such as Type of material, Load, and Uniform size, for Topography optimization.

Table No.: 3.1 Process Parameters

FACTORS	**LEVELS**		
	1	**2**	**3**
Type of Material (A)	Steel	Nickel	Inconnel
Load (N) (B)	300 N	500 N	700 N
Uniform size (mm) (C)	20	30	40

The table above lists the chosen process parameters and their levels. The Type of material, Load, and Uniform size are taken into account in this work to analyze their effects on Displacement in the body.

3.1. Selection of orthogonal array

The choice of a specific orthogonal array from the standard (O. A) depends on the total number of degrees of freedom, the levels of each factor, and the number of factors.

i) Number of control factors = 3

ii) Number of levels for each control factors = 3

iii) Over all mean =1

iv) Total degrees of freedom of factors = 3 x (3-1) = 6

v) Number of experiments to be conducted (6+1) = 7.

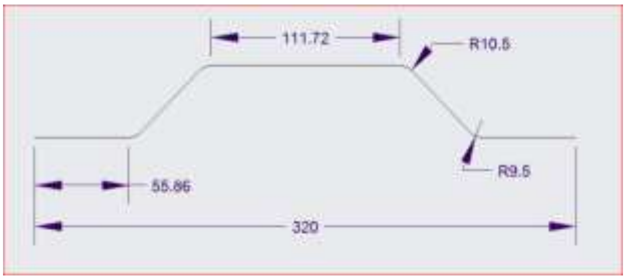
Based on these values and the required minimum number of experiments to be conducted are 7, the nearest O.A fulfilling this condition is $L_{09}(3^3)$.

Table No. 3.2: Taguchi L9 Orthogonal with parameter values

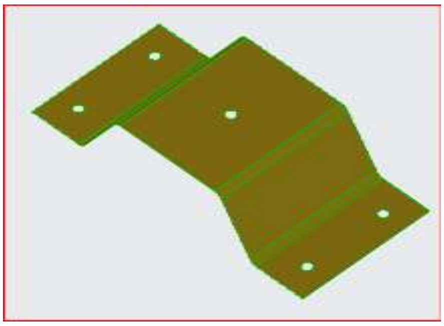
No. of Exp.	**Material (A)**	**Load (N) (B)**	**Uniform Size (mm) (C)**
1	Steel	300	20
2	Steel	500	30
3	Steel	700	40
4	Nickel	300	30

5	Nickel	500	40
6	Nickel	700	20
7	Inconnel	300	40
8	Inconnel	500	20
9	Inconnel	700	30

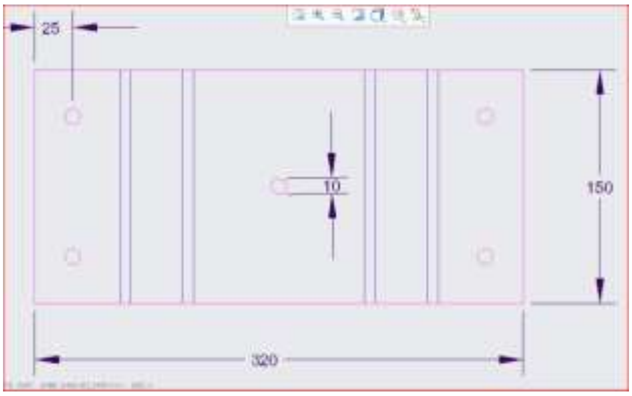
3.2: Design of Sheet metal bracket



Front view of Bracket



Isometric view of Bracket



Top view of Bracket

Condition 1: The results for Steel bracket subjected to 300N, and Uniform size 20mm.

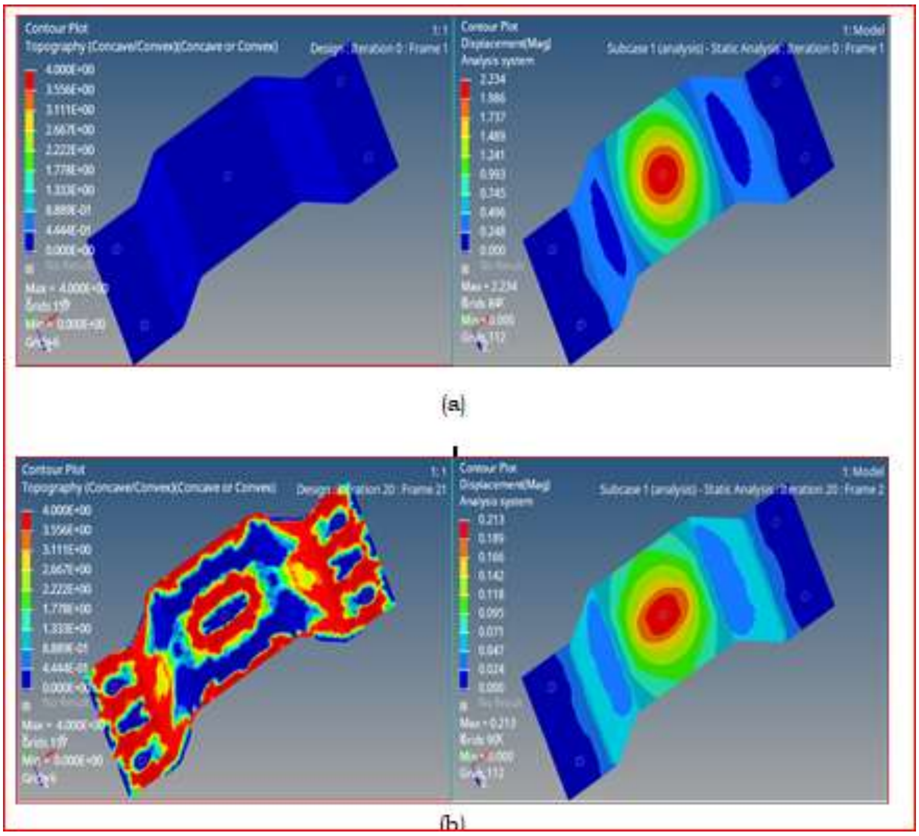


Figure 3.1: Steel Condition -1. a) Displacement before Topography optimization b) Displacement after Topography optimization.

Condition 2: The results for Steel bracket subjected to 500N, and Uniform size 30mm.

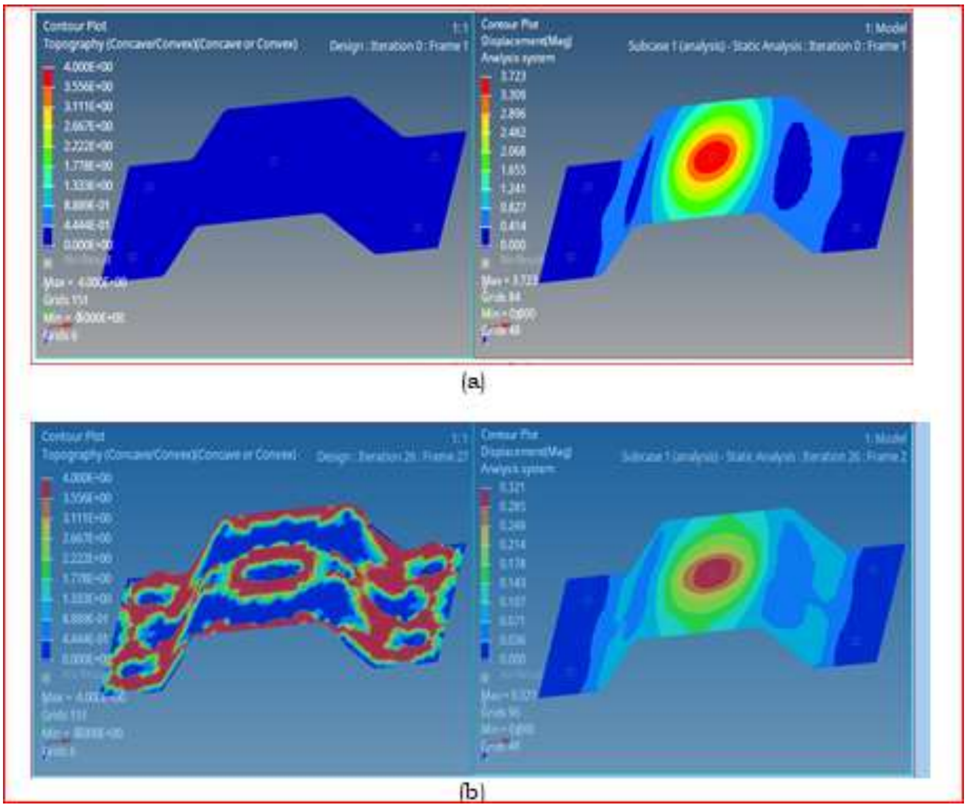


Figure 3.2: Steel Condition -2. a) Displacement before Topography optimization b) Displacement after Topography optimization.

This procedure is followed for all 9 experiments, the consolidated deflection table for all the 9 experiments are mentioned below.

Table 3.3: Output parameter results for different conditions

Exp. No.	Material	Load (N)	Uniform Size (mm)	Displacement (before)	Displacement (after)	amount of reduction %
1	Steel	300	20	2.23	0.21	90.58
2	Steel	500	30	3.72	0.32	91.40
3	Steel	700	40	5.21	0.45	91.36
4	Nickel	300	30	2.32	0.2	91.38
5	Nickel	500	40	3.88	0.34	91.24
6	Nickel	700	20	5.43	0.47	91.34
7	Inconel	300	40	2.25	0.19	91.56
8	Inconel	500	20	3.75	0.32	91.47
9	Inconel	700	30	5.25	0.46	91.24

4. DATA ANALYSIS

4.1: Results related to Material

4.1.1: Steel

Exp. No.	Material	Load (N)	Uniform Size (mm)	Displacement before	Displacement after	amount of reduction %
1	Steel	300	20	2.23	0.21	90.58
2	Steel	500	30	3.72	0.32	91.40
3	Steel	700	40	5.21	0.45	91.36

For Experiment 1, under a load of 300 N and a uniform size of 20 mm, the displacement before optimization was recorded as 2.23 mm, and after optimization, it was reduced to 0.21 mm, resulting in a 90.58% reduction in displacement. This indicates that the optimization process was highly effective in reducing the displacement under this load condition.

Similarly, in Experiment 2, with a load of 500 N and a uniform size of 30 mm, the initial displacement was 3.72 mm, and after optimization, it decreased to 0.32 mm, showing an even higher reduction of 91.40%. This demonstrates the robustness of the optimization technique in handling increased loads while maintaining high displacement reduction efficiency.

In the final experiment (Experiment 3), with a load of 700 N and a uniform size of 40 mm, the displacement before optimization was 5.21 mm. After optimization, the displacement dropped to 0.45 mm, corresponding to a 91.36% reduction. This shows that even under the highest load condition, the optimization method significantly minimized the displacement, maintaining a consistent reduction percentage.

4.1.2: Nickel

Exp. No.	Material	Load (N)	Uniform Size (mm)	Displacement before	Displacement after	amount of reduction %
1	Nickel	300	30	2.32	0.2	91.38
2	Nickel	500	40	3.88	0.34	91.24
3	Nickel	700	20	5.43	0.47	91.34

In Experiment 1, conducted under a load of 300 N and a uniform size of 30 mm, the displacement before optimization was measured at 2.32 mm. Following the optimization process, the displacement was reduced to 0. 20 mm, resulting in a 91.38% reduction. This demonstrates the high capability of the optimization method in significantly reducing deformation under these loading conditions for nickel.

For Experiment 2, where the load was increased to 500 N and the uniform size was set to 40 mm, the initial displacement was 3.88 mm. After optimization, it dropped to 0.34 mm, achieving a displacement reduction of 91.24%. This highlights the consistency of the optimization process in handling increased loads while maintaining a high percentage reduction in displacement, showing that the process scales effectively with varying conditions.

In the final Experiment 3, under the heaviest load of 700 N and a uniform size of 20 mm, the displacement before optimization was recorded at 5.43 mm. After the optimization, the displacement was brought down to 0.47 mm, resulting in a reduction of 91.34%. This result reinforces the observation that the optimization methodology is robust enough to manage high loads and different uniform sizes, with consistently high displacement reduction percentages.

4.1.3: Inconel

Exp. No.	Material	Load (N)	Uniform Size (mm)	Displacement before	Displacement after	amount of reduction %
1	Inconel	300	40	2.25	0.19	91.56
2	Inconel	500	20	3.75	0.32	91.47
3	Inconel	700	30	5.25	0.46	91.24

In Experiment 1, under a load of 300 N and a uniform size of 40 mm, the displacement before optimization was 2.25 mm. After optimization, the displacement was reduced to 0.19 mm, resulting in a reduction of 91.56%. This is an impressive result, indicating that the topography optimization process is highly effective in reducing displacement in Inconel under moderate loading conditions.

Experiment 2, with a higher load of 500 N and a smaller uniform size of 20 mm, showed an initial displacement of 3.75 mm. After the optimization process, the displacement was brought down to 0.32 mm, representing a 91.47% reduction. This experiment demonstrates that even under increased load and decreased size, the optimization methodology remains effective, achieving a consistently high percentage of displacement reduction.

For Experiment 3, conducted under the heaviest load of 700 N and a uniform size of 30 mm, the displacement before optimization was recorded at 5.25 mm. After optimization, the displacement decreased to 0.46 mm, resulting in a 91.24% reduction. Despite the increased load, the process was able to maintain a high level of displacement reduction, showing that the optimization technique is robust and scalable for high-stress conditions.

4.2: Comparative analysis

Exp. No.	Material	Load (N)	Uniform Size (mm)	Displacement (before)	Displacement (after)	amount of reduction %
1	Steel	300	20	2.23	0.21	90.58
2	Steel	500	30	3.72	0.32	91.40
3	Steel	700	40	5.21	0.45	91.36
4	Nickel	300	30	2.32	0.2	91.38
5	Nickel	500	40	3.88	0.34	91.24
6	Nickel	700	20	5.43	0.47	91.34
7	Inconel	300	40	2.25	0.19	91.56
8	Inconel	500	20	3.75	0.32	91.47
9	Inconel	700	30	5.25	0. 46	91.24

Steel: In the case of steel, the experiments conducted under varying loads of 300N, 500N, and 700N show that the material experiences an increase in displacement before loading as the load increases. However, the displacement after applying the load is relatively low across all conditions. The lowest post-load displacement for steel is observed at 300N with a uniform size of 20 mm, where the displacement after loading is 0.21 mm. This results in a reduction percentage of 90.58%. While the percentage of reduction remains fairly consistent across all loads, the optimum condition for steel, in terms of minimizing displacement after load application, occurs at 300N.

Nickel: Nickel exhibits similar behaviour, with an increase in displacement before loading as the load increases from 300N to 700N. The lowest displacement after the load application is recorded at 300 N with a uniform size of 30 mm, where the displacement reduces to 0.20 mm, resulting in a reduction percentage of 91.38%. Although the percentage of reduction remains relatively stable across all loads, the optimum condition for nickel is achieved at 300 N, where the displacement after topography is the lowest, indicating this load condition is best for minimizing deformation.

Inconel: Inconel, known for its high strength and resistance to deformation, also follows a similar pattern of increasing displacement with increasing load. The lowest displacement after load application is observed at 300 N with a uniform size of 40 mm, where the displacement after loading is 0.19 mm, resulting in a reduction percentage of 91.56%. This is the highest reduction percentage among the materials tested. The optimum condition for Inconel, in terms of minimizing displacement after topography, is clearly at 300N. This makes Inconel the most effective material at this load in maintaining its structure with minimal deformation.

When comparing the materials, the optimum condition—characterized by the lowest displacement after topography—occurs at 300N across all three materials. Inconel shows the lowest displacement after load at 0.19 mm, followed by nickel at 0.20 mm, and steel at 0.21 mm. While all three materials exhibit stable performance under this load, Inconel demonstrates superior resistance to deformation, making it the most optimal material for applications that require minimal displacement after topographic loading. Nickel also performs well, closely followed by steel, which shows slightly more variation but still maintains low post-load displacement at 300 N.

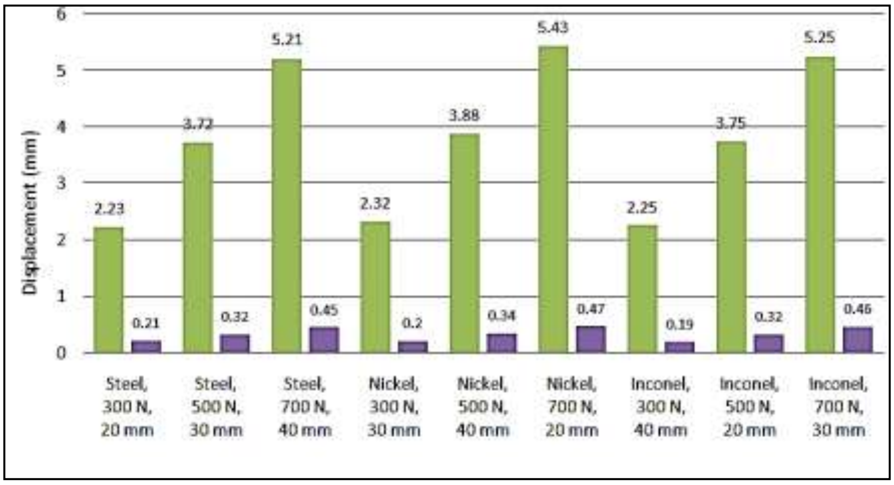


Figure 4.1: Topography optimization of Displacement (before and after)

5. CONCLUSIONS

After the successful completion of the project, the following conclusions can be drawn.

- The project examined displacement across three materials—Steel, Nickel, and Inconel—under varying loads and sizes to assess the effectiveness of topography optimization.
- Topography optimization greatly reduced the displacement in all materials, making them more stable under applied loads.
- The best result for Steel was at a load of 500 N and size 30 mm, with a post-optimization displacement of 0.32 mm and a 91.40% reduction in displacement. For Nickel, the best result was at 300 N and size 30 mm, with a post-optimization displacement of 0.20 mm and a 91.38% reduction. Inconel performed the best at 300 N and size 40 mm, with the lowest displacement of 0.19 mm and the highest reduction of 91.56%.
- Inconel showed the best overall performance, achieving the lowest displacement of 0.19 mm at 300 N and size 40 mm.
- Inconel is a great choice because of its strong strength-to-weight ratio and its ability to handle high temperatures, making it ideal for applications where strength and stability are essential.
- Topography optimization was very effective, reducing displacement by 90.58% to 91.96% across all materials, improving their stability and performance under different conditions.
- These results highlight how important it is to choose the right material and use optimization techniques to improve performance and stability in engineering projects.

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References

1. P. Krishnan and Z. Yang, "Topography optimization of a sheet metal assembly of repetitive features", SAE Technical paper, 2023.
2. R. R. Chakravarty, "Study of topography optimization on automotive body structure" SAE Technical paper, 2019.
3. Scurtu, et al., "Topography optimization of a bracket used for car bodywork reinforcement", Proceedings of the 4th International Congress of Automotive and Transport Engineering, pp. 67–72, 2023.
4. C. Wang and F. Liao, "Topography optimization and parametric analysis of bead layout for sheet metal bracket", SAE international, 2010.
5. Y. S. Kong, S. Abdullah, M. Z. Omar, and S. M. Haris, "Topological and topographical optimization of automotive spring lower seat", Latin American Journal of Solids and Structures, vol. 13, pp. 1388-1405, 2016.
6. P. N. Salunke and S. M. Patil, "Skid plate development by using topography optimization", International Journal of Analytical, Experimental and Finite Element Analysis (IJAEFEA), vol. 09, 2022.
7. J. Brennan and K. Hayes, "Recent applications of topology and topography optimization in automotive design", American Institute of Aeronautics and Astronautics, 2012.
8. A. Albers and B. Krönauer, "Stiffening of sheet metal with failure-free bead patterns", ASME 2010 International Mechanical Engineering Congress and Exposition, vol. 05, 2010.
9. Y. Chuman, H. Katsuura, and T. Okafuji, "Innovation of design and development process using structure optimization technology", Mitsubishi Heavy Industries Technical Review, vol. 52, no. 4, 2015.
10. S. N. Reddy, I. Ferguson, M. Frecker, and T. W. Simpson, "Topology optimization software for additive manufacturing", ASME 2016 International Design Engineering Technical Conferences, 2019.
11. M. P. Bendsoe and O. Sigmund, Topology Optimization: Theory, Methods, and Applications, "Berlin, Germany: Springer," 2nd edition, 2003.
12. K. Suresh and A. M. Mirzendehdel, A Hands-On Introduction to Topology Optimization. "CreateSpace Independent Publishing Platform," 2017.
13. Altair Engineering Inc., "Altair Topology Optimization Software.
14. PD Solutions, "Topology Optimization Software with CAESS ProTOP.
15. National Academies of Sciences, Engineering, and Medicine, Exploiting Advanced Manufacturing Capabilities: Topology Optimization in Design: Proceedings of a Workshop. Washington, DC: The National Academies Press, 2022.
16. J. N. Reddy, "Energy Principles and Variational Methods in Applied Mechanics", 2nd edition. Hoboken, NJ: Wiley, 2002.
17. T. J. R. Hughes, "The Finite Element Method: Linear Static and Dynamic Finite Element Analysis", Dover Publications, 2000.