The Dissipation Properties of Additively Manufactured Lattice Frame Structure of Various Size by Dynamic and Thermal Analysis

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Keywords

Additive Manufacturing (AM)
Selective Laser Melting (SLM)
Topology Optimization
Lattice Structure
Finite Element Analysis (FEA)

Abstract:
Additive Manufacturing (AM) has emerged as a revolutionary technology, contrasting sharply with traditional subtractive machining processes by enabling the construction of complex components through layer-by-layer deposition from CAD models. Among the various metal AM techniques, Selective Laser Melting (SLM) stands out as a particularly effective method for producing topologically optimized structures. In this study, lattice-based structural optimization techniques will be employed to design components with enhanced structural damping properties. Topology optimization approaches will be used to create geometries with equivalent mass and frequency characteristics of lattice structures. Three different finite element models will be developed to compare their damping coefficients as obtained from finite element analysis (FEA). The material chosen for all designs is SS 316L. Experimental validation will involve assessing the influence of lattice unit cell geometry on damping behaviour using dynamic mechanical analysis (DMA). The research is expected to yield valuable insights into the relationship between lattice unit cell geometry and structural damping properties. By comparing the damping coefficients of different finite element models, the study aims to identify key design parameters that optimize damping performance.

1. Introduction

Topology optimization is an advanced structural design method which can obtain optimal structure configuration via tailoring the material distribution satisfying specified load conditions, performance objectives and constraints.
Over last three decades, several topology optimization methods have been proposed, among which the density based method, the revolutionary structural optimization (ESO), the level set method (LSM) are the most representatives. In density-based method, a 0–1 discrete optimization problem is transformed into a continuous optimization problem in order to relax the binary design form. Originally, the homogenization method was utilized to map specified micro structure controlled by density variable to effective properties, but it is difficult to implement for mathematical complication.
Subsequently, an alternative approach named solid-isotropic material with penalization (SIMP). Compared to homogenization, element elastic modulus penalized exponentially in terms of density variables. SIMP has soon become the most popular topology optimization and been embedded in commercial software to solve engineering problems for its concise form.

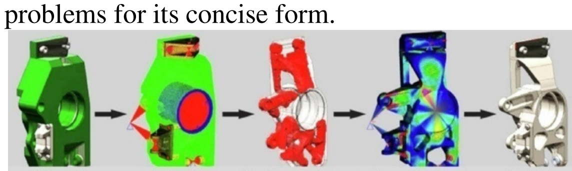

Figure1. *Topology Optimization Process.*

Objectives: To develop lattice-based structural elements using optimization methods to improve their damping characteristics. To apply topology optimization strategies to generate models with the same lattice structure mass and frequency and evaluate their damping coefficients.

Modal analysis is used to study the dynamics of SLM-manufactured metallic lattice structures. It is observed that specific lattice geometries provide superior damping compared to bulk materials. The Rayleigh damping model is experimentally validated, showing high accuracy in approximating the system behaviour [1]. A multi-scale topology optimization framework is proposed for lattice structures, utilizing NURBS hyper-surfaces to define pseudo-density fields. The approach combines SIMP and strain energy-based homogenization for efficient scale transition. Sensitivity analysis and length-scale constraints are incorporated to ensure manufacturability and mechanical performance [2]. A novel design method replaces the solid core of turbine blades with optimized graded lattice structures using topology optimization and TPMS geometries. Finite element analysis shows a weight reduction of 33–41% and an improvement in deformation resistance by 7.35–19.38% under thermal loads [3]. Hybrid structures integrating topology-optimized solids with strut-based lattices are designed using the BESO method. Applied to the MBB beam, these structures demonstrate enhanced stiffness, buckling resistance, and energy absorption compared to pure solid or lattice structures, despite a slight reduction in natural frequency [4]. A comprehensive review discusses the integration of topology optimization and additive manufacturing. It addresses challenges such as material anisotropy, fatigue, and scale effects and emphasizes the importance of a holistic approach covering material, structure, process, and performance [5]. A general design approach is introduced to create functionally graded hybrid structures suitable for additive manufacturing. The method enhances manufacturability by supporting overhangs and optimizes mechanical performance using a hybrid element model. Experimental validation shows superior stiffness and strength [6]. The mechanical behavior of 21 different topology-optimized 3D lattice unit cells is studied and compared with conventional truss lattices. Both numerical and experimental results confirm that optimized lattices exhibit superior stiffness and strength at high relative densities [7]. An inverse topology optimization (ITO) method is proposed to design auxetic composites with re-entrant and chiral geometries. The approach enables the discovery of novel 2D and 3D auxetic configurations, with detailed qualitative and quantitative analysis of their properties [8]. The influence of minimum length-scale constraints on multi-scale topology optimization is investigated. Numerical and experimental studies reveal that excessively small unit cell sizes reduce stiffness and strength, offering guidelines for optimal unit cell sizing [9]. A displacement-driven topology optimization method is presented, employing NURBS hyper-surfaces and the SIMP approach. The algorithm defines structural topology based on displacement requirements and is validated through 2D and 3D benchmark problems [10]. A topology optimization-based method is proposed to design functionally graded solid-lattice hybrid structures. The lattice supports overhangs, improving manufacturability. Simulation and experimental results confirm enhanced mechanical properties compared to conventional designs [11]. A topology optimization framework is developed for compliance minimization in stress and buckling-constrained structures. It employs K–S aggregation, a stability transformation method, and a continuation strategy to improve accuracy and robustness. Numerical examples validate its effectiveness [12]. A design method is proposed for creating solid-lattice hybrid structures using topology optimization. Functionally graded lattices are integrated with solid regions to improve manufacturability and mechanical performance, as validated through simulations and experiments [13]. A stiffness-based structural analysis framework is introduced to study continuum structures. It explores the coupling of elastic and geometric stiffness and proposes methods to identify key stiffness paths responsible for resisting deformation [14]. The potential of SLM-manufactured lattice structures to enhance damping capacity is investigated. Experimental and FE simulation results show improved damping behavior compared to bulk materials, attributed to stress concentration in specific lattice regions [15]. A stiffness-based algorithm is proposed for geometrically non-linear structural analysis. By discretizing loads and iteratively updating nodal displacements and geometry, the method achieves improved accuracy compared to conventional stiffness matrix methods [16].

2. Methodology & Experimental Procedure

2.1 Methodology

Lattice structures of varying sizes (20x20 mm, 10x10 mm, and 5x5 mm) with the same length are defined in Creo. Ansys 2023 is then utilized to conduct an additive manufacturing study, evaluating residual stress, deformation, and print time. To mitigate internal stress, heat treatment techniques are applied to the developed models. A modal analysis is performed on the three distinct lattice structures to determine their frequency responses. Additionally, damping analyses are conducted on different lattice structure sizes to compare their damping characteristics. The study further integrates solid geometry and topology optimization techniques, imposing mass and frequency constraints to refine the lattice-aligned geometry. The damping properties of various topology-optimized models are assessed and compared, followed by a frequency analysis of the topology-optimized models. Finally, the damping characteristics of the topology-optimized structures and the lattice structures are evaluated to understand their performance under dynamic conditions.

2.2 Experimental Procedure

The lattice is configured with outer horizontal, vertical, and angular beams to form a BCC (Body-Centered Cubic) lattice. Beam cross-sections are set based on lattice size: 6 mm circular beams for 20x20 mm, and 3 mm circular beams for both 10x10 mm and 5x5 mm lattice structures. The Extrusion tool is used to fill lattice gaps with solid geometry made of powder material. Next, an assembly file is created to combine the lattice structure with the powder material. The Boolean operation is performed by navigating to Component Operations in the Assembly drop-down, selecting the Cut operation, and using the 3D lattice structure as the modified component while the powder material solid geometry is the modified model. Finally, the part file is saved with a meaningful name in the desired location. The created geometry is utilized in Ansys additive manufacturing analysis, including evaluations of residual stress, deformation, and print time.

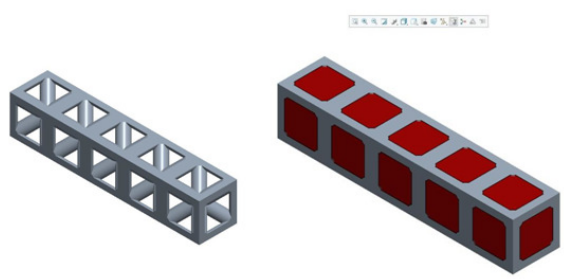

Figure2. *20X20 3D Lattices Structure*

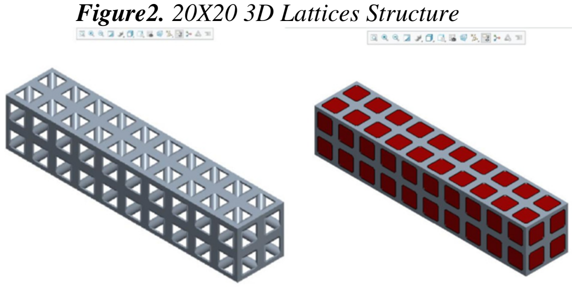

Figure3. *10X10 3D Lattices Structure*

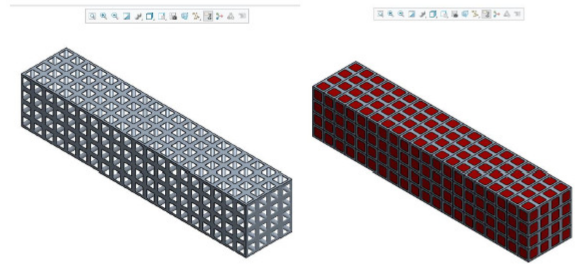

Figure4. *5X5 3D Lattices Structure*

3. Results and Discussions

3.1 Additive Manufacturing

Additive manufacturing analysis of the 20×20 lattice structure showed that applying a 200°C preheating temperature resulted in a final build temperature of 43.4°C. Post-printing, the total deformation of the structure was measured at 0.59 mm, with a residual stress of 942 MPa. The entire model construction process took 5833 seconds, equivalent to approximately 1.62 hours**.**

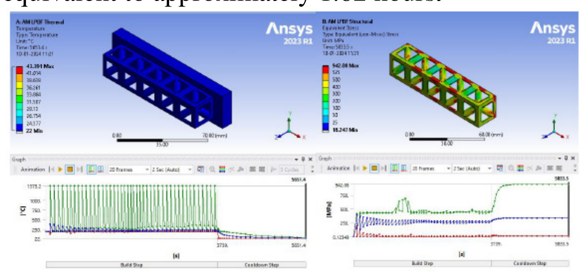

Figure5. *AM Results of 20X20 3D Lattices Structure*

Additive manufacturing results for the 10×10 lattice structure indicate that a preheating temperature of 200°C led to a final build temperature of 54°C. After printing, the structure exhibited a total deformation of 0.39 mm and a residual stress of 796 MPa. The complete model construction took 4504 seconds or approximately 1.25 hours.

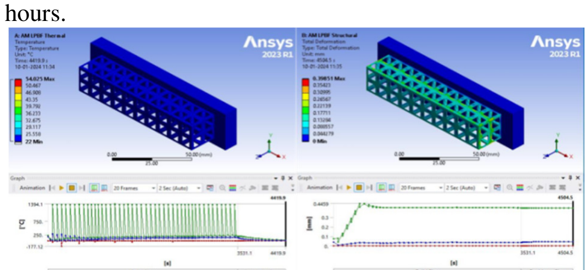

Figure6. *AM Results of 10X10 3D Lattices Structure*

Additive manufacturing analysis for the 5×5 lattice structure showed that applying a preheating temperature of 200°C resulted in a final build temperature of 54.4°C. Post-printing, the structure experienced a total deformation of 0.44 mm and a residual stress of 638 MPa. The entire construction process took 4126 seconds, or approximately 1.14 hours.

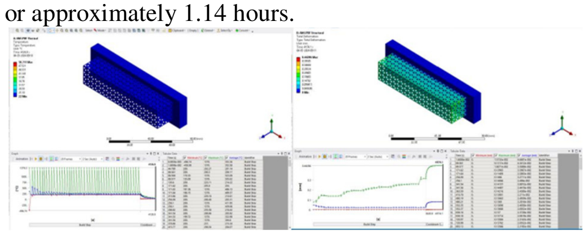

Figure7. *AM Results of 5X5 3D Lattices Structure*

The 10×10 lattice model exhibits a noticeably higher final temperature compared to the 20×20 model, while the 20×20 model shows greater total deformation. Internal stresses are highest in the 20×20 variant and lowest in the 5×5 model. Additionally, the 20×20 model requires significantly more build time than the more compact 5×5 structure.

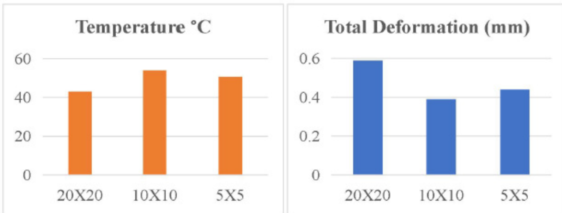

Figure8. *Temperature & total deformation of three different lattice structures.*

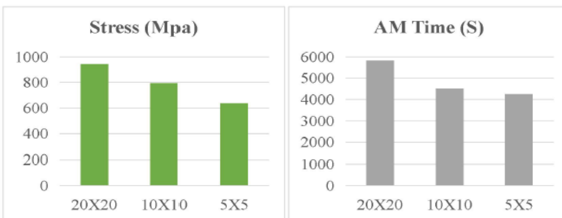

Figure9. *Stress & AM Time of three different lattice structures.*

3.2 Heat Treatment

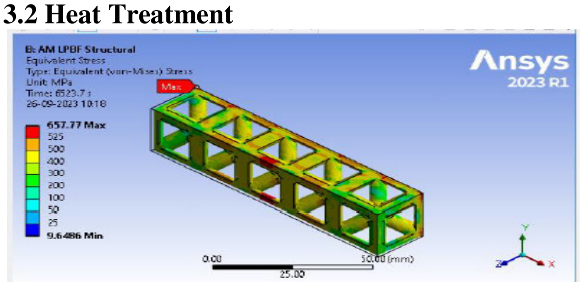

Figure10. *Stress in 20x20 model after HT process.*

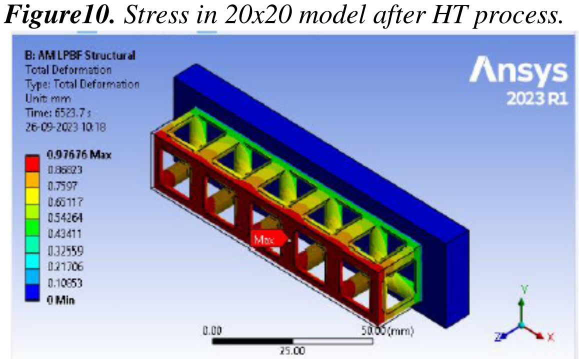

Figure11. *Total deformation in 20x20 model after HT process*

In this process, the stress value decreases from 942 MPa to 657 MPa compared to the standard preheating method. However, the total deformation of the model increases from 0.5 mm to 0.97 mm, and the overall process duration is also extended.

The model experiences a total deformation of 0.51 mm, with a reduced stress value of 555 MPa, and the operation is completed in 6080 seconds. Compared to the conventional preheating approach, this method lowers the stress from 942 MPa to 555 MPa while maintaining the model's deformation at 0.5 mm. However, incorporating the heat treatment stage further extends the process duration to 7200 seconds.

Table1. The various temperatures in Heat treatment process and stress achieved as shown.

Temperature (°C)	Heating Convection Coefficient (W/mm².°C)	Cooling Convection Coefficient (W/mm².°C)	Reached Temperature (°C)	Stress (Mpa)
300	1.e-005	1.e-005	300	548
450	1.e-005	1.e-005	445	558
600	1.e-005	1.e-005	594	551
750	1.e-005	1.e-005	742	550
900	1.e-005	1.e-005	900	556
1050	1.e-005	1.e-005	1038	555

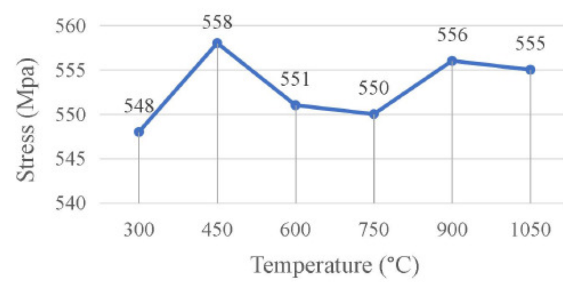

Figure12. *Stress levels at varies temperatures*

The model experiences a total deformation of 0.53 mm, with a stress value of 566 MPa, and the process is completed in 5833 seconds. Compared to the standard preheating method, this approach reduces the stress from 942 MPa to 566 MPa while maintaining the overall deformation at 0.53 mm. However, the inclusion of the heat treatment stage extends the total process duration to 7200 seconds.

Table2. Stress at various convection coefficient

Temperature (°C)	Heating Convection Coefficient (W/mm².°C)	Cooling Convection Coefficient (W/mm².°C)	Reached Temperature (°C)	Stress (Mpa)
300	2.e-005 – 2Hrs	1.e-005 – 2Hrs	300	548
300	3.e-005 – 2Hrs	1.e-005 – 2Hrs	300	548
300	2.e-005 – 2Hrs	5.e-006 – 4Hrs	300	548
450	2.e-005 – 2Hrs	1.e-005 – 2Hrs	450	552
450	3.e-005 – 2Hrs	1.e-005 – 2Hrs	450	566
450	2.e-005 – 2Hrs	5.e-006 – 4Hrs	450	556

Among all heat treatment scenarios, uniform heating and cooling with a convection coefficient at 300°C—resulted in the lowest stress level of 548 MPa. Due to its superior stress reduction performance, this heat treatment method was selected for application across all remaining lattice models.

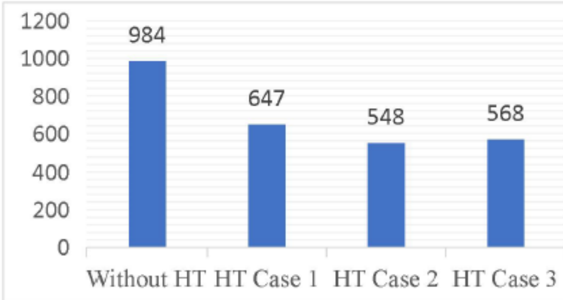

Figure12. *Stress level in different cases*

For the 10×10 lattice structure, heat treatment reduced the residual stress from 796 MPa to 595 MPa, while total deformation remained nearly unchanged at 0.46–0.47 mm. Although the stress levels improved significantly compared to the standard preheating process, the heat treatment increased the overall processing time from 4504 to 7200 seconds, with a total operation time of 18,905 seconds.

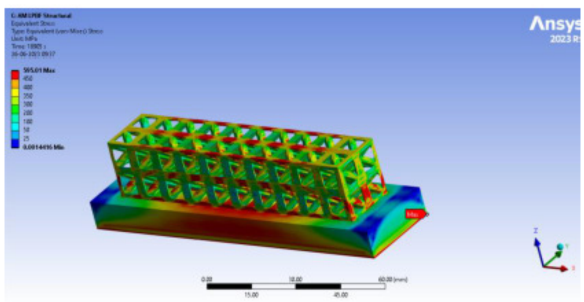

Figure13. *Stress in 10x10 model after HT process*

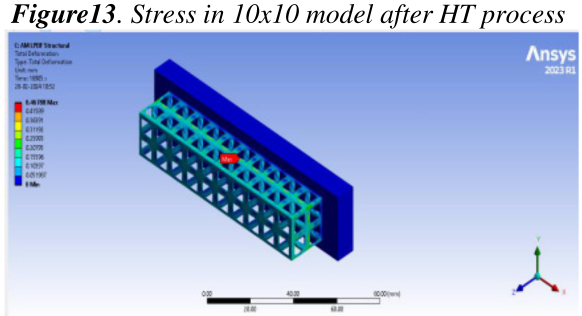

Figure14. *Total deformation in 10x10 model after HT process*

For the 5×5 lattice structure, heat treatment reduced the residual stress from 638 MPa to 596 MPa, while the total deformation remained low at 0.41 mm. Although stress levels improved slightly, the heat treatment increased the process completion time to 7200 seconds, extending the overall operation duration beyond the initial 4126 seconds required in the standard preheating method.

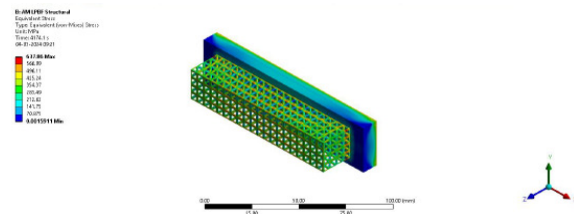

Figure15. *Stress in 5x5 model after HT process*

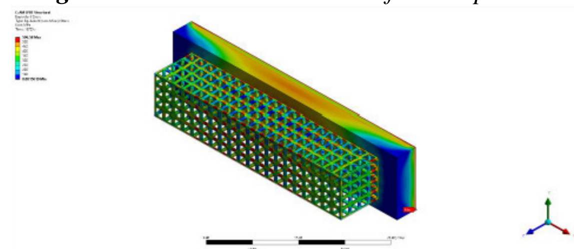

Figure16. *Total deformation in 5x5 model after HT process*

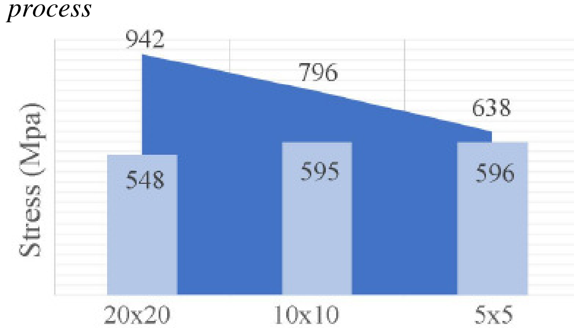

Figure17. *Internal Stresses before and after HT Process*

3.3 Lattice Structure Model Analysis

Modal analysis of the three lattice structure variants revealed that the 20×20 model exhibited the highest natural frequency at 1146.8 Hz, followed by the 10×10 model at 1011.7 Hz, and the 5×5 model at 981.4 Hz. This trend indicates that larger lattice sizes contribute to increased structural stiffness and higher frequency responses.

Table2. Frequency of Lattice Structures

Mode	20X20 Lattice frequency (Hz)	10X10 Lattice frequency (Hz)	5X5 Lattice frequency (Hz)
1.	1146.8	1011.7	981.4
2.	1146.9	1011.7	982.3
3.	2890.8	4588.3	4851.1
4.	6036.9	5530.3	5394.9
5.	6036.9	5530.5	5397.2
6.	7457.4	7525.5	7648.8

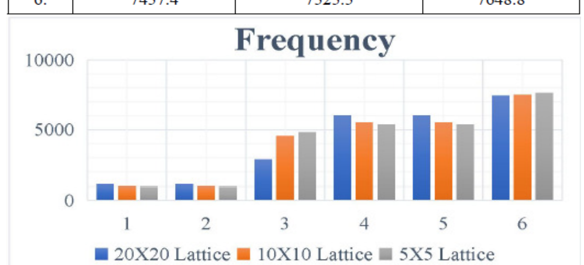

Figure15. *Lattice structure frequencies in three different variants*

3.4 Damping Analysis

Damping analysis of the 20×20 lattice structure and its Equivalent Mass and Frequency (EMF) model revealed that the lattice model experienced a maximum deformation of 0.672 mm, while the EMF model showed significantly lower deformation at 0.420 mm. This indicates that the EMF design offers improved damping performance with reduced structural deformation.

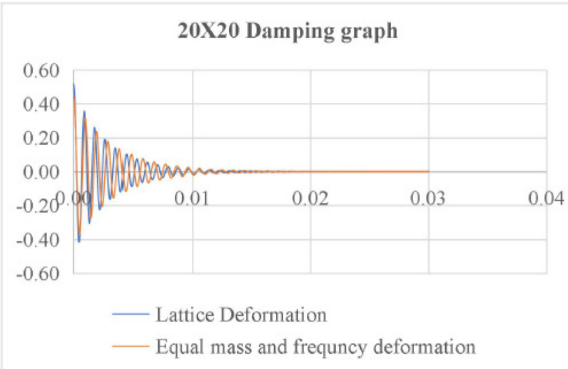

Figure16. *20x20 model damping results*

Damping analysis of the 10×10 lattice structure and its Equivalent Mass and Frequency (EMF) model showed that the lattice model exhibited a maximum deformation of 0.672 mm, whereas the EMF model demonstrated reduced deformation at 0.420 mm. This suggests that the EMF model provides better damping efficiency and structural stability compared to the lattice configuration.

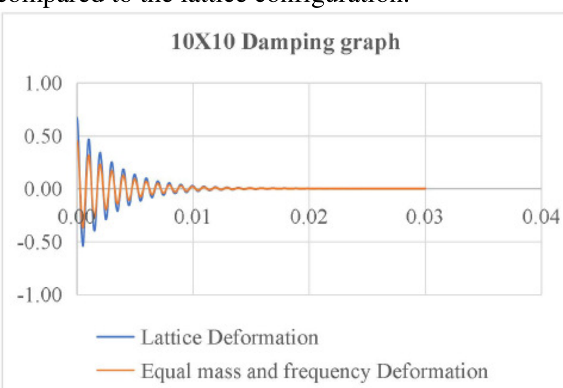

Figure17. *10x10 model damping results*

Damping analysis of the 5×5 lattice structure and its Equivalent Mass and Frequency (EMF) model indicates that the lattice model undergoes higher maximum deformation at 0.672 mm, while the EMF model shows reduced deformation at 0.420 mm. This highlights the superior damping performance and structural efficiency of the EMF design over the conventional lattice structure.

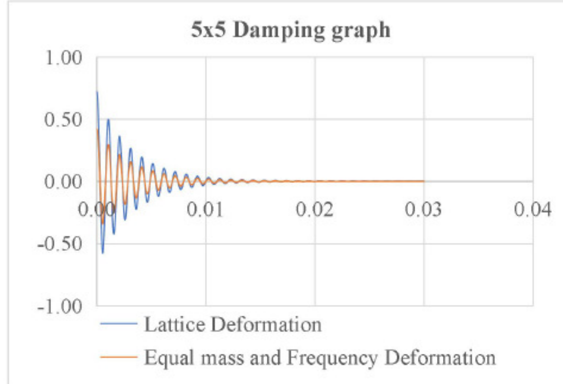

Figure18. *5x5 model damping results*

After importing the analysis data into MATLAB and executing the relevant commands, the damping ratio (ε) for the 20×20 lattice structure was found to be 0.049564, while the Equivalent Mass and Frequency (EMF) model exhibited a slightly lower damping ratio of 0.045254. These results indicate that the lattice structure provides better damping performance compared to its EMF counterpart.

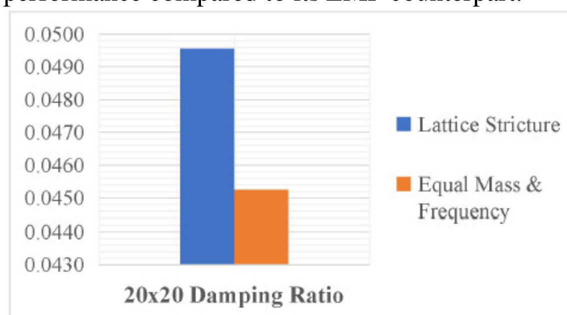

Figure19. *Damping ratio of 20x20 lattice & equivalent mass & frequency model*

MATLAB analysis of damping ratios based on the first five peak values revealed that the 10×10 lattice structure has a slightly higher damping ratio (ε = 0.049583) compared to its EMF model (ε = 0.049480), indicating better damping performance in the lattice design. However, in the 5×5 model, the EMF structure showed a higher damping ratio (ε = 0.042432) than the lattice structure (ε = 0.040906), suggesting improved damping behavior in the EMF design for smaller lattice configurations.

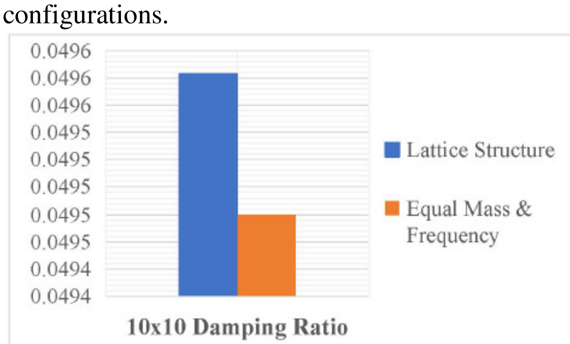

Figure20. *Damping ratio of 10x10 lattice & equivalent mass & frequency model*

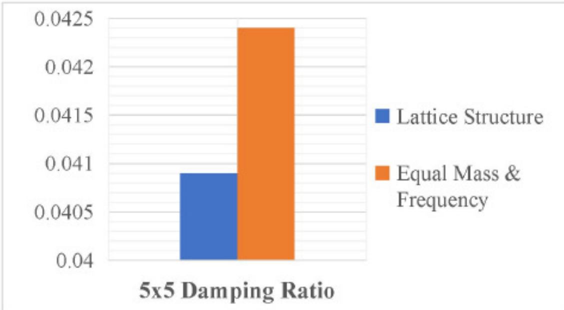

Figure21. *Damping ratio of 5x5 lattice & equivalent mass & frequency model*

4. Conclusions

This study explores the potential of topology optimization in designing components with integrated lattice structures to enhance damping performance. Finite element analysis (FEA) was conducted on additively manufactured lattice models to evaluate internal friction, deformation, residual stress, and thermal effects. High residual stresses were observed, prompting heat treatment through post-printing annealing and preheating of powder material, following IS 6911:1992 standards for 316 stainless steel. Heat treatment effectively reduced internal stress across lattice sizes, with the 20×20 model decreasing from 942 MPa to 548 MPa, the 10×10 from 796 MPa to 595 MPa, and the 5×5 from 638 MPa to 596 MPa. Modal analysis assessed frequency response, leading to a topology-optimized Equivalent Mass and Frequency (EMF) design that maintained frequency characteristics. Damping analysis revealed that 20×20 and 10×10 EMF models exhibited higher damping ratios than their lattice counterparts, while the 5×5 lattice outperformed its EMF equivalent due to size constraints and internal friction effects. The study concludes that damping properties are influenced not just by lattice size but by an optimal combination of size and shape, highlighting the need for tailored designs to maximize damping efficiency for a given mass.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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