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Lattice and Topology Optimization of Additively Manufactured Turbine Blade

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Abstract – The main purpose of the current study has been the structural analysis and topology optimization of turbine blade model that is fabricated using additively manufactured alloy. Additively manufactured alloys are widely utilized in applications such as aerospace and biomedical. The microstructure of additively manufactured Ti-6Al-4V is known to exhibit columnar β grains and a lamellar α phase, which can induce anisotropy in mechanical properties;an important consideration in turbine blade design. The reason for why these alloys are selected is due to their high strength-to-weight ratio and corrosion resistance in several applications. In this study a static structural analysis was performed with 9 kN centrifugal forces in both X and Z directions to simulate actuality conditions. The turbine blade was fixed along Z-axis and deformation, elastic strain, equivalent stress and strain energy were calculated. Results showed that total deformation increased from fixation region to blade tip with maximum deformation of 6.5 mm. Elastic strain distribution had minimum values near fixation region and blade tips and maximum strain values are observed around blade stem with values between 0.003-0.005 mm/mm. Elastic strain distribution exhibited minimum values near the fixation region and blade tips, while maximum strain values were observed around the blade stem, ranging between 0.003-0.005 mm/mm. Equivalent stress patterns has a similar tendency with the elastic strain distribution, and its with maximum stress values ranges between 544 MPa and 326 MPa. Strain energy distribution had its peak value of 105 mJ at the mid section of the blade. To reduce weight, lattice structures were added to the design with highest density near fixation region (0.778-0.667) and moderate density around blade stem (0.445-0.556). A topology optimized design was generated with a dome like structure near the turbine blade stem which is different from the initial geometry. These results can be used to improve turbine blade design by optimized material distribution and structural efficiency.

Keywords – Additive Manufacturing, Lattice Structures, Topology Optimization, Mechanical Properties, Turbine Blade.

I. INTRODUCTION

Ti-6Al-4V alloys are widely utilized in biomedical and aerospace applications stem from its excellent mechanical properties [1–4]. Along with Nickel alloys, Ti-6Al-4V is one of the most popular materials for biomedical and aerospace applications including gas turbines [5] due to its high strength to weight ratio and corrosion resistance [6–9]. Recently, additive manufacturing has attracted significant interest in academia and industry due to its ability to create complex geometries, efficiency in material use and applications of rapid prototyping. One of the most commonly used metal additive manufacturing techniques include electron beam melting (EBM) [3], directed energy deposition (DED) [8], and selective laser melting (SLM) [7], each with its own advantages depending on the application and material requirements. In additive manufacturing processes like laser metal deposition (LMD) the fabrication of titanium alloys often results in columnar β grains along with lamellar α phase which significantly affects the mechanical properties of the material [10]. In DED and SLM it is known that β grains always elongate along the building direction due to the directional heat transfer that occurs during solidification [11]. Compared to SLM DED fabricated specimens remain above the β transus temperature for longer period and hence have coarser β grains. The high cooling rates of the melt pools is the reason behind the formation of resultant microstructure. The presence of columnar prior β grain structure is generally detrimental as it induces anisotropy in mechanical properties [12,13], which is not favorable when designing complex Ti-6Al-4V components [14,15]. These are some of the important microstructural aspects to be considered when designing Ti-6Al-4V components using additive manufacturing as they demonstrate a crucial role in selecting the most suitable AM technique. Utilization of lattice structures and application of topology optimization is recently of interest by many scholars due to maintaining acceptable strength and achieving weight reduction.

In the current study, topology optimization and lattice structure applied to a Ti6Al4V alloy turbine blade. Structural analysis was made to obtain mechanical property distribution.

II. MATERIALS AND METHOD

A model of a turbine blade to do topology optimization is shown in Figure 1. Finite element analysis was done using ANSYS software. The material properties assigned to the functional part was done using library for additively manufactured Ti6Al4V alloy. Initial weight of the turbine blade was calculated to be around 0.387 kg. The number of the elements and nodes for the simulations were 5701 and 10823, respectively. The young modulus of the alloy was 107 GPa while the density is 4405 kg/m^3. The poisson ratio is found 0.323 whereas a shear modulus of 40.4 GPa was used in the current study. One of the most dominant forces that turbine blades are being subjected to what is referred to be as centrifugal forces during the operation. Based on the possible forces that a turbine blade could be subjected to in real life operations, two forces with different directions but same magnitude were applied to the part. The part was fixed from one side and the forces were applied in the simulation environment. The magnitude of the forces was determined to be around 9 kN in Z and X axes. The axis where the part was fixed was along the Z direction. These were the boundary conditions for a structural static analysis as shown in Figure 2.

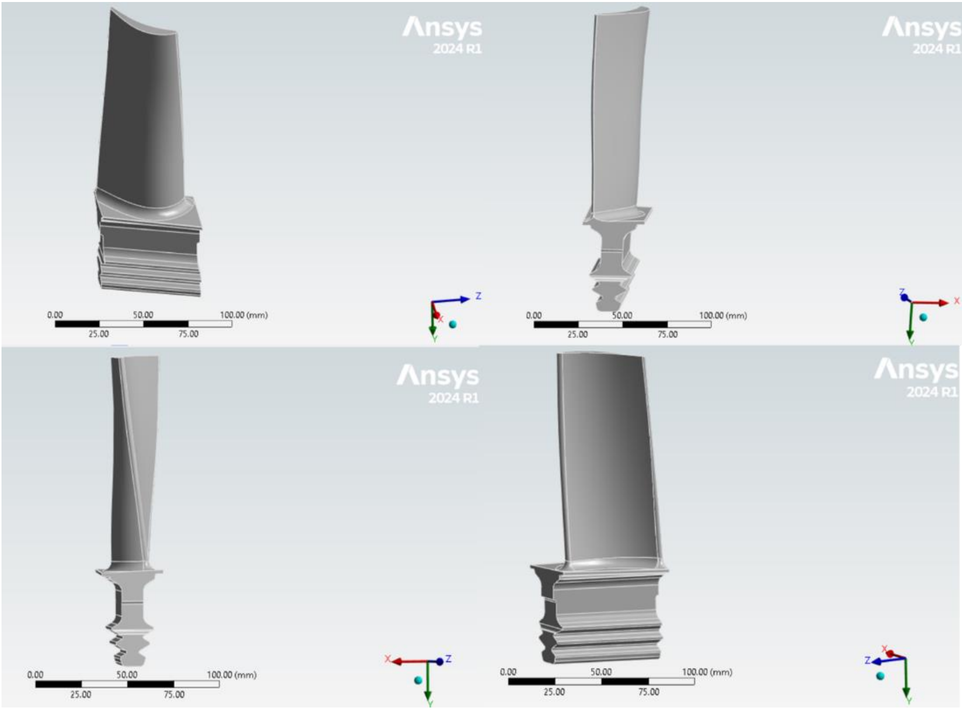

Figure 1. CAD model of the turbine blade that is assigned additive manufacturing properties.

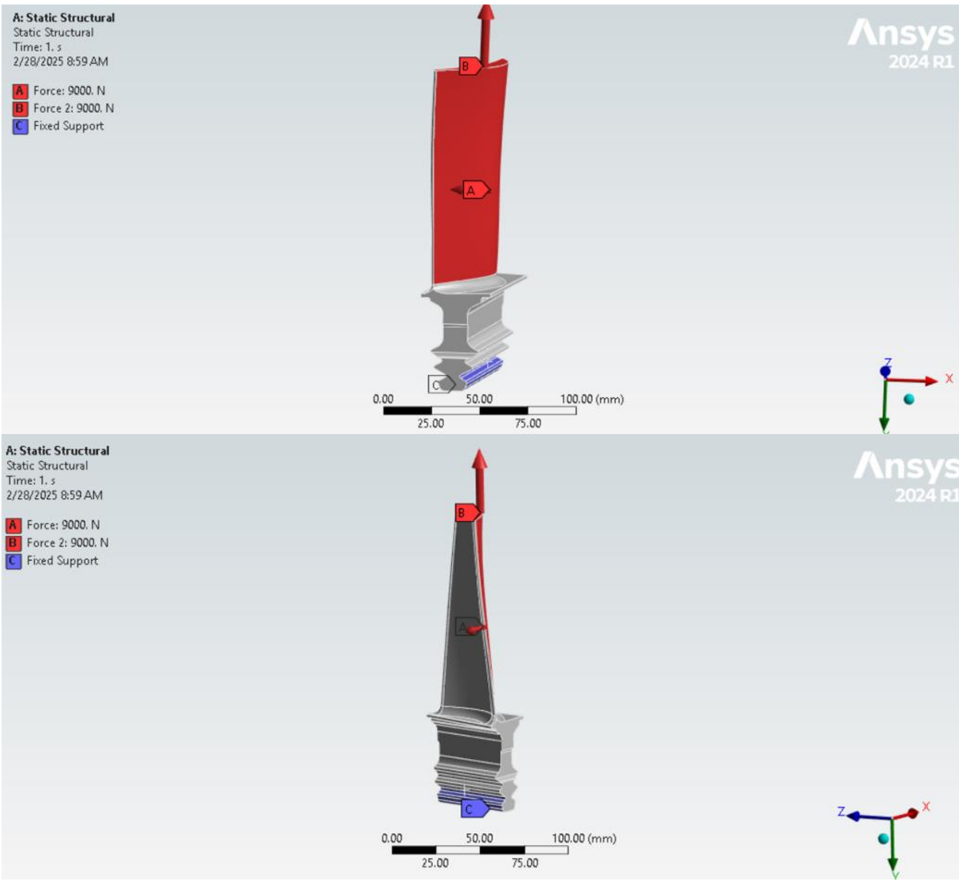

Figure 2. Boundary conditions applied for structural analysis, clarifying the fixed regions and applied loads.

III. RESULTS

A static structural analysis was applied to the part was demonstrated in Figure 3. The total deformation was gradually increasing from the fixed region to the tip of the turbine blade. The deformation was approximately near zero in the part that is close to fixation region. The value of the maximum total deformation was around 6.5 mm near the tip of the blade where the deformation shows its maximum value. The average deformation is to be 0.78 mm.

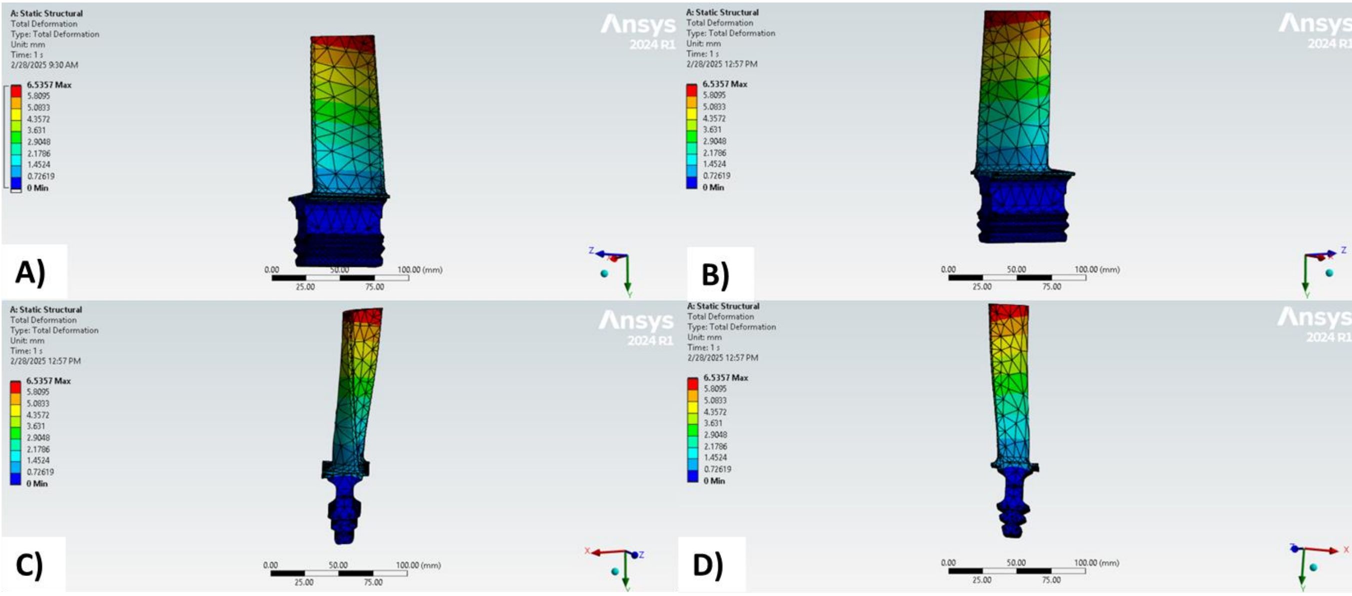

Figure 3. Total deformation distribution of turbine blade based on finite element analysis. A-D represent different perspectives of the part.

The figure 4 represents elastic strain distribution behaviour of the deformed turbine blade. Distribution completely shows a different tendency than what was demonstrated by deformation map in Figure 3. The minimum values were around the places for fixation as it is in Figure 3 for deformation behaviour however, blade tips were also showing minimum values as completely opposite to the deformation maps. One other key difference is where the maximum strain is observed. In the case of equivalent strain, that location is actually around the blade stem, not the blade tip as previously maximum value was observed for deformation value. The value of the maximum strain is around between 0.003-0.005 mm/mm. The average elastic strain is found 0.0014 mm/mm.

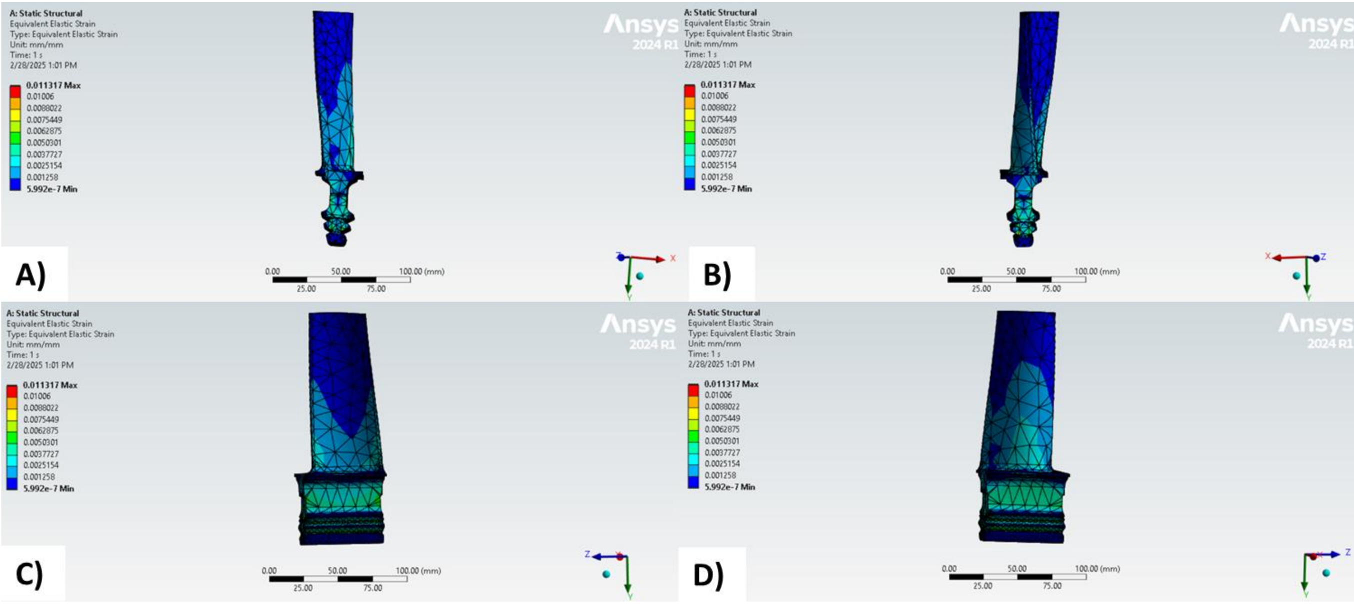

Figure 4. Equivalent elastic strain distribution of turbine blade based on finite element analysis. A-D represent different perspectives of the part.

Equivalent stress variation was as it is displayed in Figure 5. A similar distribution to the what was observed for elastic strain has been seen in the case of equivalent stress behavior. Again the minimum values were obtained near fixation and blade tip regions whereas the maximum stress is obvious around blade stem. The attained value for the maximum stress is ranging between 544 MPa to 326 MPa. The average stress is determined to be around 127 MPa.

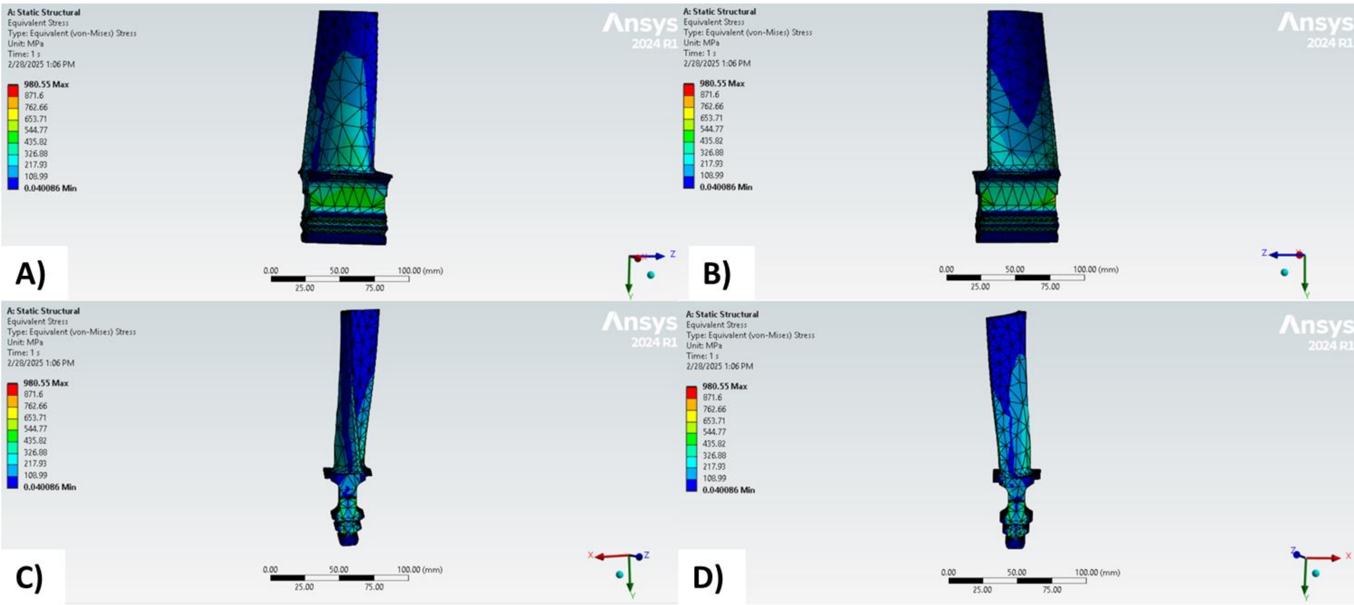

Figure 5. Equivalent stress distribution of turbine blade based on finite element analysis. A-D represent different perspectives of the part.

Total strain energy evaluation was also done in the current study. The strain energy distribution has also shown a unique tendency as one can see according to Figure 6. Obtained results suggests that the regions corresponded to maximum strain extends across the Y direction starting from near fixation and blade stem. The maximum point of the strain energy is located in the middle of the geometry considering the plane across Z direction and its value determined to be around 105 mJ. The total strain energy is calculated to be around 14089 mJ.

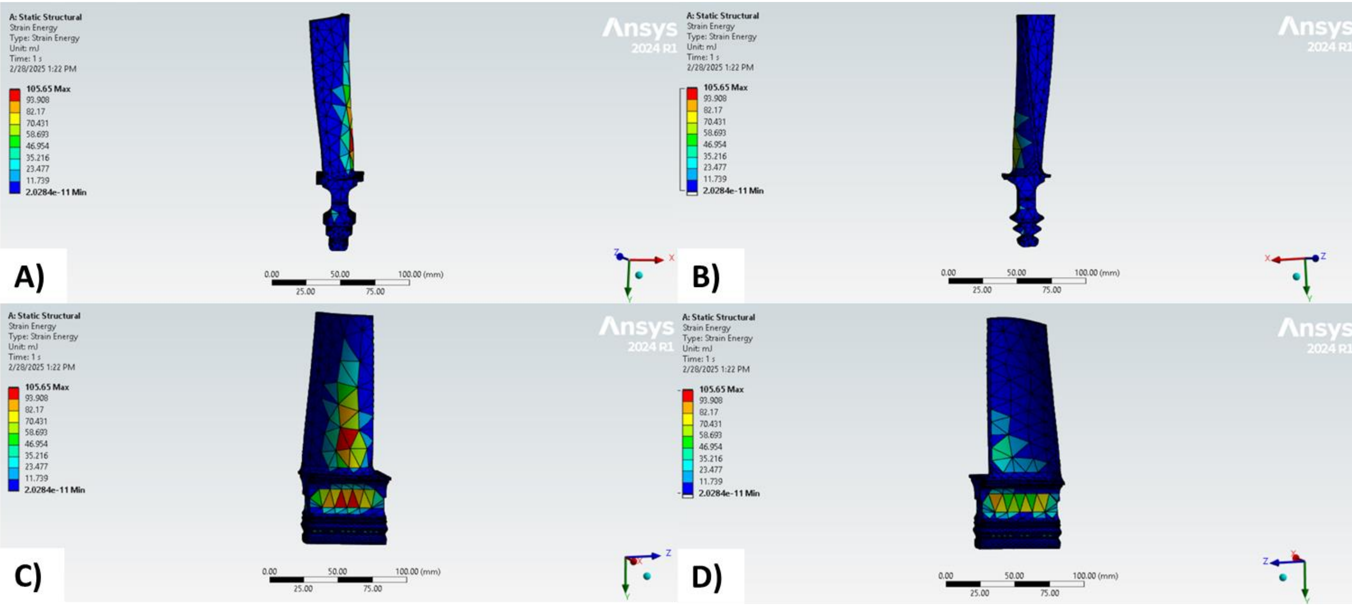

Figure 6. Strain energy distribution of turbine blade based on finite element analysis. A-D represent different perspectives of the part.

Lattice structure was assigned to the designed model to achieve lightness in the part. The maximum lattice structure was assigned to the part near fixation regions and its value are ranging between 0.778-0.667. The second most lattice common regions were determined to be around blade stem which is around 0.445-0.556. Adapting lattice structure on the designed part yielded a mass reduction from 0.38 kg to 0.21 kg. Reduction in the weight is determined to be around 46% via lattice assignment process.

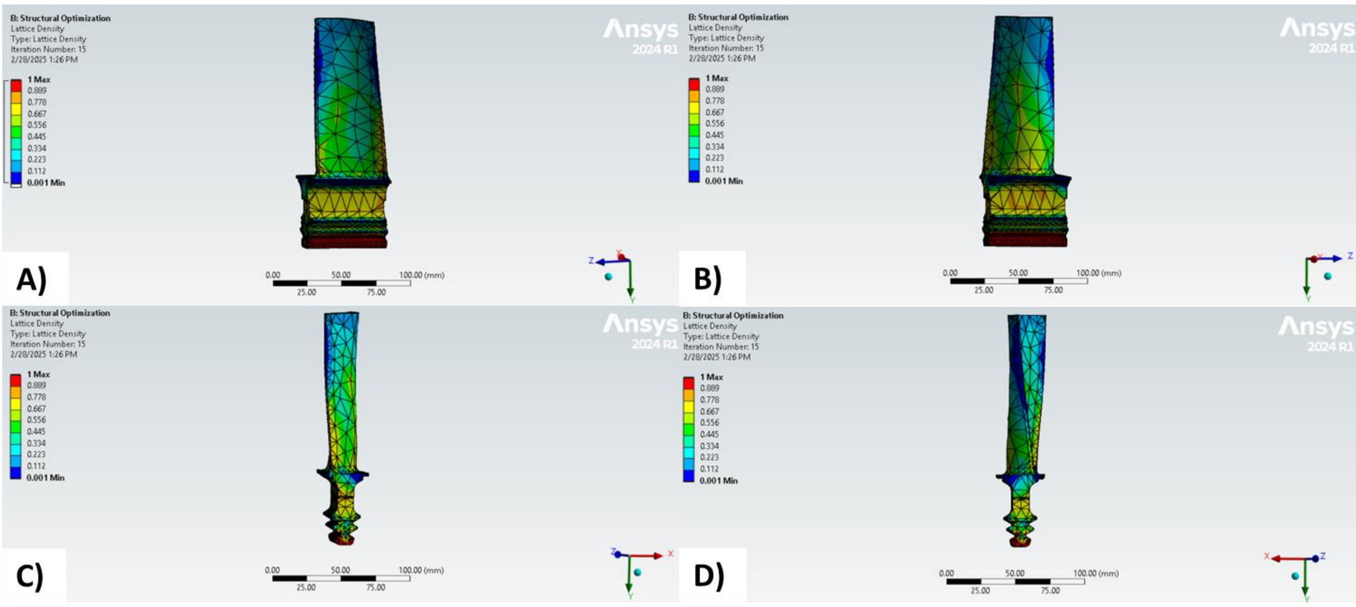

Figure 7. Lattice density distribution of turbine blade based on finite element analysis. A-D represent different perspectives of the part.

In addition, based on boundary conditions selected, a design using topology optimization was intended to be studied, and a suggested geometry was obtained based on analyses as it was shown in Figure 8. The geometry was shown using five different perspectives. A doom-similar structure is observed near turbine blade stem which is different than the case of what was observed for initial geometry. Using topology density, almost a 20% weight reduction has been achieved. The original mass of the turbine blade was

0.38 kg, following the application of topology optimization, the mass of the recreated design was found to be around 0.31 kg.

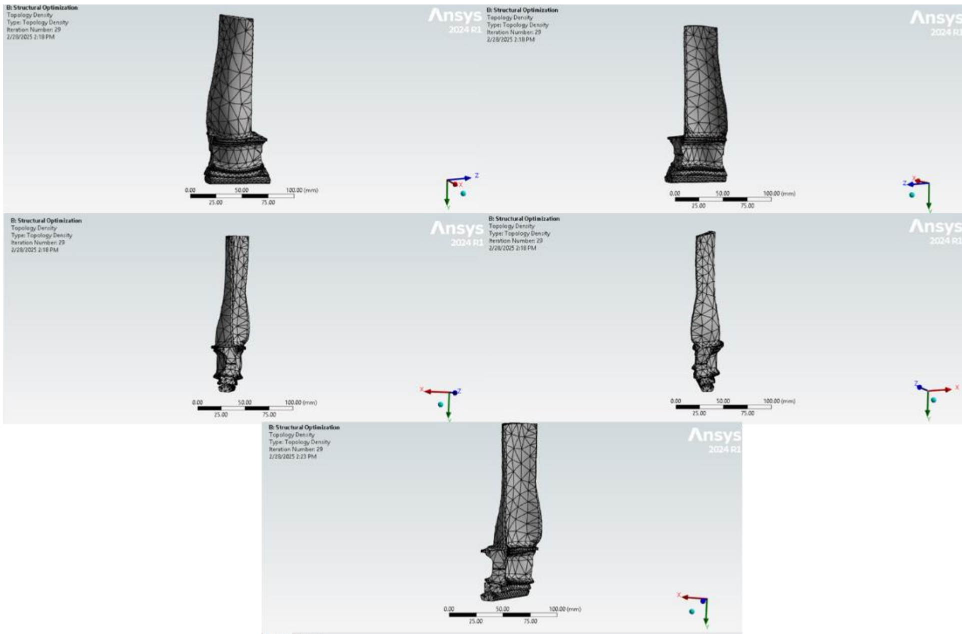

Figure 8. Turbine blade model subjected to weight reduction and captured corresponded part images by different perspectives.

IV. DISCUSSION

The total deformation was gradually increasing from the fixed region to the tip of the turbine blade as was shown in Figure 3. This tendency of distribution completely shows a different behaviour than what was displayed by strain map in Figure 4. Stress distribution also presents a similar behaviour to that of strain which is one of the most striking results of the current study. This is hypothesized because of that possibility; deformation is more like a global effect and it is possible to be influenced by overall stiffness and constraints. In the case of strain, it is considered to induce a local effect depends of deformation distribution. Stress also shows a similar tendency to that of strain, because there is the possibility of being related to linear elastic materials. The obtained weight reduction value could be considered a fair value. Topology optimization has been widely utilized across different engineering applications. With ongoing research and development efforts by engineers and designers aims to enhance its integration into innovative manufacturing methods such as additive manufacturing [16]. Parts such as brackets are one of the most common applications of topology optimization. When it was compared across the literature, Hanush et al. applied a level set based topology optimization approach and obtained 44.8% weight reduction with a factor of safety of 2.3 for AlSi12Mg alloy modelled bracket, where the selective laser melting type additive manufacturing data was used for simulations [17]. A similar value around 20%, as also what was obtained in the current study, was attained in study conducted by Okorie et al. In the mentioned study, PLA bracket was made using fused filament fabrication method [16]. A lattice structure is a carefully designed porous framework. The lattice structures are made up via repeating unit cells arranged in a specific pattern [18]. Many animal bones and plant stems feature naturally occurring porous lattice structures. These structures contribute to their strength and at the same time keeping them lightweight [18]. Researches indicate that lattice structures induces properties such as outstanding strength, energy absorption, thermal insulation, noise reduction, and being lightweight [19,20]. These acquired properties give them advantage of being beneficial for various engineering applications. When a lattice structure is assigned to the turbine blade a 46% weight reduction was possible to be realized which could be considered as a significant decrease in the weight.

V. CONCLUSION

The structural analysis and topology optimisation in this study showed the mechanical behaviour of a turbine blade under pre-defined forces influenced by centrifugal forces. The deformation, strain and stress patterns highlighted the areas of mechanical loading and the blade stem was found to be a high stress area. The integration of lattice structures reduced material use with maintaining the robust structure, especially near the fixation areas. The topologically optimized geometry with a dome like structure near the blade stem has potential of mechanical stability and provided weight reduction. These results can be helpful in order to generate more robust and lighter turbine blades designs for aerospace applications. Future work regarding abovementioned study has a potential to be carried on with the subject of experimental validation of the attained results for further improvement of the design.

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