IJPAS ISSN:2149-0910 | INTERNATIONAL JOURNAL PURE AND APPLIED SCIENCES

Vol.11(1); 240-251 (2025)
DOI: 10.29132/ijpas.1643610

Research Article

Design and Finite Element Analysis of 2.5D Lattice Structures for Internal Air-Cooled Gas Turbine Blades

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Received: 20.02.2025

Accepted: 12.06.2025

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Abstract: Making lightweight designs without changing the properties of materials is very important for aviation. In addition, effective cooling of metallic jet engine parts operating at high temperatures, such as gas turbine blades, is necessary to increase the efficiency of the engine and extend the service life of the gas turbine blade. In this regard, in parallel with the developments in additive manufacturing, lattice structures that provide both significant weight reduction and large surface area for effective cooling have recently started to be a hot topic. In this study, square, triangular and hexagonal 2.5D lattice structures were designed for the internal air-cooled gas turbine blade and analyzed by the finite element method. A conventional gas turbine blade with air cooling channels was used as a reference. The results showed that up to 17.14% weight reduction and up to 93.43% air cooling surface area increase can be achieved in the gas turbine blade thanks to lattice designs. When the results of maximum stress, FOS and deformation in turbine blades, as well as weight reduction and surface area increase, were evaluated together, it was concluded that the most suitable 2.5D lattice design was hexagonal.

Keywords: lattice structure; turbine blade; inconel 718; finite element analysis; mechanical properties; weight reduction

Araştırma Makalesi

Dahili Hava Soğutmalı Gaz Türbini Kanatçıkları için 2.5D Kafes Yapılarının Tasarımı ve Sonlu Elemanlar Analizi

Özet: Malzeme özelliklerini değiştirmeden hafif tasarımlar yapmak, havacılık için çok önemlidir. Ayrıca, yüksek sıcaklıklarda çalışan metal jet motoru parçalarının, örneğin gaz türbini kanatçıklarının etkili bir şekilde soğutulması, motor verimliliğini artırmak ve gaz türbini kanatçıklarının ömrünü uzatmak için gereklidir. Bu bağlamda, eklemeli imalat alanındaki gelişmelerle paralel olarak, hem önemli ölçüde ağırlık azaltımı sağlayan hem de etkili soğutma için büyük yüzey alanı sunan kafes yapılar, son zamanlarda oldukça popüler bir konu haline gelmiştir. Bu çalışmada, iç hava soğutmalı gaz türbini kanaçıkları için kare, üçgen ve altıgen 2.5D kafes yapıları tasarlanmış ve sonlu elemanlar yöntemi ile analiz edilmiştir. Hava soğutma kanallarına sahip geleneksel bir gaz türbini kanadı referans olarak kullanılmıştır. Sonuçlar, kafes tasarımları sayesinde gaz türbini kanadında %17,14'e kadar ağırlık azaltımı ve %93,43'e kadar hava soğutma yüzeyi artışı sağlanabileceğini göstermiştir. Maksimum gerilme, güvenlik faktörü (FOS) ve deformasyon gibi sonuçlar ile birlikte ağırlık azaltımı ve yüzey alanı artışı değerlendirildiğinde, en uygun 2.5D kafes tasarımının altıgen olduğu sonucuna varılmıştır.

Anahatar Kelimeler: kafes yapısı; türbin kanatçığı; inconel 718; sonlu elemanlar analizi; mekanik özellikler; ağırlık azaltımı.

1. Introduction

The demand for air transportation, which is one of the fastest transportation methods in the world, is constantly increasing. Past oil crises, fuel prices, declining fuel stocks, and increasing environmental concerns have drawn the attention of the aviation industry to the need for reasonable use of fuel [1], [2]. Fuel consumption directly affects cargo and passenger demand through operational costs and thus prices. Airlines, aware of the consequences of market loss due to rising prices and inability to compete, are more willing than ever to cut fuel costs. Fuel is such a huge cost for airlines that it is the focus of industry-wide effort to find ways to improve efficiency [3], [4]. A focus on fuel efficiency makes both business and environmental sense, as aviation fuel typically accounts for more than 25% of airline costs and more than 97% of airline CO2 emissions. For this reason, it is very important to use lighter materials in aircraft to reduce weight in air transport [5], [6], [7].

A jet engine, also known as a gas turbine engine, is an aviation machine that compresses air from the atmosphere and burns it with jet fuel. The gases emerging as a result of this combustion are rapidly thrown out, and a reverse thrust occurs, and with this thrust, the vehicle to which the engine is connected is provided to move. A jet engine consists of an air inlet, a compressor, combustion chambers, outlet turbine and nozzle sections [8], [9], [10]. The air-inlet is the part that allows the required air to enter the engine and is shaped considering the performance of the aircraft at the front. This section is designed in different ways, taking into account that the aircraft flies below the speed of sound and above the speed of sound. The basis of the jet engine is the high temperature and pressure turbine blade unit, which converts the expansion energy of the combustible gases into torque. A turbine blade of a jet engine is a component that performs the jet engine turbine section. These turbine blades are exposed to extremely high temperatures as well as pressure when the engine is running. The turbine blades should be made from the materials with complex figure, high surface quality and accuracy, and heat resistant. The production cost of this component increased so. The machining of the turbine blade materials is difficult and, they can be manufactured from high quality materials. These materials should exhibit relatively high strength, creep, fatigue and corrosion resistance in extreme conditions. For this purpose, nickel-based materials such as Inconel and Waspaloy have high thermal resistance [11], [12], [13], [14], [15]. It is well known that the Ni-based alloys have anti-corrosion and thermal stability and display good mechanical properties under high temperature, and the machining of the alloys has posed considerable challenges due to rapid work hardening and low thermal conductivity. The improving of machining efficiency, the reducing of cutting forces, 5-axis machines with high-performing cutting tools and high part precision are the main challenges in jet engine turbine blades. The process efficiency of turbines is well known to rise with the inlet temperature of the turbine. The improving engines of the turbine activate at very high temperatures and in parallel high pressure rates. If the turbine inlet temperature rises, the transferred heat to turbine blade increases, the blades attain a metal temperature and the metal tends to creep. The current design rules require the modification of internal air cooling channels to decrease the creeping of the blade and advance functional life. It is well known that the geometry of these internal cooling channels is quite complicated [16], [17]. The cooling degree which may be obtained in turbine blades with basic internal air-cooling is achieved with small quantities of cooling air for good cooling.

The design of the cooling performance of internal air-cooled turbine blades affects the properties and quality where both aerodynamic and geometric variables are considered [18]. The coefficient of a high internal heat-transfer, a minimum cooling flow, the cooling air pressure drop and a large internal cooled surface area are the necessary and compulsory requirements to good and productive cooling in turbine blades [18], [19].

To find the creep-rupture failure life of the gas turbine blade, it is investigated at a very high inlet temperature using the parameter model of Larson-Miller. This model studies the temperature and thermal stress distribution inside the turbine blade with the cooling channel geometry [20]. To predict the electrical conductivity of nickel-based Inconel 718 alloy, the serial electrical conductivity model and Wiedemanne-Franz Law are used [21]. The maximum cutting temperature is directly related to the electrical conductivity of the surface conductive active medium coating and decreases with the increase of conductivity. The turbine blades are modelled and simulated with Solidworks software [22]. Three types of materials, Inconel 625, Palladium and Titanium alloys, tested and discussed. It is reported that the Inconel 625 is the most suitable among the three compositions. It is declared that the fuel efficiency advanced with the increase in the compressor pressure ratio and fuel cell electric power [23]. In a different study, a jet hybrid engine having a solid oxide fuel cell coupled with a fan was investigated [24]. The performance of solid oxide fuel cell advanced and also it is noted that the weight optimization and thermodynamic design must be done to enhance the practical application of the engine. The fracture on the turbine blades is studied by Balli [25]. The losses of the material, cracks and deformation were observed on the surface of the blades. These can be attributed to the repeated loads and thermal fatigue.

On the other hand, materials with lattice structures come to mind when weight reduction and more surface area for effective cooling are needed. Periodically repeating unit cell elements in space form lattice structures. Lattice structures can also be divided into two classes as 3D and 2.5D. If a periodic pattern is created in the 2D plane and then extruded in one direction, a lattice structure called 2.5D is formed. In recent years, thanks to the important developments in additive manufacturing technologies, lattice structures have also gained importance. In this way, it is possible to produce metals with a very sensitive and high resolution micro-sized lattice structure. Previous studies have shown that the mechanical properties of metals with lattice structure produced by the additive manufacturing method can be easily controlled [26], [27], [28], [29], [30].

In this study, square, triangular and hexagonal 2.5D lattice structures were designed for the internal air-cooled gas turbine blade and analyzed by the finite element method. The main purpose of the study was to reduce the turbine blade weight, save material and increase the surface area of the internal air-cooling channels. A conventional gas turbine blade with internal air-cooling channels was used as a reference. In this way, the most suitable lattice structure in terms of mechanical properties, internal cooling channel surface area and total blade weight will be selected from the designs.

2. Material and Methods

2.1. Design Of 2.5D Lattice Structures For Internal Air-Cooled Gas Turbine Engines

The primary aim of this study is to reduce the weight and increase the surface area of internal air channel of conventional internal air-cooled gas turbine blades. For this aim, square, triangular and hexagonal shaped 2.5D lattice structures were created inside a conventional gas turbine blade having simple cylindrical air-cooling channels as seen in Figure 1.

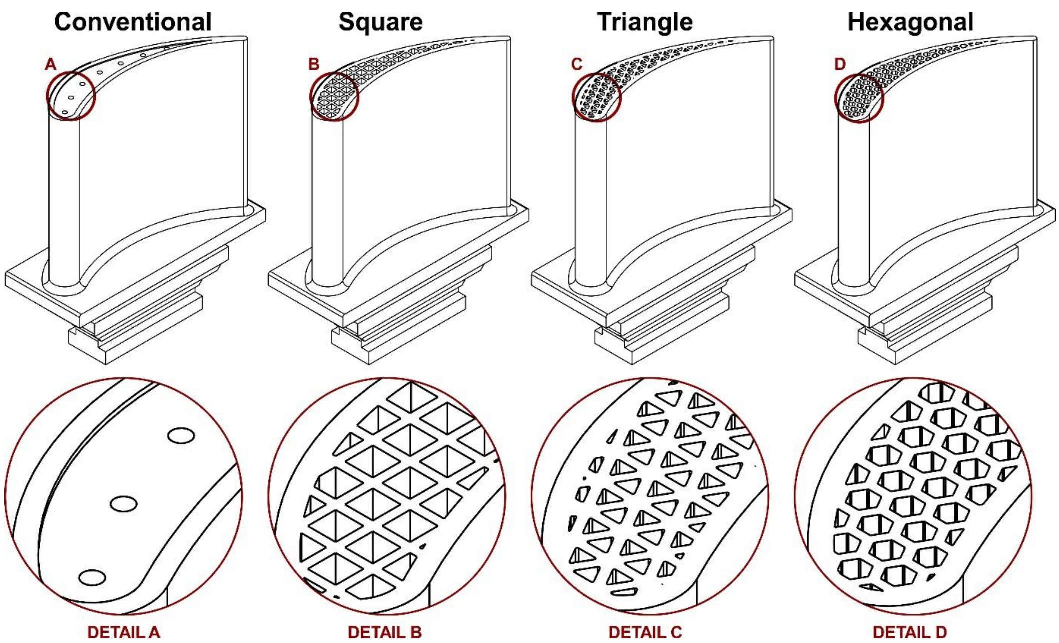

Figure 1. Conventional turbine blade having internal air cooling channels. Square, triangle and hexagonal 2.5D lattice designs for turbine blades.

3D models of all designs were made in SolidWorks software. Then, 2.5D lattice structures were created on these 3D models using Creo Parametric software. Conventional turbine blade had 8 cooling channels with 2 mm diameter. One of the ones closer to the trailing edge had a diameter of 1 mm. In the same way in all designs, a channel was created for the passage of cooling air in the turbine platform and dovetail. In all designs, 2.5D lattices with a wall thickness of 1 mm extended from the platform of the turbine blade to its tip (80 mm). In addition, the shell thickness was 2 mm. In the square design, the side length of a cell was 4 mm, and in the triangular design, both the base length and the height were 4 mm. In the hexagonal design, the diameter of the circle was 4 mm. In this way, as can be seen in detail in Figure 1, 2.5D lattice structures that will act as internal cooling in gas turbine blades were created.

2.2. Material Properties and Meshing

Inconel 718 (IN718) is the metallic material used in commercial turbine blades owing to its excellent mechanical properties at extreme temperatures, oxidation and corrosion resistance [31], [32], [33], [34]. In addition, since it is suitable for production with the additive manufacturing method, the properties of IN718 material were used in this study (Table 1).

Table 1. *Physical and mechanical properties of Inconel 718* [31], [33].

Density	8.19 g/cm^3
Melting Temperature	1430 °C
Young's Modulus	200 GPa
Poisson's Ratio	0.3
Tensile Yield Strength	1100 MPa
Tensile Ultimate Strength	1375 MPa

Turbine blades designed using SolidWorks and Creo Parametric software were imported into the Static Structural module of the finite-element analysis (FEA) software (ANSYS® Workbench). Then, meshing was performed using tetrahedron meshes, thus the turbine blades divided into infinite elements (Figure 2 (a)). As can be seen in Table 2, the number of nodes and elements of each turbine blade were different, as their geometries were different in each design. Moreover, resolution level was 5th and adaptive sizing was used. Additionally, element size was selected as default.

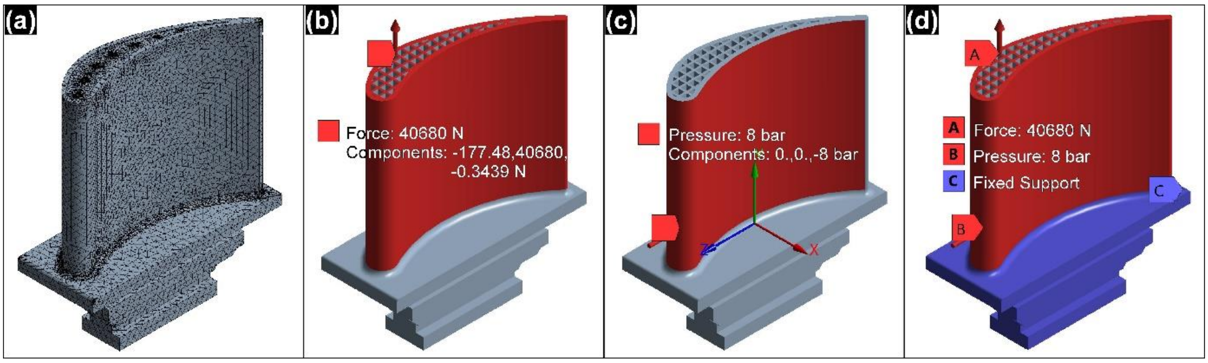

Figure 2. (a) finite element model of turbine blade, definition mechanical loads on turbine blade: (b) resultant of axial, tangential and centrifugal forces, (c) pressure acting on turbine blade and (d) application of force, pressure and fixed support on turbine blade.

Table 2. *The number of mesh nodes and elements.*

Design	Nodes	Elements	Algorithm
Conventional	345625	239563	Tetrahedrons
Square	488456	310842	
Triangle	932418	617292	
Hexagonal	537544	340888	

2.3. Boundary Conditions and Analysis

In this study, as mentioned above, static structural analysis of turbine blades was carried out using Ansys software. As seen in Figure 2(a), three axial forces act on the turbine blade. These are the centrifugal force (resultant: 40680 N) acting along the Y axis, the tangential force (177.48 N) acting along the Z axis and the axial force (0.3439 N) acting along the X axis [35], [36]. These forces were applied to all surfaces of the turbine blade (surfaces of the leading edge, pressure side, trailing edge, vacuum side and tip). Also, in this study, pressure (8 bar) was applied to the surfaces of leading edge and pressure side of the turbine blade due to the turbine pressure (Figure 2 (c)). The resultant of the forces and the pressure applied to the turbine blade can be seen in Figure 2 (d). The surface of the turbine blade platform and all surfaces of the dovetail were defined as fixed support (Figure 2 (d)). Ambient temperature was set to 1100 °C. Depending on the designs, the reductions in the total weight and the total increase in the surface area of the internal air-cooling zone of the turbine blades were calculated. In addition, the maximum equivalent (von-Mises) stress, stress safety factor and total deformation amount at the specified boundary conditions were estimated.

3. Results and Discussion

3.1. The Effect Of 2.5D Lattice Designs On Weight Reduction And Total Surface Area Of Turbine Blade

Thanks to the lattice structures, it is possible to control the mechanical properties of a material, to reduce its weight significantly and to increase the heat transfer as it provides a larger surface area [1]. As seen in Figure 3, a weight reduction between 7.56 % and 17.14 % has been achieved in the weight of the turbine blade having conventional cooling channels, thanks to 2.5D lattice designs.

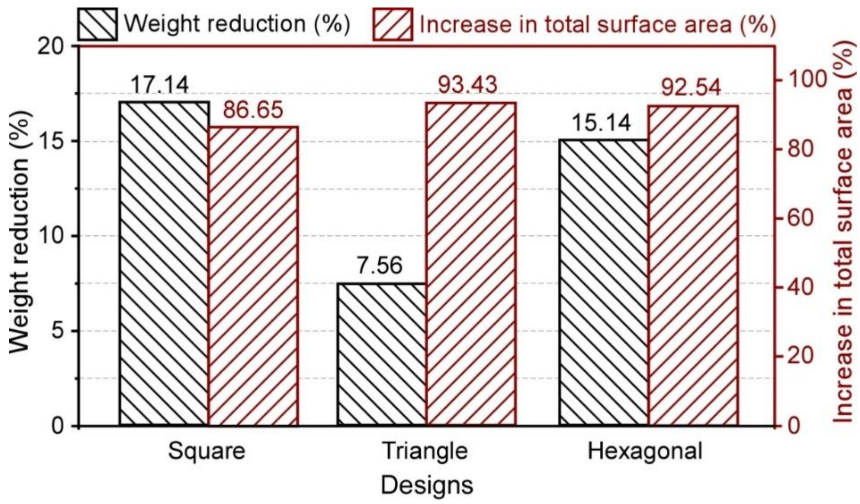

Figure 3. Rate weight reduction and increase in total surface area.

The biggest contribution to the weight reduction of turbine blade was in the square lattice design (17.14 %). In the hexagonal lattice design, there was a 15.14 % weight reduction. The least weight reduction (7.56 %) was in turbine blade with triangular lattice design. Alkebsi et al. [31] created 3D gyroid, primitive and diamond lattice structures in the turbine blade by making topology optimization and achieved a weight reduction between 33.41% and 40.32%. There were two reasons why the researchers achieved greater weight reduction than our study. The first of these was due to the weight of the turbine blade having lattice structure in proportion to the weight of the turbine blade without air cooling channel in the weight reduction calculation made by the researchers. The second was that the researchers created the same lattice structure in the dovetail of the turbine blade. However, in this study, when calculating the weight reduction, the weight of the turbine blades with lattice structure was proportioned to the weight of the conventional turbine blade with air channels, and the lattice structure was not created in the dovetail. Because there was an air channel in the dovetail of both conventional and 2.5D lattice structured turbine blades. For these reasons, the maximum weight reduction in this study was calculated as 17.14%. On the other hand, there has been an important increase in the total surface area of the air cooling zones of turbine blades having 2.5D lattice designs (Figure 3). As expected, increase of the total surface area was greatest in the triangular design (93.43 %) as it divided the area into smaller pieces. Moreover, due to the its close packed geometric shape, the increase in total surface area of the turbine blade with the hexagonal lattice design (92.54 %) was almost the same as that of the triangular lattice design. Therefore, a more effective air cooling is expected due to this significant increase in the surface area of the internal air channels of the 2.5D lattice designed turbine blades.

3.2. The Effect Of Different 2.5D Lattice Designs On Equivalent (Von-Mises) Stress

In order to avoid permanent deformation of the turbine blade, the maximum equivalent (Von-Mises) stress value under static load must be lower than the yield strength value of IN718. On the other hand, safety factor defines the structural capacity of the system depending on the applied loads and is calculated as the ratio of the yield strength of the material to the Von-Mises stress that occurs in the system as a result of the applied load [37]. Equivalent (von-Mises) stress distributions and maximum values resulting from the load and pressure applied to the conventional and 2.5D lattice designed turbine blades were given in Figure 4. The distribution of the factor of safety (FOS) and its maximum values obtained as a result of the ratio of the yield strength of IN718 to the von-Mises stress formed on the turbine blade were shown in Figure 5.

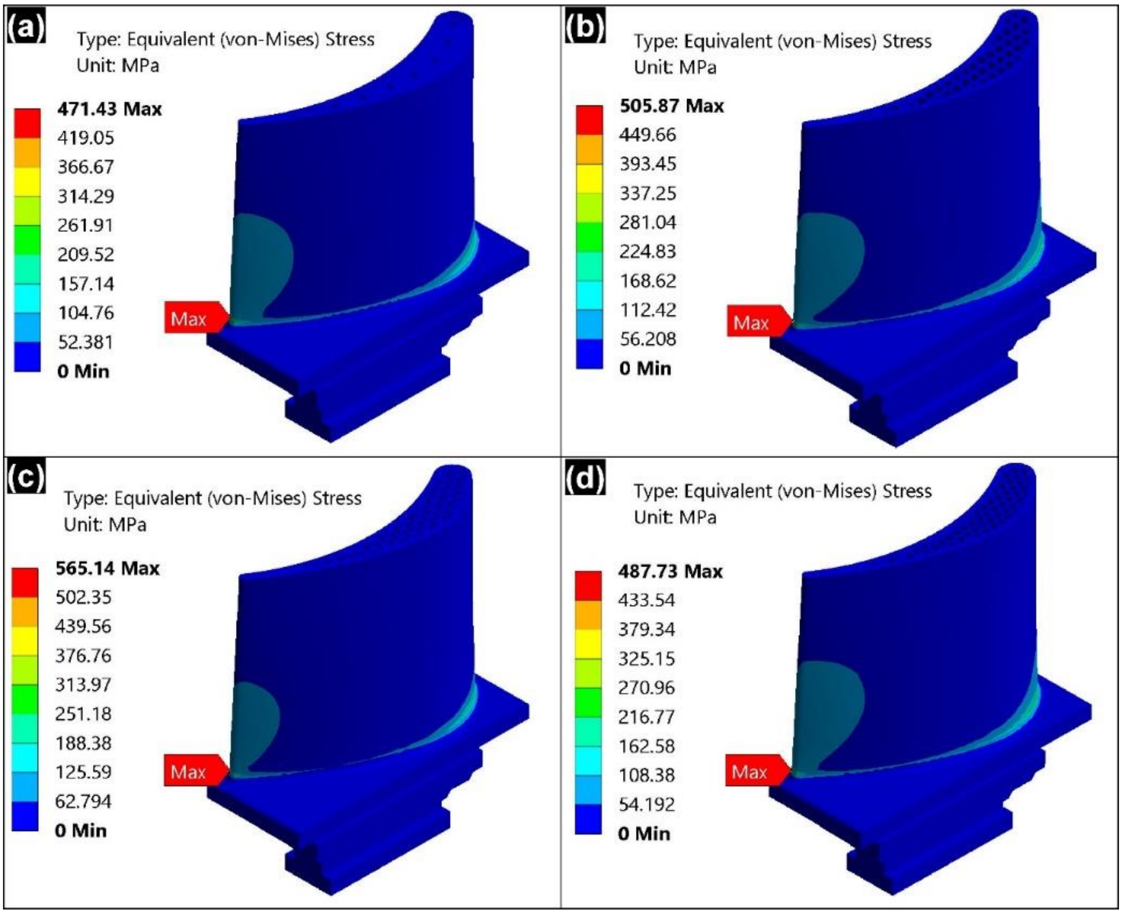

Figure 4. Equivalent stress distributions on the gas turbine blades. (a) conventional, (b) square, (c) triangle and (d) hexagonal.

As can be seen clearly in Figure 4, the maximum stress on all turbine blades occurred at the lowest point of the trailing edge (where the turbine platform intersects the trailing edge). It was normal for the maximum stresses to occur in this region. Because gas turbine blades had a geometry that narrowed the cross-sectional area towards the trailing edge. Because of this narrow cross-sectional area of the trailing edge, the stresses were concentrated here. While the maximum equivalent stress value in the conventional turbine blade was 471.43 MPa (Figure 4 (a)), it increased to 487.73 in the hexagonal design (Figure 4 (b)). These two values were very close to each other. On the other hand, the equivalent von-Mises stress values for square and triangular designs were 505.87 MPa (Figure 4 (c)) and 565.14 MPa (Figure 4 (d)), respectively. The maximum von-Mises stress values in turbine blades were lower than yield strength of IN718 (1100 MPa). Therefore, it was safe to use 2.5D designs in turbine blades, as can be seen from the FOS distributions given in Figure 5. The minimum FOS values for conventional, square, triangular, and hexagonal designs were 2.33, 2.17, 1.95, and 2.26, respectively. As expected, the minimum FOS occurred in the region of the turbine blade where the maximum stress was observed, and the FOS values of the conventional (2.33) and hexagonal (2.26) designs were very close to each other. The lowest FOS value was observed in the triangular turbine blade (1.94). This was thought to be due to the excessive stress concentration occurring at the narrow-angled edges of the triangular design. Chintala and Gudimetla [38], obtained a FOS value of around 1.77 for titanium alloy turbine blade, despite applying a lower load than the loads applied in this study, not applying pressure and not using any air cooling channel. The main reason for this was that the yield strength (830 MPa) of the titanium metal chosen by the researchers was lower than the yield strength of the IN718 alloy. Therefore, both the materials and designs used in this study were suitable for the actual working conditions of internal air-cooled gas turbine blades. According to the equivalent von-Mises and FOS values, the most suitable 2.5D lattice design for internal air-cooled gas turbine blades was hexagonal.

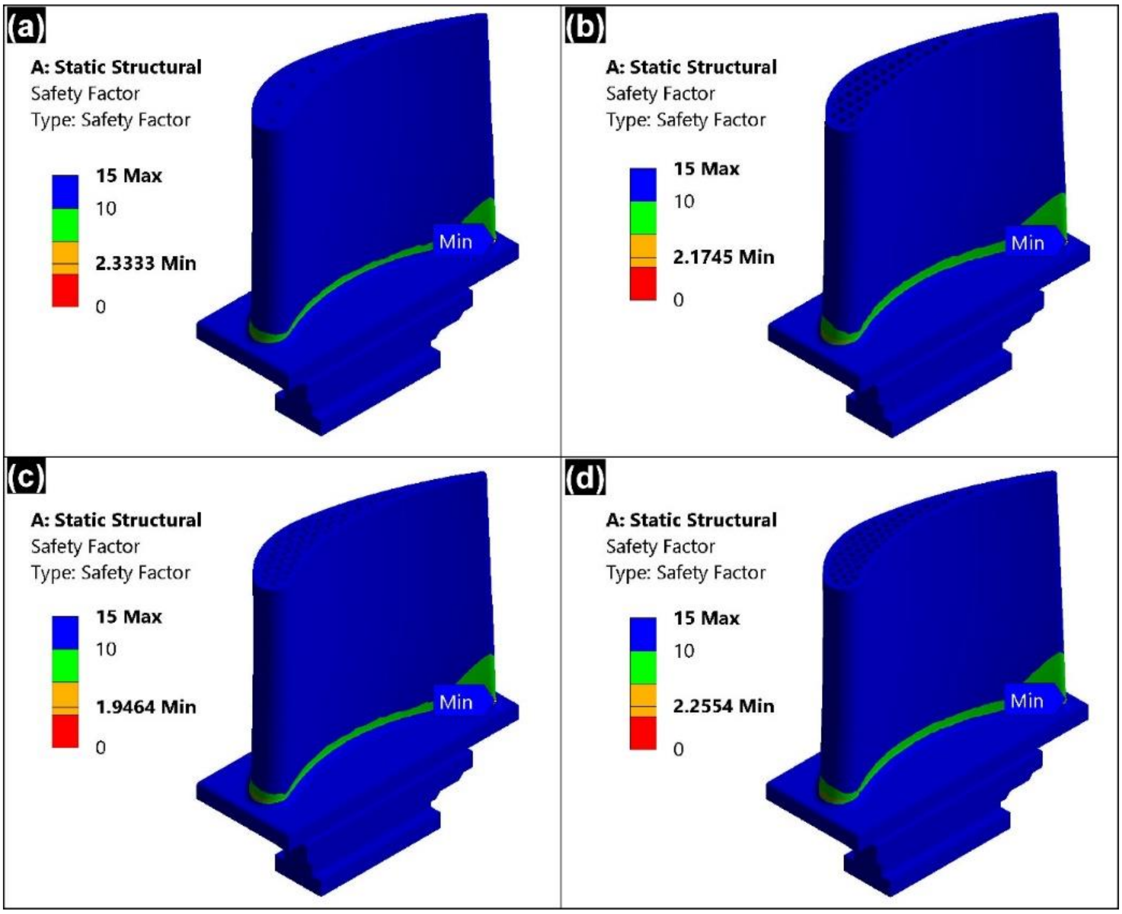

Figure 5. FOS distributions on the gas turbine blades. (a) conventional, (b) square, (c) triangle and (d) hexagonal.

3.3. The Effect Of Different 2.5D Lattice Designs On Deformation Of Turbine Blade

The maximum deformation values of turbine blades and their distributions were given in Figure 6. The maximum and minimum values were represented by the red and blue contours, respectively. Obviously, the maximum deformation in all turbine blades occurred at the top end of the trailing edge (free end of the blade). Because this region was the farthest point in the same direction from both the fixed support and the region where the maximum stresses (see Figure 4) occurred. The maximum deformation at the top end of the trailing edge of the turbine blade decreased towards the leading edge and became minimal as it approached the turbine platform. The maximum deformation amounts at this region were between 0.123 mm and 0.146 mm. Aniekan et al. [35] designed gas turbine blades from IN738 and U500 materials, which do not have air cooling channels, and analyzed them by using finite element method. According to the results they obtained, they showed that 0.162 mm and 0.121 mm total deformation occurred in turbine blades with IN738 and U500 materials, respectively. Therefore, it was concluded that the total deformation values obtained in this study were also compatible with the literature. Therefore, when the gas turbine blades with 2.5D lattice design examined in this study were evaluated in terms of maximum equivalent stress, FOS and total deformation, they were safe to use in jet engines as a potential gas turbine blade.

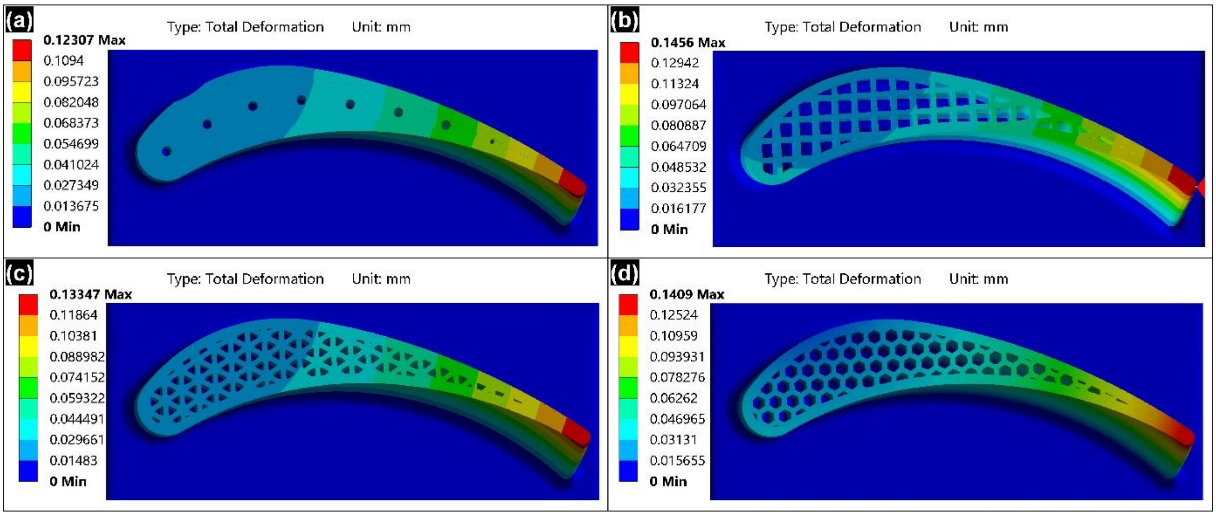

Figure 6. Total deformation distributions on the gas turbine blades. (a) conventional, (b) square, (c) triangle and (d) hexagonal.

4. Conclusions

In this study, the design and numerical analysis of 2.5D lattice structures for internal air-cooled gas turbine blades were carried out. The conventional turbine blades having air cooling channels and newly designed turbine blades having 2.5D lattice structures were analyzed by using Ansys software. Inconel 718 were used as the turbine blade material. Important results are listed in the following items.

1. Thanks to the lattice designs, a reduction between 7.56% and 17.14% had been achieved in the weight of the turbine blade having conventional air-cooling channels. The weight reduction was 15.14% in the hexagonal design.
2. An increase of 86.65% to 93.43% was achieved in the total surface area of the air cooler section of the turbine blade. The increase in surface area was 92.54% thanks to the hexagonal design.
3. The maximum equivalent von-Mises stress occurred in all turbine blades were lower than the yield strength of IN718. The maximum stress value in the hexagonal design (487.73 MPa) was close to that of the conventional turbine blade (471.43 MPa). In addition, values of FOS for stress were higher than 1.95.
4. The maximum total deformations occurring in turbine blades were between 0.123 mm and 0.146 mm, and it was concluded that these results were compatible with the literature.

When weight reduction, increase in total surface area, maximum stress, FOS and deformation results were evaluated together, it was concluded that the most suitable 2.5D lattice design for internal air-cooled gas turbine blades was hexagonal.

Acknowledgment

The author(s) would like to thank the reviewers and editorial boards of the *International Journal of Pure and Applied Sciences*.

Conflict of Interest

The author(s) declare that there is no conflict of interest regarding this article.

Research and Publication Ethics Statement

The author(s) declare that this study complies with research and publication ethics.

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