T.R.

GEBZE TECHNICAL UNIVERSITY

ENERGY TECHNOLOGIES INSTITUTE

DESIGN FOR ADDITIVE MANUFACTURING OF THE TURBOJET ENGINE PART VIA TOPOLOGY OPTIMIZATION AND STRUCTURAL ANALYSIS

FATİH EKİNCİ

A THESIS SUBMITTED FOR THE DEGREE OF

MASTER OF SCIENCE

DEPARTMENT OF APPLIED PROPULSION SYSTEM

DESIGN& ENGINEERING FOR AEROSPACE TECHNOLOGIES

GEBZE

2022

T.R.

GEBZE TECHNICAL UNIVERSITY

ENERGY TECHNOLOGIES INSTITUTE

DESIGN FOR ADDITIVE MANUFACTURING OF THE TURBOJET ENGINE PART VIA TOPOLOGY OPTIMIZATION AND STRUCTURAL ANALYSIS

FATİH EKİNCİ

A THESIS SUBMITTED FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF APPLIED PROPULSION SYSTEM DESIGN& ENGINEERING FOR AEROSPACE TECHNOLOGIES

THESIS SUPERVISOR

Ph.D. MAHMUT AKŞİT

GEBZE

2022

GEBZE TEKNİK ÜNİVERSİTESİ	**YÜKSEK LİSANS JÜRİ ONAY FORMU**

GTÜ Enerji Teknolojileri Enstitüsü Yönetim Kurulu'nun 21/03/2022 tarih ve 2022/05 sayılı kararıyla oluşturulan jüri tarafından 25/03/2022 tarihinde tez savunma sınavı yapılan Fatih Ekinci'nin tez çalışması Enerji Teknolojisi Anabilim Dalında YÜKSEK LİSANS tezi olarak kabul edilmiştir.

JÜRİ

ÜYE
(TEZ DANIŞMANI) : Dr. Öğr. Üyesi Mahmut AKŞİT

ÜYE : Prof. Dr. Mahmut Faruk AKŞİT

ÜYE : Prof. Dr. Osman Saim DİNÇ

ONAY

Gebze Teknik Üniversitesi Fen Bilimleri Enstitüsü Yönetim Kurulu'nun
…..…/…..…/..…… tarih ve ……/…….. sayılı kararı.

İMZA/MÜHÜR

SUMMARY

Improving application performance of a single part or whole engine requires creating new materials and/or improving part design and manufacturing. Additive Manufacturing (AM) is advancing rapidly in aviation industry and allows us to produce detailed complex shapes that cannot be produced by traditional methods or allows us to use materials that can not be used by traditional methods.

The goal of this study is to investigate the possibilities of using Topology Optimization as a tool to generate stronger and lighter designs for a turbojet blisk (Blade-Integrated diSK). Therefore, the Topology Optimization tool of ANSYS software was used for structural optimization of blisk part.

The blisk was optimized by modification of its original geometry, attaching it to all loading cases and running the topology optimization on ANSYS to meet the weight objective without exceeding the yield strength of the material. The optimization had only been able to allow static structural loads due to topology optimization tools in ANSYS does not support thermal loads.

The final design enables a significant weight reduction and the geometry was verified with respect to the initial loading cases. This study presents the results of topology optimization and design for AM technology on the final geometry.

Key Words: Topology Optimization (TO), Additive Manufacturing (AM), Design for AM, Aviation, Turbojet Engine, Blisk

ÖZET

Tek parça veya tüm motor performansını iyileştirebilmek, yeni malzemeler oluşturmayı ve tasarım ve üretimi iyileştirmeyi gerektirir. Katmanlı İmalat (AM), havacılık endüstrisinde hızla ilerlemekte ve geleneksel yöntemlerle üretilemeyen karmaşık şekillerin detaylarını üretmemize veya geleneksel yöntemlerle kullanılamayacak daha fazla malzeme kullanmamıza olanak sağlamaktadır.

Bu çalışmanın amacı, jet motorunda kullanılan türbin bliskleri için daha güçlü ve daha hafif tasarımlar yapabilmek için Topoloji Optimizasyonu'nu bir araç olarak kullanma olanaklarını araştırmaktır. Blisk, ANSYS ticari yazılımı Topoloji Optimizasyon aracı kullanılarak optimize edilmiştir.

Bu çalışmada konu parça, orijinal geometri ile optimize edilir, tüm yükleme koşulları eklenir ve malzemenin akma mukavemetini aşmadan ağırlık hedefini karşılamak için topoloji optimizasyonu ANSYS yazılımı üzerinde çalıştırılır. ANSYS'deki topoloji optimizasyon araçları termal yükleri desteklemediği için optimizasyon yalnızca statik yapısal yükler ile çalıştırılabilmiştir.

Nihai tasarım, önemli bir ağırlık kazanımı sağlamaktadır ve geometri, ilk yükleme durumlarına göre değerlendirilmiştir. Bu çalışma, nihai geometri üzerinde topoloji optimizasyonu ve katmanlı imalat için tasarım sonuçlarını sunmaktadır.

Anahtar Kelimeler: Topoloji Optimizasyonu, Katmanlı İmalat, Havacılık, Turbojet Motorlar, Eklemeli İmalat için Tasarım

ACKNOWLEDGEMENTS

First of all, I would like to give my warmest thanks to my supervisor Ph.D. Mahmut AKŞİT whose expertise was invaluable in formulating the research questions and methodology. His guidance and advice carried me through all the stages of writing my project.

Further, I would like to thank my leader Rifat YILMAZ and my manager Güray AKBULUT for their support and encouragement throughout the project.

I would also like to thank my collegues, Alican KILIÇASLAN and Görkem TÜREN, for their valuable support throughout my studies. You provided me with the tools that I needed to choose the right direction and successfully complete my project.

Finally, I would also like to give special thanks to my wife Gülşen EKİNCİ and my daughter Nisan Bal EKİNCİ for their continuous support and understanding when undertaking my research and writing my project. Your prayer for me was what sustained me this far.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviations and Acronyms		Explanations
W	:	Watt
Pa	:	Pascal
MPa	:	Mega Pascal
℃	:	Degree Celcius
μm	:	Mikrometer
mm	:	Milimeter
m	:	Meter
kg	:	Kilogram
K	:	Kelvin
N	:	Newton
Rad/s	:	Radian per Second
BLISK	:	Blade-Integrated Disk
AM	:	Additive Manufacturing
SIMP	:	Solid Isotropic Material With Penalisation
ESO	:	Evolutionary Structural Optimization
BESO	:	Bi-Directional Evolutionary Structural Optimization
CAD	:	Computer-Aided Design
SLM	:	Selective Laser Melting
TO	:	Topology Optimization
TEI	:	TUSAS Engine Industries Inc.
SAS	:	Secondary Air System
FEM	:	Finite Element Method
UTS	:	Ultimate Strength

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Many parts families or groups that are developed according to design principles for manufacturing and assembly processes have similar geometric features. This is because geometric features are limited by different factors such as functionality and operating by the relevant part, the operating conditions, the volume it can use in the assembly and manufacturing limitations in engineering fields such as in the aerospace and automobile industries.

Parts are designed and produced in line with the geometry limiting factors listed above also have various disadvantages. One of these disadvantages is weight. The negative effects of part weights on the final product are particularly important in the aviation industry. From this point, additive manufacturing methods bring many freedoms to product design and enable a creative design process. As a result, a wide variety of advantages can be enabled, including weight reduction, reduction of the number of parts and the number of fasteners thanks to the integrated design, providing better flow forms and achieving better mass and heat transfer performance with inner duct designs.

There are lots of studies carried out in the literature to demonstrate all the advantages listed above. These studies can generally be grouped under the title of design optimization (Section 2.1).

Currently, jet engine components working in high pressure or high temperature conditions, such as BLISKs (Blade-Integrated diSKs) are manufactured by expensive conventional manufacturing techniques, such as five-axis milling, electro chemical machining and linear friction welding [30].

Additive manufacturing has the potential to become a new key technology in aviation propulsion by opening up new attractive prospects in the manufacture of gas turbines. This is why many aviation companies have been investing in this innovative technology since the early 2000s, and are now pushing the industrialization and commercialization of these processes.

With the use of topology optimization in the additive manufacturing process, the evaluation of the structural performance of the part designed as a result of the optimization is performed easier by making trial productions, so the design cycle can be shortened effectively [16-18]. Topology optimization is a simulation-oriented

method applied to create conceptual structures. The structures designed as a result of the process are generally organic and it is not possible to complete the production with traditional manufacturing methods without simplifying the model. For this reason, the developing of additive manufacturing technologies has enabled the application of topology optimization results [19].

1.1. Motivation of Research

Conventional Manufacturing of aviation engine parts are not compatible with topologically optimized geometries due to manufacturability related restrictions on the design. As AM simply uses a layer-upon-layer manufacturing method, difficult geometries are rapidly turning into the designs that are easy to produce.

Combination of topology optimization and additive manufacturing technologies provides an effective approach for the development of light-weight and high-performance structures. Thus, Additive Manufacturing is now more compatible with topologically optimal geometries.

There are two main motivations behind this work. The first is to explore the possibilities of using topology optimization as a tool to find stronger and lighter designs for the jet engine turbine blisk, by a commercial software which is selected as ANSYS. The second is to manufacture the optimized geometry with AM technology and compare the manufacturing process to conventional manufacturing methods. Furthermore, AM post processes are going to be applied to the manufactured part to prior to tests.

1.2. Objective and Impact of Research

The objective of this research is to find possible designs with given original loads and boundary conditions to minimize the weight compared to the original design.

The topology optimization is a suitable tool to ensure minimum material requirements within the defined design space to minimize the weight of the component. Unfortunately designs found by this method might be difficult to manufacture by conventional methods due to complexity of generated geometries. If AM is used together with this optimization technology, difficult geometries are now

possible to manufacture. This research is also expected to provide guidance on developing design for manufacturing framework and design methodologies for minimizing production processes.

In this study, the topology optimization of the candidate part which is selected as turbojet engine turbine blisk has been made using ANSYS commercial software. Then, the final geometry has been produced by the selective laser melting (SLM) method, one of the additive manufacturing technologies. The material has also been altered to improve the strength of the part for it to withstand the loading conditions. Structural analysis of the new geometry obtained was completed and critical stress concentration and failure regions were determined.

1.3. Thesis Outline

This thesis is divided into five chapters: Chapter 1 focuses on introduction to Topology Optimization technology and its integration to Additive Manufacturing. This chapter also covers problem statement and motivation of this research. Before starting the methods of this thesis an introduction to design optimization, optimization types and additive manufacturing is explained in Chapter 2. Chapter 3 details the methods of this research. This includes the material comparison for original geometry and optimized geometry, the topology optimization setup and limitations. Chapter 4 presents the results of the topology optimization case described in detail in Chapter 3. Chapter 5 provides details on the manufacturing process. This includes manufacturing simulations, additive manufacturing simulation and applied post processes. Chapter 6 summarizes the contributions of the research to literature and discusses possible extensions of the research in the future.

2. LITERATURE REVIEW

2.1. Design Optimization

Ideal structure for a mechanical part can be defined as optimized structure by the means of weight and functionality. With developing technology, design and production processes of high performance and lightweight products have gained great importance. For this purpose, in the design processes, structural optimization is applied to the product to achieve the ideal structure. Among the structural optimization methods reported in the literature such as size, shape and topology optimization. Topology optimization is considered the most comprehensive method because it provides engineers and designers flexibility without considering each design step to reach final design [1].

The size optimization is accomplished by finding the optimal cross-sectional area of each element in the structure and change its dimensions in order to reach the ideal form. The shape optimization is the optimization of the external shape of the structure without changing its connections. Topology optimization, on the other hand, explains how the elements that create the structure can be connected in the best way [2]. For this reason, topology optimization is the most general definition of structural optimization. It is the optimization of the material distribution in order to achieve the ideal structure [3].

Structural optimization can be also defined as achieving the optimum design by changing the material distribution or the shape of the boundaries. The process starts from a fixed design space under certain boundary conditions and constraints. The design process is implemented in three stages as shown in Figure 2.1.

1. Optimum starting topology is created with existing methods.
2. This topology is processed with the help of computer imaging techniques and transformed into designs.
3. The shape optimization is applied to give a proper shape to the contours and holes of the structure. Then, if necessary, the final dimensions of the structure are determined by size optimization.

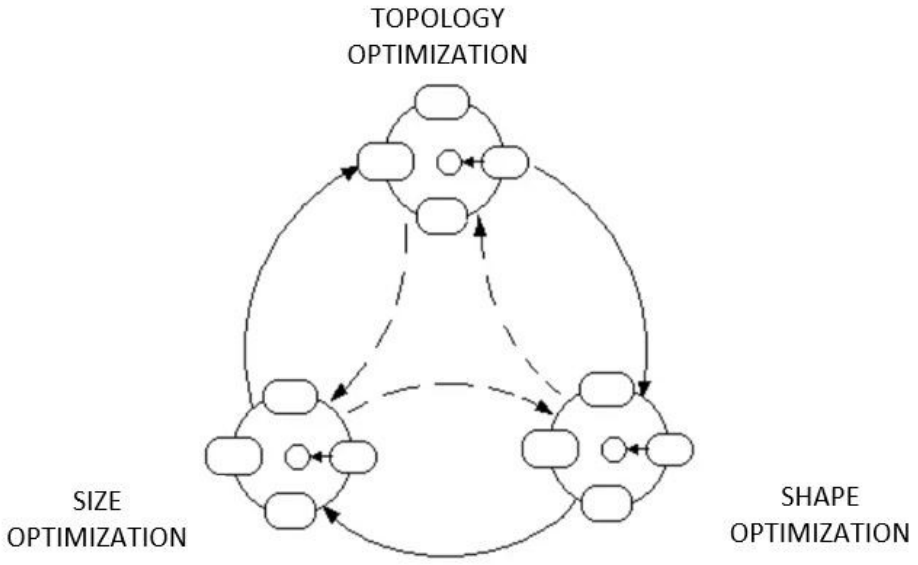


Figure 2.1: Structural design optimization cycle.

The disadvantage or limiting feature of size and shape optimization methods is that the design topology is considered as fixed [5].

Definitions of terms frequently used during this thesis are given below.

Design Space: It is the optimization volume that is allowed to change the material distribution or geometric elements in a way that does not corrupt the functionality of the product. In order to give a shorter and more accurate result for the analysis, a coarse volume is usually chosen outside the areas where the load is applied.

Design Variables: Parameters such as edge length, thickness, volume, density and orientation angle, whose size and-or coordinates are changed in order to achieve the targeted values as a result of the optimization process.

Constraints: These are the limit values determined in order to be able to manufacture the model that is going to be optimized, to not to exceed the design criteria and to get more accurate results. Optimization process is carried out by observing the limitations such as maximum and minimum element sizes to be protected from modification,

maximum local stresses, repeating geometries, symmetry axes and manufacturing direction.

Objective Functions: These are functions that are not restricted numerically, whose maximum or minimum values are tried to be approached during optimization. Minimization of model volume, stresses, and displacement values can be given as examples of objective functions. During the optimization process, the best combination of design parameters is searched and the iteration process continues until the boundary conditions are met to achieve the objective function.

After the boundary conditions of the geometry with a design volume are determined, its structural strength is examined by dividing it into finite elements. With the help of mathematical optimization methods, the best geometry is obtained by solving the model for which limitations and objective functions are determined. The geometry for which material distribution has been changed by dividing it into finite elements as a result of optimization is not in the appropriate file format. The improper geometries are arranged with the improvement software and the design is made manufacturable. An optimization flow chart expressed over the bracket part of General Electric is shown in Figure 2.2 [4].

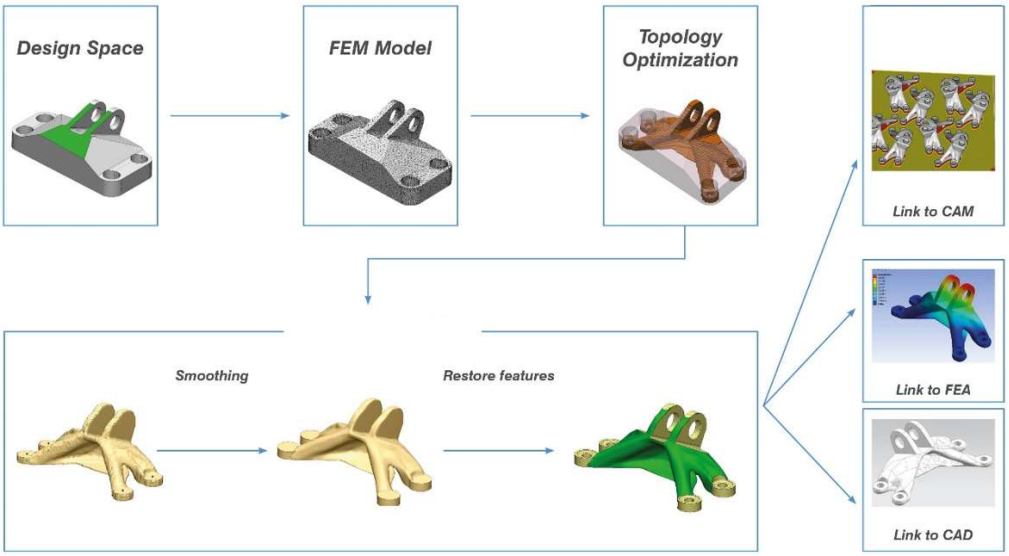


Figure 2.2: Structural design optimization flow chart.

In general, the structural optimization problem can be examined under four titles: size, shape, topology and topography optimization. The oldest known structural optimization method in the literature is size optimization (also called parametric optimization). Next comes shape optimization, and the most recent is topology optimization [6].

2.1.1. Optimization Types

2.1.1.1. Size Optimization

It is the simplest optimization approach applied to improve the structural performance of products whose conceptual design has been completed. In size optimization, the optimum combination of variables such as cross-sectional area, moment of inertia, length, sheet thickness in beams is investigated and the model is optimized until the target performance is reached. With size optimization, processes that change the material distribution, such as defining new holes in the structure, cannot be performed. Concept design is used to obtain the best design from the completed geometry [6]. In Figure 2.3, the wall thickness of the I profile beam structure are defined as variable. The stiffness of the beam can be increased by finding the best combination of these parameters together with size optimization [7].

Similarly, the whole of the vehicle body structural parts with optimized wall thickness value is shown in Figure 2.4.

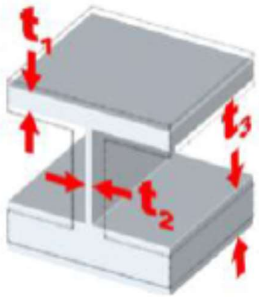


Figure 2.3: I section profile size optimization parameters.

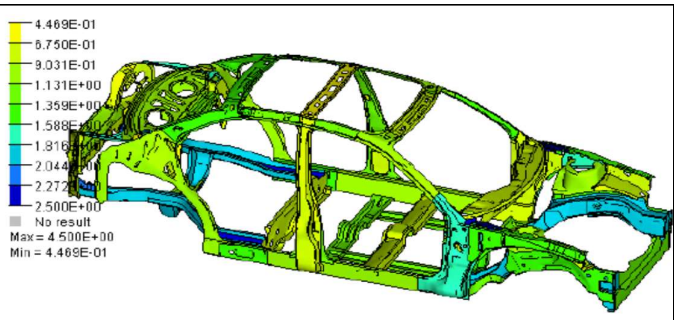


Figure 2.4: Sheet thickness optimized vehicle body.

Since size optimization is related to the thickness and cross-section dimensions of a structure, it is also used in the design of composite structures made of layers of different thicknesses. Since there are so many variables in the design of composite structures, the ideal thickness of each layer is created by using size optimization and the design development time is shortened [8].

2.1.1.2. Shape Optimization

It is the optimization of the outer boundaries and hole geometries of a conceptually designed structure according to the places where the loading and stresses are concentrated. Unlike size optimization, complex edge geometries, holes and surfaces can also be optimized. However, as in size optimization, it is based on predetermined geometries. A beam structure with shape optimization applied to the existing holes on the geometry is shown in Figure 2.5 below [6].

Similarly, in Figure 2.6, a sample part geometry is shown where local stress values have been decreased by applying shape optimization to the holes on the part [5].

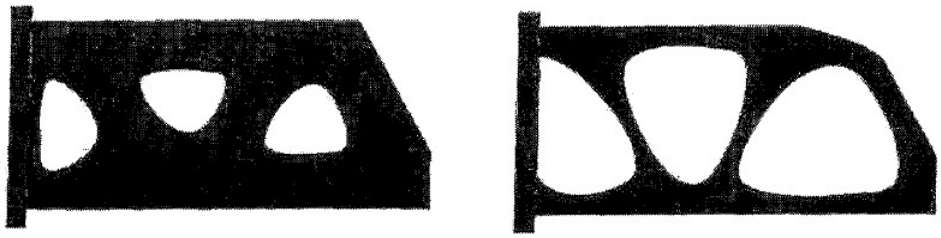


Figure 2.5: Shape optimization applied beam structure.

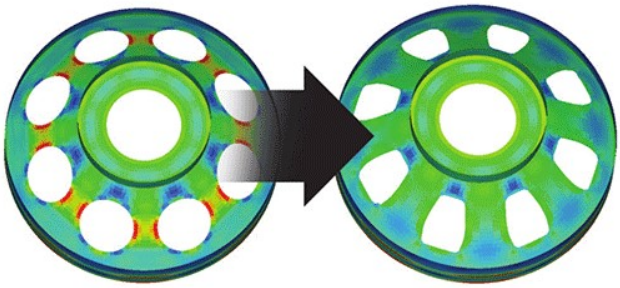


Figure 2.6: Hole geometries are optimized to decrease the local stresses.

2.1.1.3. Topography Optimization

Since sheet metal parts are used extensively in many sectors such as household appliances, automotive, aviation and space industries, it is thought that making them lighter and more rigid without going beyond the design criteria will provide a great economic benefit. Therefore, it is aimed to increase the rigidity and natural frequencies of the structure by creating indentations – called beads or swages – in different positions and shapes on the sheet models at the conceptual design level with topography optimization.

The first geometry enters an iteration process by changing the parameters such as the positions, height, width, elevation angle, recess direction of the beads (swages) to be created, and the optimum sheet geometry is obtained under specified boundary conditions (See Figure 2.7) [9].

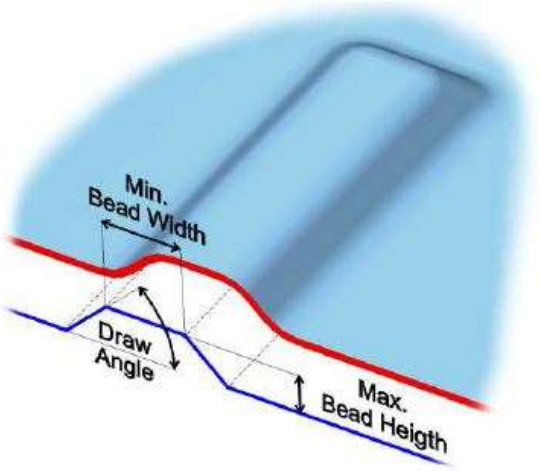


Figure 2.7: Bead/Swage parameters.

The vibration amplitudes of the resonant parts gradually increase. This situation shortens the life of the product and causes noise. For example, it is desired that the sheet metal parts used in automobiles (fuel tank, hood, etc.) do not resonate in the engine speed range. Such problems can be solved by topography optimization without adding weight.

Topology optimization geometry on the fuel tank is shown in Figure 2.8 and the performance gain obtained as a result of topography optimization is shown with a graph in Figure 2.9 below [9].

Figure 2.8: Optimized fuel tank geometry.

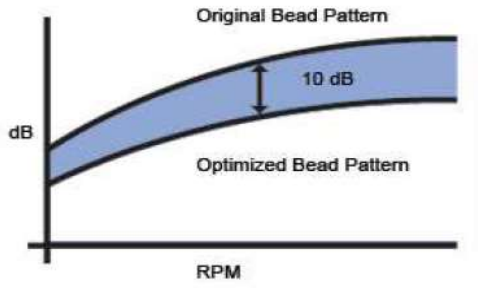


Figure 2.9: Sound emission-RPM graph

(-10dB sound emission).

In a study, a thin-walled tank filled with liquid was modelled, and boundary conditions and loading conditions were determined. Since the model that will emerge as a result of the optimization is desired to be symmetrical in three axes, the necessary limitations have been specified before the optimization as shown in Figure 2.10 & Figure 2.11 [9].

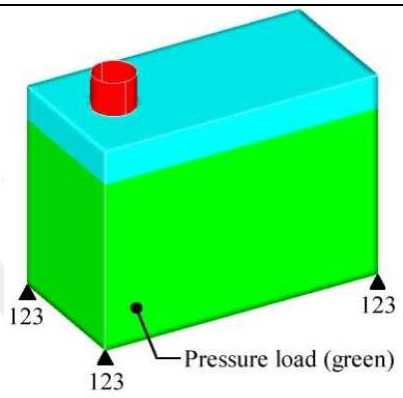


Figure 2.10: Thin walled tank filled with fluid & boundary conditions.

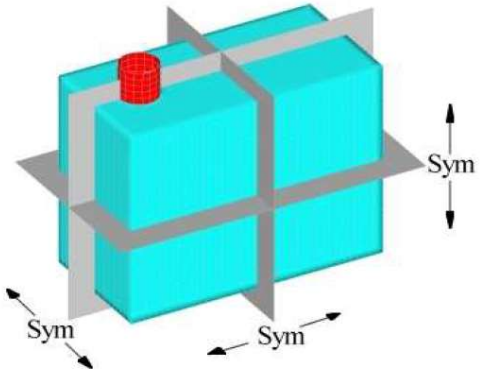


Figure 2.11: Symmetry axis.

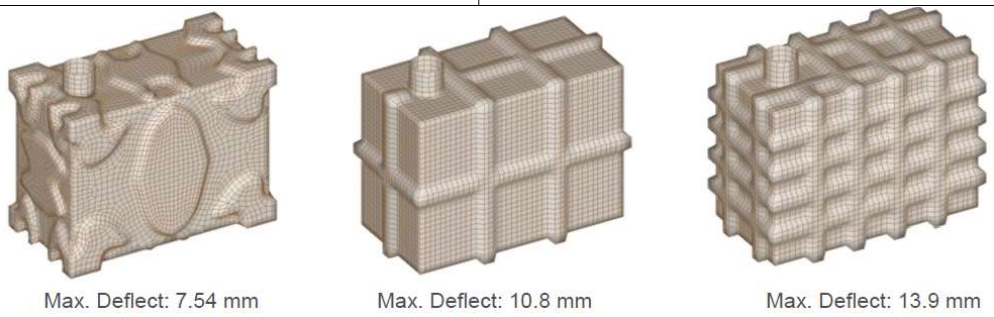


Figure 2.12: Liquid tank maximum displacement comparison.

The topography optimized geometries are shown in Figure 2.12 and the minimum deflection achieved model is on the left side. As a result, the rigidity of the part is related to its shape and position rather than the number of indentations or ribs [9].

2.1.1.4. Topology Optimization

Topology optimization is the modification of material distribution and boundary lines and shapes under certain boundary conditions and manufacturing constraints so that a given design model can be optimized in line with the objective functions.

In the conceptual design process, it is possible to make major changes on the material distribution, as the model has not yet been detailed. Therefore, topology optimization is used at the concept design level to meet design, performance and manufacturability criteria. By making the optimization in this process, the time lost with iterative design changes is prevented and design development costs are reduced (See Figure 2.13).

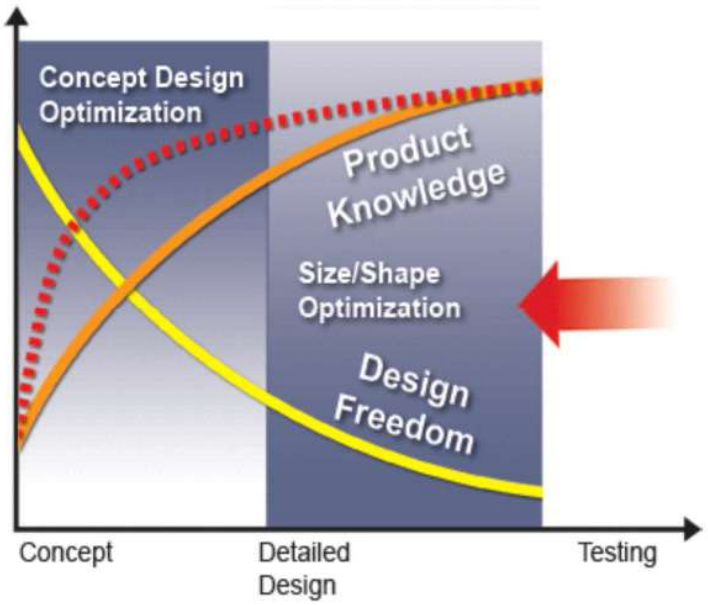


Figure 2.13: Design Freedom & Optimization relation.

There are different mathematical optimization methods (See Section 2.1.2) used to determine new design variables in topology optimization. The quality and duration of the solutions provided by these methods may vary according to the design volume, design variables, objective function, and limitations that are determined before optimization. Therefore, choosing the appropriate methods for the optimization problem is very critical to improve the solution quality.

2.1.2. Optimization Methods

2.1.2.1. Homogenization Method

It is a mathematical approach developed by Bendsoe and Kikuchi in 1998 to obtain the optimum topologies of the structures [10]. In this method, the design volume is divided into a finite number of microstructures with homogeneous material properties. Initially, each element in the design volume contains the gap (See Figure 2.15) with same dimension and orientation. The dimensions and orientation angles of this gap inside each element aped as rectangular are defined as the design variable. The variables are optimized to increase the rigidity of the volumetric or mass constrained design geometry [6].

Figure 2.14 and Figure 2.15 show the examples of 2D and 3D microstructures, respectively.

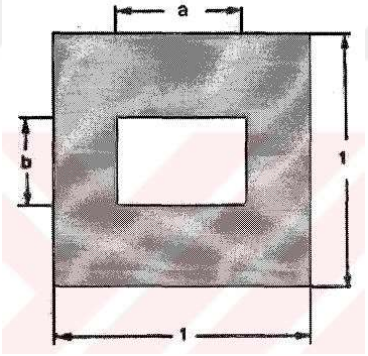


Figure 2.14: Variables defined 2D micro structure sample.

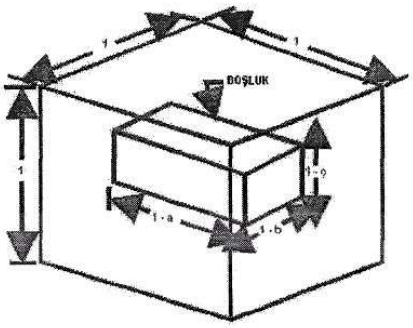


Figure 2.15: Variables defined 3D micro structure sample.

The effective material property is calculated according to the size of the gap in the microstructure. Equivalent anisotropic material property is used to calculate the stiffness matrix by rotating it in the direction of the inside gap. In order to make these calculations, the dimensions and orientation angles of the hole geometry within each microstructure must be defined. In order to make definitions, 6 variables are required for 3 dimensional elements and 3 variables are required for 2 dimensional elements. The great number of design variables poses a disadvantage for the homogenization method, as it extends the solution time [6].

After the optimization process, the density of the microstructures take values between 0 and 1. However, since there can be no medium density structures, the formation of medium density elements is prevented due to application of special functions. Closed solid shapes and lattice structures may occur after optimization. This method also inspired the development of another structural optimization method, Solid Isotropic Material with Penalisation (SIMP) [6].

2.1.2.2. SIMP (Solid Isotropic Material With Penalisation) Method

It is the optimization method in which the material density is accepted as the design variable. It is also known as the density method. It can be used with isotropic and an-isotropic materials, including composite materials. The effective elasticity of structures is equal to the product of a scalar function of the material density and the original elasticity value (Young's modulus) as shown in equation (2.1). Therefore, the stiffness of the design geometry changes in direct proportion to the original material properties [6].

$$\frac{E_i}{E_0} = \rho^n \tag{2.1}$$

$$Ei = \text{Effective Elasticity Modulus} \quad E_0 = \text{Oriiginal Elasticity Modulus}$$

$$\rho = \text{Material Density} \quad n = \text{Constant}$$

In the study conducted by Wang, Y. et al. in 2013, optimization of a beam structure using the SIMP method was included. The design volume and FE nodes defined for the relevant beam structure in this study are given in Figure 2.16. In Figure 2.17, the geometries obtained step by step with the SIMP method are shown [11].

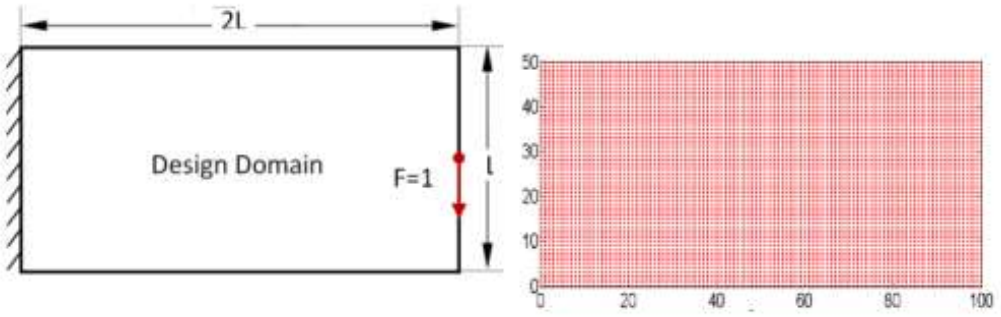


Figure 2.16: Design volume and FE nodes in design volume of the beam structure.

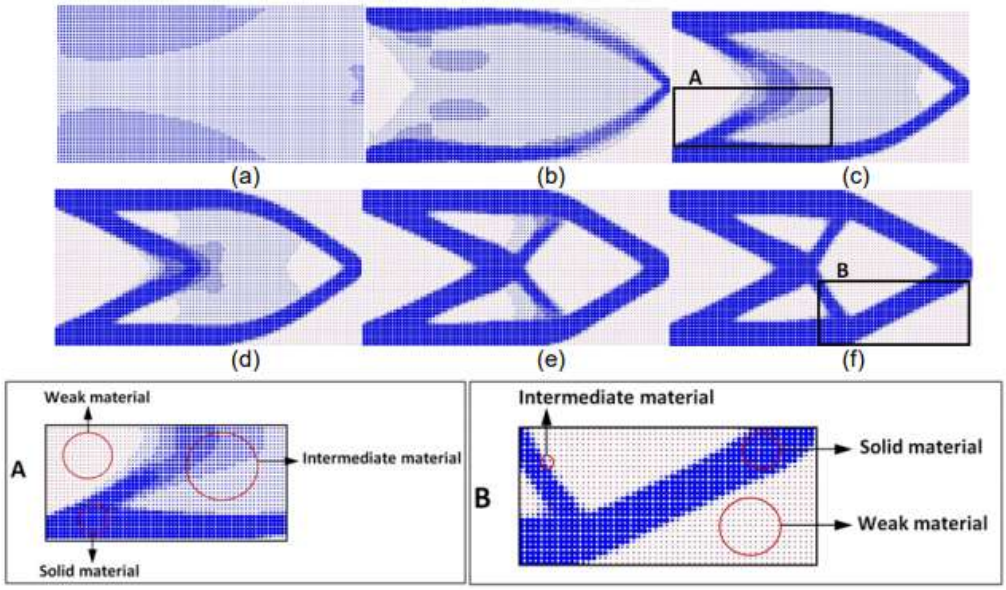


Figure 2.17: Geometries obtained during optimization steps.

2.1.2.3. ESO (Evolutionary Structural Optimization) Method

In this approach, which was put into practice by Xieve and Steven in 1993, the optimization process is carried out by gradually removing unnecessary materials from the finite element model of the structure. It has gained popularity due to the simplicity of the approach, and as a result of extensive researches on it, the basis for the development of the BESO (Bi-directional Evolutionary Structural Optimization) method is provided. Solving stiffness and displacement problems, dynamic analysis of structures, buckling analysis or solving optimization problems with more than one

criterion have become applicable with the development of the ESO method over time [10].

When the displacement or stress values of the elements on the design geometry exceed their maximum allowed values, the structure breaks down. In this approach, elements below the critical stress or displacement value are considered unnecessary. Therefore, it is accepted that every element on the geometry in the ideal case has equal stress values [10].

The ESO method can be applied depending on the stress or strain energy. In the stress-dependent ESO approach, the material removal criterion is determined according to the Von-Mises stresses, which give the average stress value on the finite elements of the structure. For each element, the Von-Mises stress is calculated with the equation (2.2) given below [10].

$$\sigma_e^v = \sqrt{\sigma_{11}^2 + \sigma_{22}^2 - \sigma_{11} + \sigma_{22} + 3\sigma_{12}^2} \tag{2.2}$$

The stress value in each element is obtained by finite element analysis and compared with the maximum stress value (σ_{max}^v) that the structure can withstand. A new material distribution is created by deleting all the elements that meet the following condition (2.3).

$$\frac{\sigma_e^v}{\sigma_{max}^v} < \quad RR^t \tag{2.3}$$

RR^t denotes the elimination rate at the iteration t. After each iteration, the elimination rate (RR^t) is added up with the evolution rate determined before optimization and the elimination rate (RR^{t+1}) to be used in the new analysis is obtained as shown in equation (2.4).

$$RR^{t+1} = RR^t + ER \tag{2.4}$$

When the design geometry provides the desired stress level, for example, when there is no element subjected to stress values less than 20% of the maximum stress value (σ_{max}^v) on the structure, the iteration process ends.

In the deformation energy dependent ESO approach, the elements to be deleted are determined by considering the effects of the elements on the objective function as shown in the equation (2.5) below.

$$a_i = u_i^T K_i u_i \tag{2.5}$$

The stiffness matrix K_i and the strain vector u_i of the element on the iteration i are obtained by finite element analysis. After this point, the iteration process continues as in the stress-dependent ESO approach.

The biggest advantage of the ESO method is that it has a simple theory and can be easily applied in topology optimization. With the detection and removal of the elements that behave inefficiently under loading conditions, the model geometry that is divided into finite elements becomes smaller, which shortens the analysis time. Since the formation of intermediate density elements is not allowed, the resulting geometries occur with a clear region without any gray area, which makes the interpretation of the optimization results easier. However, in this approach, situations arise where some elements are undesirably deleted and these are irreversible. The precaution that can be taken to reduce this error may be lowering the evolution rate (ER) [10].

2.1.2.4. BESO (Bi-Directional Evolutionary Structural Optimization) Method

In this solution method, it is aimed that elements can be deleted as well as added again in order to avoid the problems that may come up with the ESO approach. Because in the ESO approach, it is not known what kind of effects of the deleted elements have on the objective function in the later stages of optimization. In this method, the design geometry includes both empty and filled elements. During iteration, elements are included and removed from the solution and their effects on the objective function are examined. Figure 2.18 shows some of the iteration stages of a shape optimized geometry with BESO and additionally a linear approach is used for its edges [12].

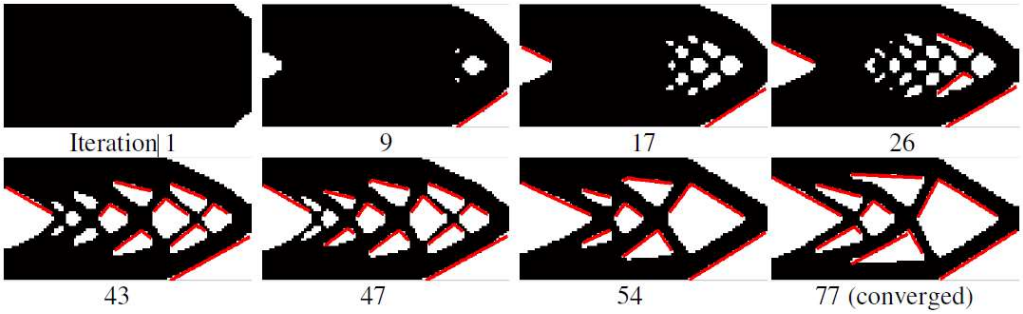


Figure 2.18: BESO optimization.

2.2. Additive Manufacturing

As defined in the VDI 3404 Additive Manufacturing Terminology Standard, the manufacturing process in which the work piece - designed part - is constructed with recurring layers or units is called additive manufacturing. Designed parts are produced from 3D solid models created with computer-aided design (CAD) software. In this process, adding the material layer by layer and thus reducing the amount of wasted material makes this technology more efficient compared to other manufacturing methods. This technology has been developed to produce prototypes of physical models using polymers as quickly as possible, greatly reducing errors and cycle times in new product development, speeding up products launch [13]. Nowadays, additive manufacturing method is developing as a repair technique for 3D printing of special parts or for functional high-value parts. In the production process with 3D printer technologies, the 3D model of the design to be printed is divided into slices by transferring it to an expert software. A 3D model of the design can be created without any tools. The process steps followed in additive manufacturing technologies are basically shown in Figure 2.19 [14].

Figure 2.19: Additive Manufacturing Technologies process steps.

A wide variety of additive manufacturing methods have been developed that differ from each other according to the materials they use and their working principles. These are; Stereo Lithography (SLA), Fused Deposition Modeling (FDM), Ink Jet Printing (IJP), 3D Printing (3DP), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), 3D Laser Cladding Process (LCP), Laminated Object Manufacturing (LOM) and Laser Chemical Vapor Deposition (LCVD) methods [15]. Compared to other conventional manufacturing methods additive manufacturing technology has been demonstrated to reduce the costs by up to 70% and the marketing time of the finished parts by up to 90%, depending on the characteristics of the part to be manufactured [16]. The fact that the prepared design file can be easily transferred, it is easy to use and install, the necessary arrangements and changes can be made quickly, the time and cost of product creation can be calculated in advance increases the preference of three-dimensional printer technologies [17]. In addition, the easy manufacturability of individual designs and structures with complex geometries and the variety of materials that can be used have increased the use and the importance of this technology by designers and engineers. The production of functional parts in the 3D printing process has enabled the development of customized and geometrically complex products as well.

One of the most important advantage of additive manufacturing methods is that it allows the production of complex geometries that are not possible with conventional manufacturing methods. In this way, for parts to be produced by additive manufacturing method, biomimetic designs consisting of complex geometries are becoming preferable instead of the traditional design approach that uses simple 2D and 3D geometric shapes. As a result, lighter designs with the same function can be

realized. The necessary step in order to benefit from all these advantages in the most way is to do the necessary optimization in part designs with an approach that is free from the constraints of conventional manufacturing methods.

However, it should not be thought that there are no restrictions in additive manufacturing methods. Especially many geometric elements such as the angle of inclination on the outer surfaces, the surface roughness value, the free hanging surface length, the minimum hole diameter and the wall thickness should be taken into account in part designs if additive manufacturing methods are preferred.

In order to achieve the required standards and specifications, or to improve surface quality, geometric dimensional accuracy and mechanical properties, metallic components usually produced by Additive Manufacturing techniques need to be proceed to post processing and surface treatment. Usual surface roughness values for metal parts produced by the SLM technology vary between 15 µm and 40 µm (Rz in XY direction). Most physical properties can be enhanced by adding well-structured post processes at the end of the additive manufacturing process chain. Machining, surface treatments and heat treatments can be used as post processes to obtain the dimensional tolerances expected from the metallic parts produced by additive manufacturing and to achieve the desired surface quality [18].

At the stage of removing the part from the additive manufacturing platform, after the separation of the support structures from the manufactured part, the part can be cleaned with chemical fluid abrasives in addition to milling, drilling and polishing operations [18].

2.2.1. Metal Additive Manufacturing Technique

Selective Laser Melting (SLM) technology was developed by the German company EOS, which was founded in 1989. It is a laser-based Powder Bed Fusion process and locally sinters metal powder using a locally focused laser beam. Extremely complex parts can be produced fully automatically without tools in a few hours, directly from 3D CAD data at approximately 100% density. This technology is a process used to produce parts which have excellent mechanical properties with high accuracy and surface quality.

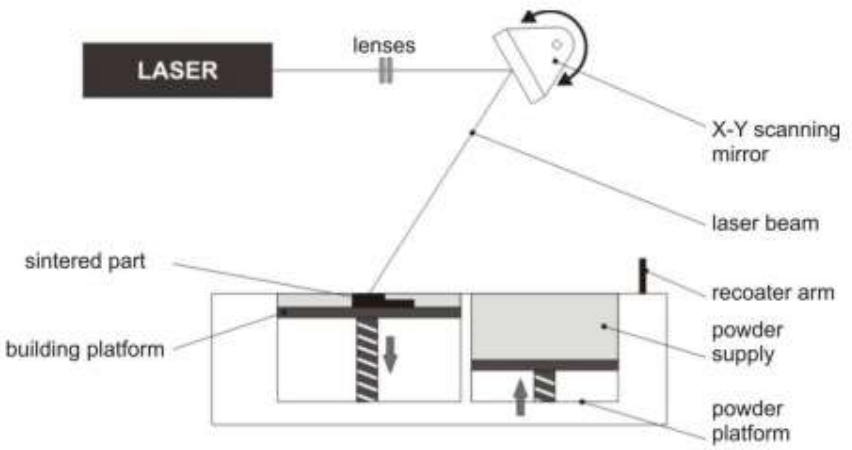


Figure 2.20: SLM Technology Process Scheme.

A schematic representation of the process can be seen on Figure 2.20. The piston in the powder section always feeds powder by moving upwards, and then a recoater arm spreads another layer of powder on the existing layer. Then the laser sinters the parts that represent the part in the 2D and XY plane parallel slices obtained from the 3D CAD model of the part to that is going to be produced. After a layer is built, the piston lowers the production platform and a new layer is created again by spreading the powder with the recoater arm. The process is repeated until the piece is finished [19].

EOS M 290 is the machine shown in Figure 2.21 that is used to manufacture the turbine blisk part by additive method of Powder Bed Fusion Technology, or most commonly, Selective Laser Melting. The construction volume is maximum 250 x 250 x 325 milimeters including the building plate and laser type is Yb-fiber laser with the power 400W [20].

Figure 2.21: EOS M 290 SLM.

3. METHODS

The basic method of TO considers an initial geometry with a larger design space. Material is then removed (or added) after every iteration until the target of the analysis is met and then the final material layout is achieved. One method of doing this (optimizing) with TO is to define the part with a larger volume than the original geometry. After applying the loads, set of constraints and the objectives the TO software can give an optimal and more valuable design.

As another method, it is also possible to do a topology optimization on the original geometry without giving it any additional volume or mass. To perform this method as in this thesis we use the ANSYS software.

For both methods the output geometry as the optimization result can be performed by the settings of the software and constraints which are determined on the beginning of the optimization process as an input.

3.1. Material

Nickel-based superalloys are suitable for high temperature applications where they offer resistance to creep, fatigue, and oxidation and avoid from corrosion. So, Inconel 738LC is being currently used for the conventional manufacturing of the blisk that we are studying to manufacture with AM.

In nickel based superalloys it is already known that, Chromium is critical to improve corrosion resistance, this is the reason why Inconel 939 has an elevated temperature strength with both hot corrosion resistance. Also the higher weight content of Cobalt increases the hot hardness and its wear resistance of the alloy 939[21]

For the above mentioned reasons Inconel 939 is the material choice for the additive manufacturing of the optimized and redesigned blisk geometry. Chemical composition comparison between Inconel 939 and Inconel 738LC can be seen on Figure 3.1 below for detail [22,23].

Inconel	Ni	Co	Cr	Mo	W	Ti	Al	Nb	Ta	Zr	C	B
738LC	Balance	8.5	16	1.75	2.6	3.4	3.4	0.9	1.75	0.05	0.11	0.01
939	Balance	19	22.5	0.2	2	3.7	1.9	1	1.4	0.1	0.15	0.01

Figure 3.1: Chemical composition Inconel 738LC vs. Inconel 939 (Nominal wt.%).

The material data from the literature search entered manually and used in ANSYS Workbench AM Library for Inconel 939. You can see the data in Table 3.1 below [22]. Because ANSYS 2020 R2 Topology optimization tool only works with linear material properties, this data is an approximation of non-linear material data which is calculated in ANSYS Workbench AM Library.

The literature physical and mechanical properties data for alloy Inconel 738LC is also given Table 3.2 below for detail comparison [23].

Table 3.1: Material data for Inconel 939.

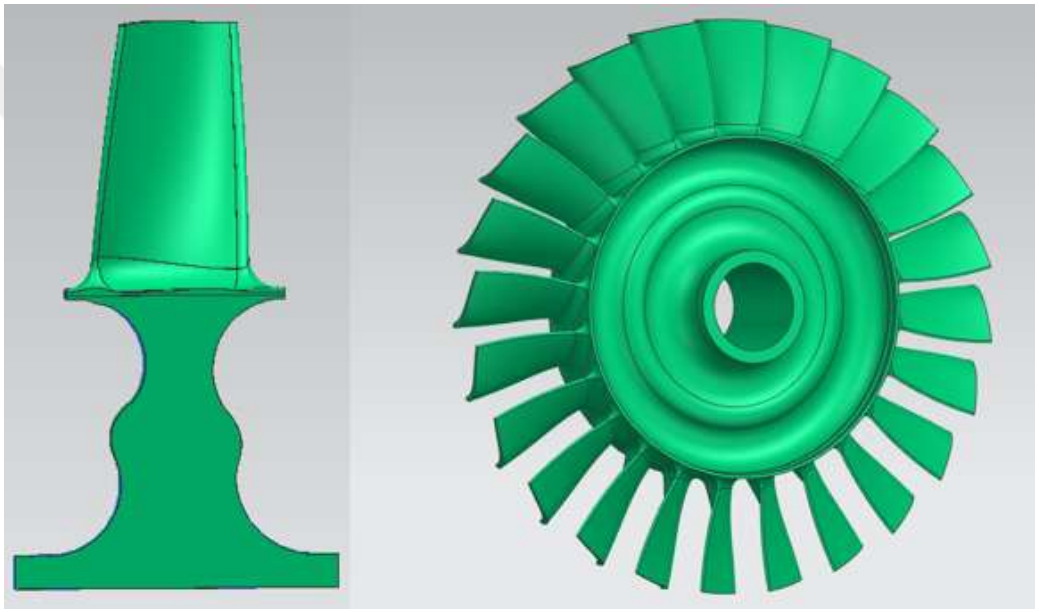
Property	**Value**	**Unit**
Density	8150	kgm^{-3}
Coefficient of Thermal Expansion	1.17E-05	K^{-1}
Young's Modulus	2.30E+11	Pa
Poisson's Ratio	0.31	
Isotropic Thermal Conductivity	12	$Wm^{-1}K^{-1}$
Maximum Service Temperature	850	°C
Ultimate Tensile Stress @25°C	1500	Mpa
%0.2 Yield Stress @25°C	1100	Mpa

Table 3.2: Material data for alloy Inconel 738LC.

Property	**Value**	**Unit**
Density	8110	kgm^{-3}
Coefficient of Thermal Expansion	1.10E-05	K^{-1}
Young's Modulus	2.00E+11	Pa
Poisson's Ratio	0.27	
Isotropic Thermal Conductivity	9.06	$Wm^{-1}K^{-1}$
Maximum Service Temperature	950	°C
Ultimate Tensile Stress @25°C	1100	Mpa
%0.2 Yield Stress @25°C	950	Mpa

3.2. Geometry

Exact dimensions are considered as confidential information of TEI and can not be provided here. The evaluated blisk is about 90 milimeters in diameter and weights nearly 200 grams, designed to be manufactured by machining with Inconel 738LC as the material. Manipulated blisk geometries are shown in Figure 3.2**: Blisk geometries as section view and 3D** below.



(a) Section view / sector geometry. (b) Blisk geometry in 3D.

Figure 3.2: Blisk geometries as section view and 3D.

Cyclic symmetry modelling is a useful tool used to simulate designs that have a repeating geometry in 360 degrees around an axis of symmetry. Common examples of cyclically symmetric geometries are turbine blade disks, gears and fans. Cyclic symmetry analysis can reduce model size and analysis time. Main idea is to analyze the single symmetric model for constructing the full model analysis result.

In this study cyclic symmetry condition was defined and 15 degree slice geometry was used in both TO and design validation analysis as can be seen in Figure 3.3. Pre-processing could be done in any CAD software including Siemens NX or ANSYS SpaceClaim. In this thesis, Siemens NX 12 was used.

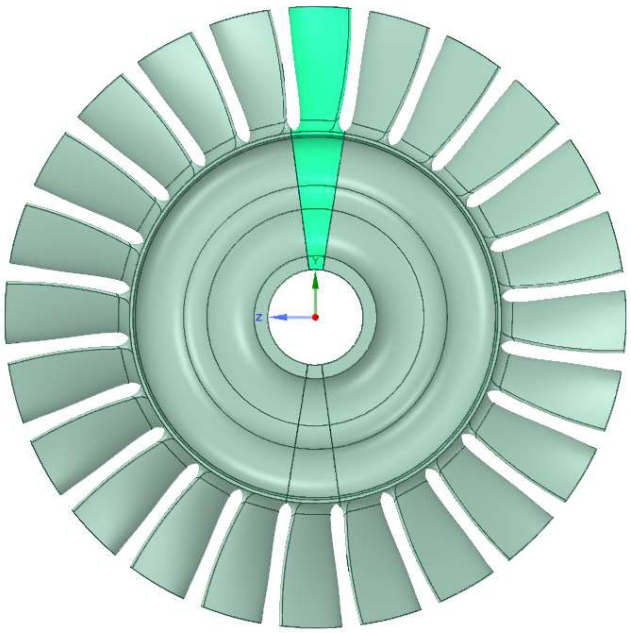


Figure 3.3: Repeating geometry for cyclic symmetry.

3.3. Analysis Setup

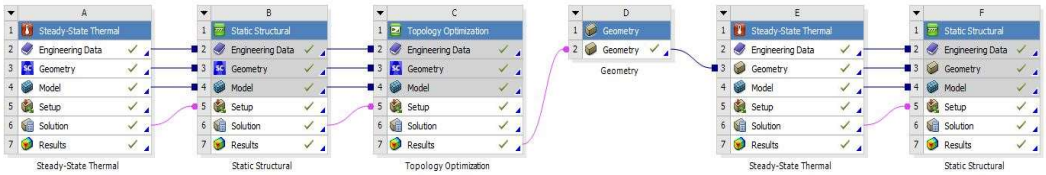
In this thesis, the geometry was topologically optimized with only static structural loads such as rotational velocity, aerodynamic and SAS pressure due to the limitations on thermal loads with ANSYS TO tool. The thermal loads has been used only for design validation of the optimized geometry.

To perform the topology optimization simulations in ANSYS the simulation model had to be properly created. The CAD model was meshed, boundary condition was set, loads were applied and TO parameters and constraints were implemented.

Figure 3. shows us the TO typical setup in ANSYS Workbench including pre-processing. As seen in Figure 3., three analysis steps – steady state thermal, static structural and topology optimization – were linked to each other. When the material was selected as Inconel 738LC from the material library, all material properties are imported from the engineering data. The next was to import the geometry to the first analysis step of the workbench which is static structural for our geometry and steady state thermal for design validation after TO. Later, in second analysis step, ANSYS Mechanical meshing was done and the model was subjected to the loadings as specified according to the actual working conditions. Finally, as the third step topology

optimization analysis could get started after the clarification of TO parameters and constraints.

Figure 3.4: Topology Optimization typical setup in ANSYS Workbench.



The last two analysis steps in Figure 3. were linked together and validate the optimized geometry with given structural and thermal loads which the final geometry should work with. So we hereby apply design validation.

3.3.1. Meshing

The element size must be smaller than the smallest dimension of each component in the projected geometry to carry out an accurate analysis and to procure well-defined sensitivities during analysis. For the structures that has small volume fraction, this cause larger number of finite element meshes are created. The mesh has been refined to decrease the number of elements by selecting finer mesh on complex geometries and coarser mesh on other geometries for sensitive analysis to increase the efficiency of the optimization. [26]

It was preferred to have multiple mesh elements across the thinnest geometry thickness to provide well defined sensitivities. In the mean of geometry projection methods it was also required that the element size should not exceed the half of the thickness of the thinnest geometry. [24,25]

In the light of this information, for the topology optimization and design validation stress analysis the whole body excluding the platform area marked in Figure 3. below was meshed relatively coarsely with hexahedron elements size of 0.3 mm as these areas were more uniform and did not contain any complex radius that was not easy to compute on. Besides, because of the complex geometry the platform area was meshed with tetrahedron elements size of 0.2 mm. This mesh size has been found after

a convergence test which the stresses are converged with %1 accuracy. The mesh structure can be seen in Figure 3..

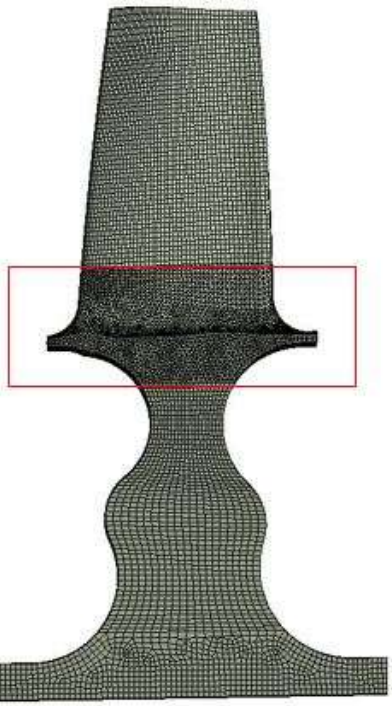


Figure 3.5: Mesh structure for Topology Optimization.

3.3.2. Boundary Conditions and Loading

The blisk was fixed with a single boundary condition, due to its close fitting assembly to the engine shaft, visualized in Figure 3..

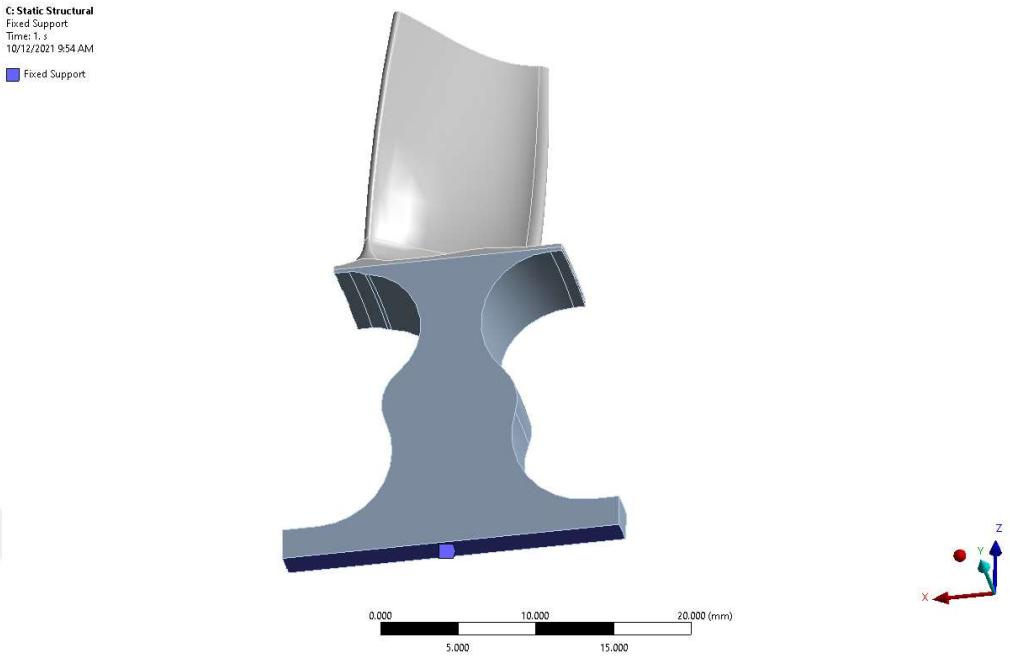


Figure 3.6: Boundary condition of the blisk section in ANSYS.

Four loads which were taken into consideration as load cases implemented in ANSYS as specified by engineering. The rotational velocity (B), the aerodynamic pressure (G,H), the pre load force (A,C) and SAS loads (D, E, F) can be seen in Figure 3., marked by red color. The values for all loads are listed in Table 3.3, however they are considered as confidential information of TEI and can not be shown. For the topology optimization analysis the values on Table 3.3 were used.

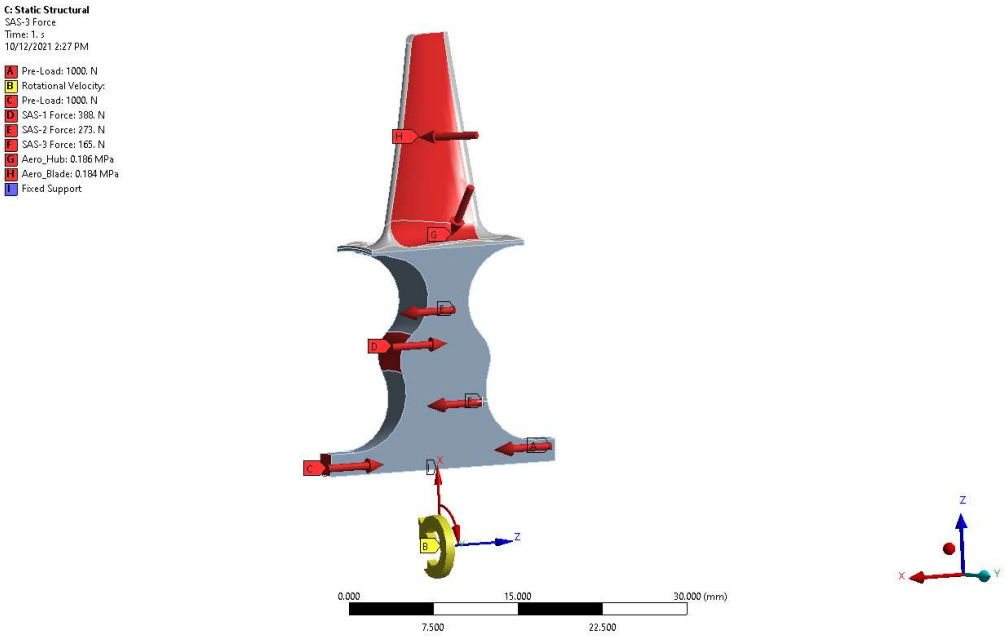


Figure 3.7: Implemented loads on blisk in ANSYS.

Table 3.3: Imported loads for the section in ANSYS Mechanical.

Load Type	Value	Unit
Rotational Velocity		rad/s
Temperature		K
Aerodynamic Pressure		Pa
SAS Pressure		Pa
Pre-Loading Force		N

The temperature distribution on the blisk was implemented as thermal mapping which was created by engineering. Temperatures were copied directly from the thermal analysis nodes to the structural analysis nodes. This kept the structural analysis independent of the thermal analysis. Besides, the thermal load was suppressed due to topology optimization tools in ANSYS does not support thermal loads. Thermal loads were used on the structural analysis of the redesigned geometry to validate the final design. Temperature distribution can be seen in Figure 3..

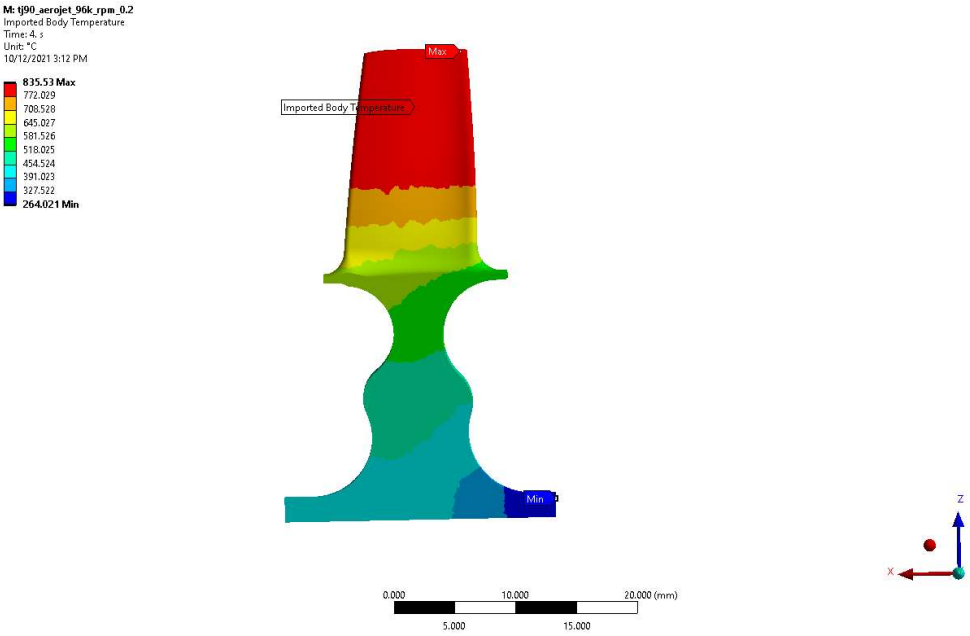


Figure 3.8: Temperature Distribution on the blisk as imported thermal map.

3.3.3. Topology Optimization Parameters and Constraints

For setting up a topology optimization in ANSYS we need to define the envelope of the structure, or in other words design space, and the parameters such as the objective and the constraints of the optimization. Optimization algorithm including objective and constraint relationship can be seen in Figure 3. below.

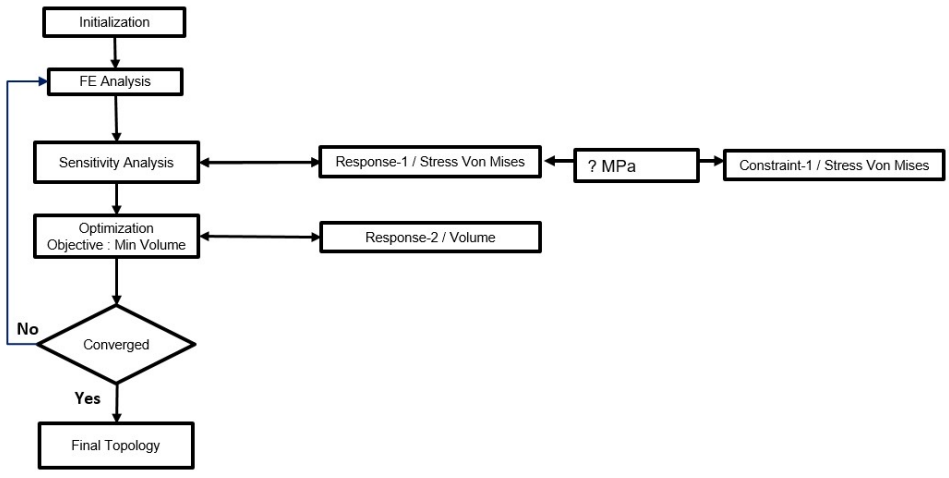


Figure 3.9: Optimization Algorithm including objective and constraint.

Flow path components (platform, root and blades) were not taken into consideration in our project in order to leave the flow surfaces constant. So they were chosen as exclusion region and kept untouched during the analysis. All boundary conditions automatically became as exclusion regions according to the analysis software. Exclusion region in red color can be seen clearly in Figure 3.. The remaining geometry was set as the design space for the optimization. In order to leave the maximum freedom to the optimization process in choosing the optimal material distribution the design space of the structure should be as wide as possible, compatibly with the project restrictions.

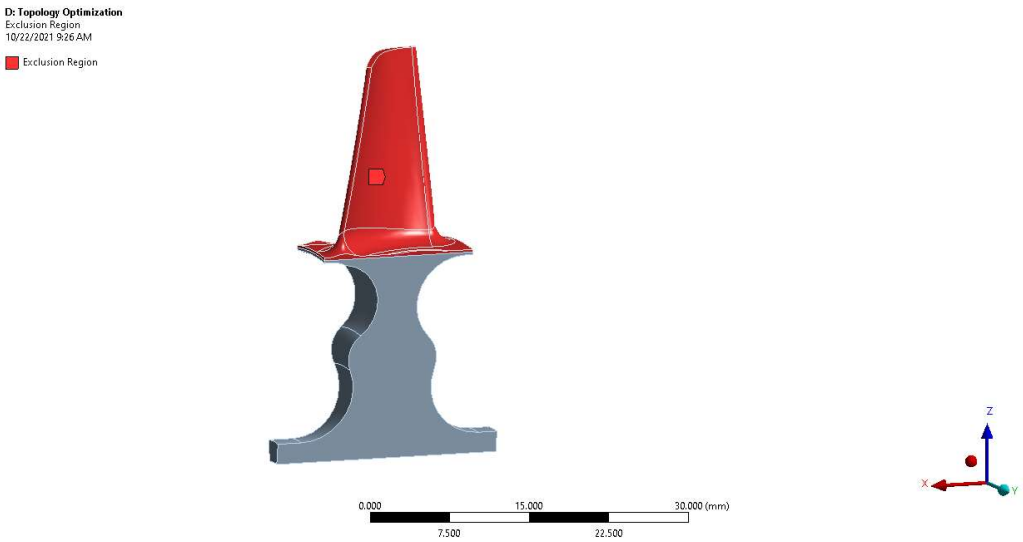


Figure 3.10: Exclusion region defined in topology optimization.

In the analysis settings of the static structural large deflection option in solver controls section and solver units in analysis data management section should be defined correctly to be on the safe side. Large deflection option was set to off for all linked analyses. Topology optimization does not support a solution selection that has large deformation turned on. Solver units was set to active system in order to prevent unit system mismatch between the environments involved in the solution.

In the analysis settings of the ANSYS TO, it is possible to define some input settings for the solver algorithm. Maximum number of iterations was set to 500 by

default. It is the maximum iteration number that the solver continues until it converges or reaches this amount of iterations.

The minimum normalized density was set to 0.001 and convergence accuracy was set to 0.1% by default.

Penalty factor was used to scale the structural stiffness matrix of each element depending on the topology density which was calculated during solution as between 0 and 1. The higher the Penalty Factor, the more the stiffness matrix is weighted towards elements with a density close to 1, means reduction of the grey region in the final design. The less the grey region, the better is the design. In this thesis penalty factor has been equal to 3 (Figure 3.11).

Details of "Analysis Settings"	
Definition	
Maximum Number Of Iterations	500.
Minimum Normalized Density	1.e-003
Convergence Accuracy	0.1 %
Penalty Factor (Stiffness)	3.
Region of Manufacturing Constraint	Include Exclusions
Region of Min Member Size	Exclude Exclusions
Region of AM Overhang Constraint	Exclude Exclusions
Solver Controls	
Solver Type	Program Controlled
Output Controls	
Store Results At	All Iterations
Analysis Data Management	

Details of "Response Constraint"	
Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Response Constraint
Response	Volume
Define By	Range
Percent to Retain (Min)	15 %
Percent to Retain (Max)	50 %
Suppressed	No

Figure 3.1: TO Analysis Settings & Volume Response Constraint.

The objective of the topology optimization is its purpose. In this thesis, minimizing compliance, which was a standard terminology in topology optimization is chosen as the objective. This is the inverse of maximizing the stiffness. The other

two objectives were minimizing volume and mass. Objective function could be set as a Volume or Mass minimization but this would over constraint the optimization analysis by reason of a mass constraint was already set which will cause an error by the analysis algorithm.

During the optimization process in ANSYS the output can be controlled by the response constraints. A response constraint determines what the topology optimization is trying to achieve. For mass or volume responses, the retain percentage was defined as range or constant value of the design region. For stress responses, the geometry was optimized to meet the stress criteria over all or individual linked structural analyses. In this study, the retained volume was arranged between 85% and 50% and Global von-Misses stress value was set less than the yield point with 10% margin.

3.4. Manufacturing Constraints

Topology optimization brings lots of advantages with the freedom of additive manufacturing. Often, companies may want to use traditional manufacturing methods for the topology optimized geometries. This means that some constraints need to be added to the analysis which the solver take into account when optimizing the geometry in order to produce an easy manufacturable geometry. In Table 3.4 below, constraint types in ANSYS are listed.

Table 3.4: Manufacturing constraints by ANSYS Topology Optimization.

Constraint Type	Information
Member Size	Sets maximum and minimum member size
Pull Out Direction	Prevents undercutting, creates castable surfaces from one direction
Extrusion	Forces a constant cross-section along an axis
Cyclic	Forces cyclic symmetry along an axis
Symmetry	Forces planar symmetry

Member size constraint is especially useful for additive manufacturing. Minimum member size can be specified for the solver purpose of avoiding thinner geometries than the minimum thickness that be produced by AM. By default when you specify program controlled it is chosen to be 2.5 times the minimum mesh element

size. In this study no manufacturing constraints were defined due to manual re-design would be applied to the output geometry.

3.5. Limitations

While performing topology optimization in 3D with the selected geometry, it has certain limitations in ANSYS. Thermal structural stresses are not supported by ANSYS topology optimization tools. Regardless, it is possible to complete the optimization with only static structural loads and procure a geometry which carry out weight reduction goal. The optimized geometry then validated with all loads including thermal features.

Besides, another limitation is related with the nature of additive manufacturing process technology. While 3D printing is known as a way of building layers on top of each other, overhang structures should be considered while redesigning the optimized geometry in order to produce it without any error. Surfaces facing down has to be minimum 35 degrees angle with the building platform. The surfaces that have lower angles required to be supported with solid material or support structures to obtain minimum angle for the production. The output geometry with solid material should be machined to obtain final geometry or support structures on the output geometry need to be removed in post processing.

Also trapped powder within any closed volume is another limitation that requires additional post processing after the manufacturing process.

In addition, as specified in section 3.3 manufacturing constraints, mesh density is required to be 4x finer than specified minimum member size which is the minimum resolution required to capture the smallest features. Mesh size in this study was determined according to the minimum thickness on the platform section.

4. RESULTS

4.1. ANSYS Results

When the optimization process was completed, the results file was checked for convergence, see Figure 4.1. In this study, convergence was reached after 17 iterations. The number of iterations need to reach the convergence depends on the complexity of the optimization geometry and type of the optimization parameters.

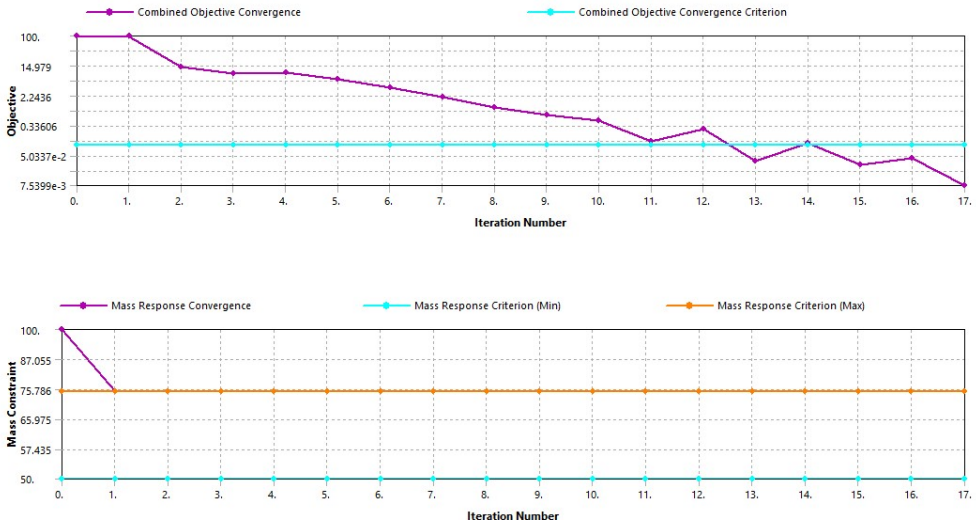
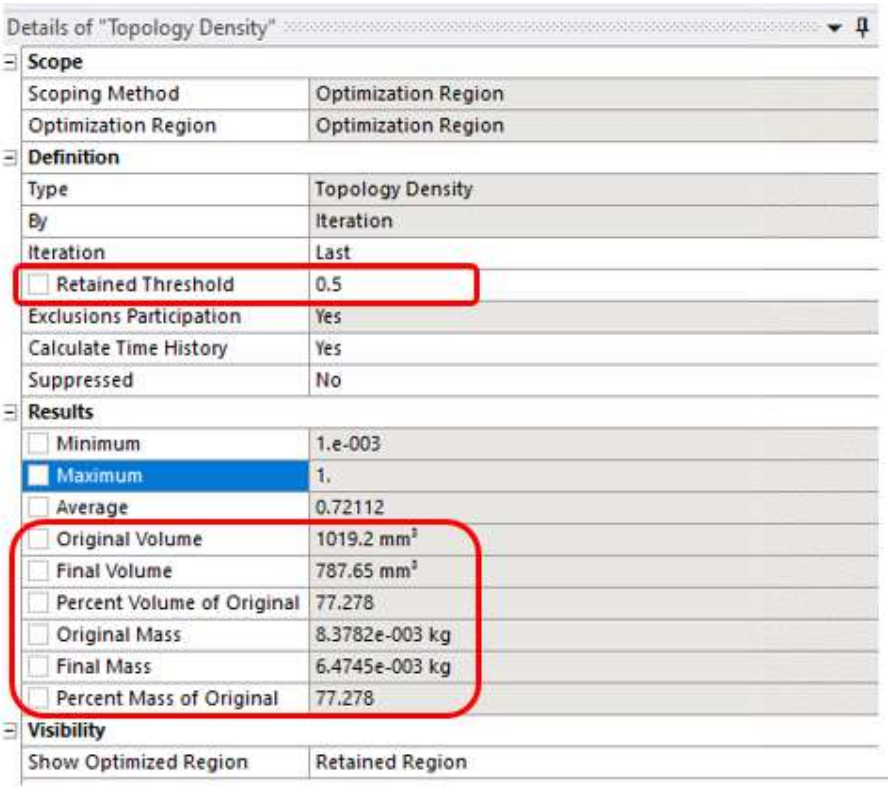


Figure 4.1: Solution convergence criteria.

Another critical step on evaluating the optimization result was determining a retained threshold value. Higher values indicate material that must be kept, lower values indicate redundant material that can be removed. After comparison on various threshold values, 0.5 as default value was selected on which the result represent the continuous structure. Details of Topology Optimization Solution is shown in Figure 4.2 below. Volume and mass of the optimized topology were computed for the selected Retained Threshold value and help the user to select the best topology.



Details of "Topology Density"	
Scope	
Scoping Method	Optimization Region
Optimization Region	Optimization Region
Definition	
Type	Topology Density
By	Iteration
Iteration	Last
Retained Threshold	0.5
Exclusions Participation	Yes
Calculate Time History	Yes
Suppressed	No
Results	
Minimum	1.e-003
Maximum	1.
Average	0.72112
Original Volume	1019.2 mm³
Final Volume	787.65 mm³
Percent Volume of Original	77.278
Original Mass	8.3782e-003 kg
Final Mass	6.4745e-003 kg
Percent Mass of Original	77.278
Visibility	
Show Optimized Region	Retained Region

Figure 4.2: Details of Topology Optimization Solution.

Final output volume was calculated as 77.23 % of original geometry. The original geometry and optimization output geometry can be seen in Figure 4.3 below. Result clearly showed that load carrying disk thickness can be slightly decreased. After post processes of the geometry the volume might be different.

Figure 4.3: Original and optimization output geometry.

The elements with the topology density below 0.5 were removed from the topology optimization output geometry and the reference model was exported as a .stl file for the re-design step. This file was required to cut down on design time which data was used investigate the optimization result and reference the optimization output for the re-design phase [29].

4.2. Redesign of Optimized Geometry

The optimization output geometry was resulted as iso surface geometries which are not suitable for additive manufacturing and validation analysis of the final part. Therefore, the geometries were remodeled as NURB (Non-uniform rational basis spline) surfaces which provides more accurate results for design validation analyses [28].

The re-design of the optimized geometry was performed in a CAD environment by taking the exported date from ANSYS software. Siemens NX 12.0 software was used as CAD environment. Final manufacturing model is given in Figure 4.4 below.

a) Optimization result. b) Final manufacturing design.

Figure 4.4: Optimization Result and Final Manufacturing Geometry.

General outline in (a) was kept while small hole that cause stress concentration was filled with material. The area connecting blade and disk section which called rim section was smoothened not to cause stress concentrations. Besides, bore section was designed according to the smooth procedure like rim section as seen in (b).

4.3. Validation Analyses

The remodeled optimization geometry was subjected to the validation analysis and it was checked if the final geometry meets the mechanical strength criterias which were defined by design engineering. For validation analysis, final CAD geometry were taken into FEM environment and analyzed with maximum loading conditions including thermal loads. Then analytical life calculations were completed by the help of tools which were developed for TEI engineering use with the fatigue and creep loadings.

The Von-Misses stress criterion was used in the FEM analyses. The stress and displacement analysis results of the optimized and re-designed final geometry is plotted in Figure 4.5 below.

As can be seen in Figure 4.5 the surface of the blade is subjected to stresses of up to roughly 650 MPa. As expected from the original geometry analysis results, there are some stress concentrations close to the platform where the blades attach to the surface of the rotor due to high rotational velocity.

The highest stresses occur on the bore section where the stresses are below UTS value, similar to the original geometry. The most important aspect of the stress evaluation is to verify that the stress is not larger than the ultimate tensile strength of the material, as this would cause a crack initiation.

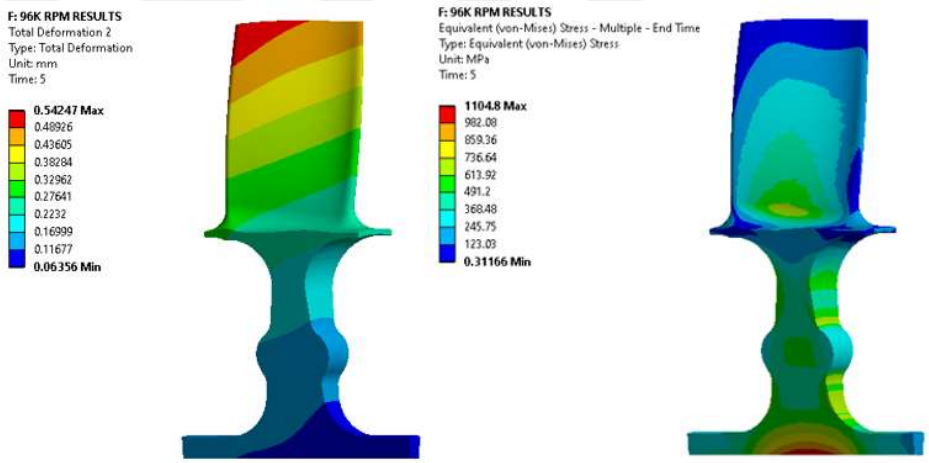


Figure 4.5: Analysis results of final design.

According to the analysis results (von-Misses stress criteria), the final geometry was checked in terms of assessments given in Table 4.1**: Engineering requirements** below. Burst margins and life calculations meet the requirements.

Table 4.1: Engineering requirements.

#	Assessment	Design Criteria
Burst	Hoop Burst Margin	15%
	Radial Burst Margin	15%
Integrity	σeqv, avg < σ0.2, min	Max rpm, Elastic Region
LCF	100 cycle	0-Max rpm-0
Creep	No rupture for 2h	Max rpm

Analysis results as Von-Mises Stress and Directional deformation are compared for original part and final geometry in Table 4.2 below. Maximum stress value increased slightly that is expected to be compensated by the new material's better mechanical properties. Moreover, directional deformation values were not increased significantly. Lastly, the final part volume decreased nearly 15% in comparison with the current component volume that is a significant mass reduction.

Table 4.2: Critical Parameters' Comparison.

Parameters	***Units***	***Original Geometry***	***Final Geometry***	***Percentage***
Equivalent(Von Mises) Stress-Averaged	Mpa	A	1.17 A	117.16%
Directional Deformation (Radial)	mm	B	1.05 B	104.65%
Volume	mm^3	C	0.86 C	85.65%

5. MANUFACTURING PROCESS

5.1. Manufacturing Simulations

After validating the mechanical properties and engineering requirements of the final part, additive manufacturing simulations were carried out. MSC Simufact Additive 4.1 was used as the mechanical solver by modeling the manufacturing process with the finite element method. Simufact Additive is a powerful and scalable software solution for the simulation of metal-based additive manufacturing processes. Simulation parameters for calculation of the thermal distortion and residual stress are given in Table 5.1 below.

Table 5.1: Simulation parameters.

Simulation Type	Mechanical
System / Material	EOS M 290 /Inconel 939
Operation (Unit cubic)	Build, Immediate release, Support removal
Post process parameters	Remove at once
Component voxel size	1 mm *(High precision voxel elements)*
Build plate voxel size	5 mm

Max. displacements and stress concentrations were found on the same area, on the upper part of the support structures.

The stresses were homogeneously distributed on the blades. There is no extremely high concentration at a certain point. Stress distribution can be seen in Figure 5.1**: Stress results of optimized part manufacturing simulation** below.

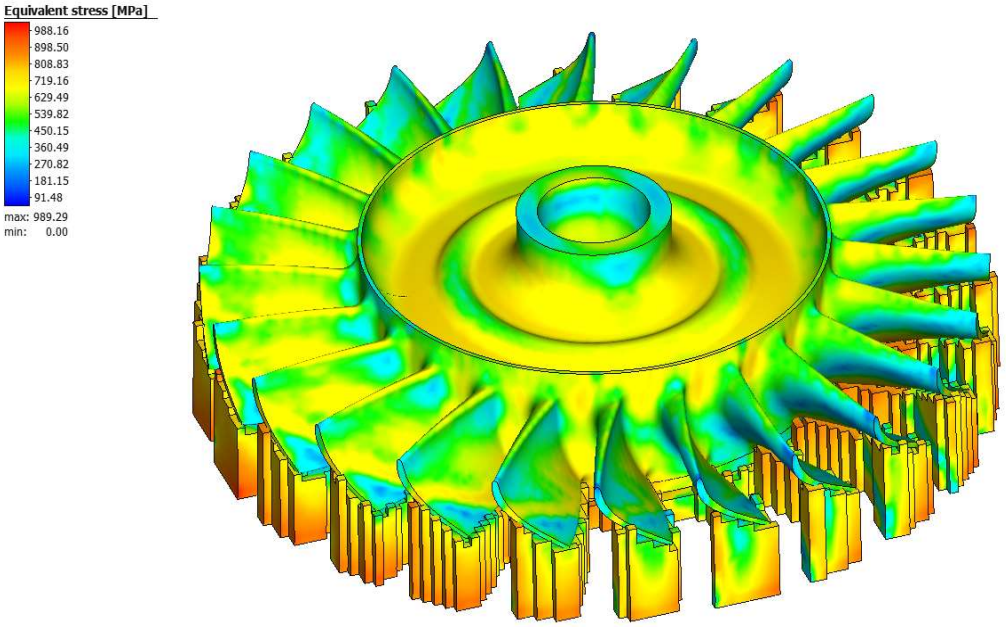


Figure 5.1: Stress results of optimized part manufacturing simulation.

The total deformation distributions were concentrated on the opposite sides of the part. In general, maximum deformation values were observed at the mating surface points with the support structures on blade tips. Total displacement distribution can be seen in Figure 5.2 below. No faults were expected during the manufacturing process of the part.

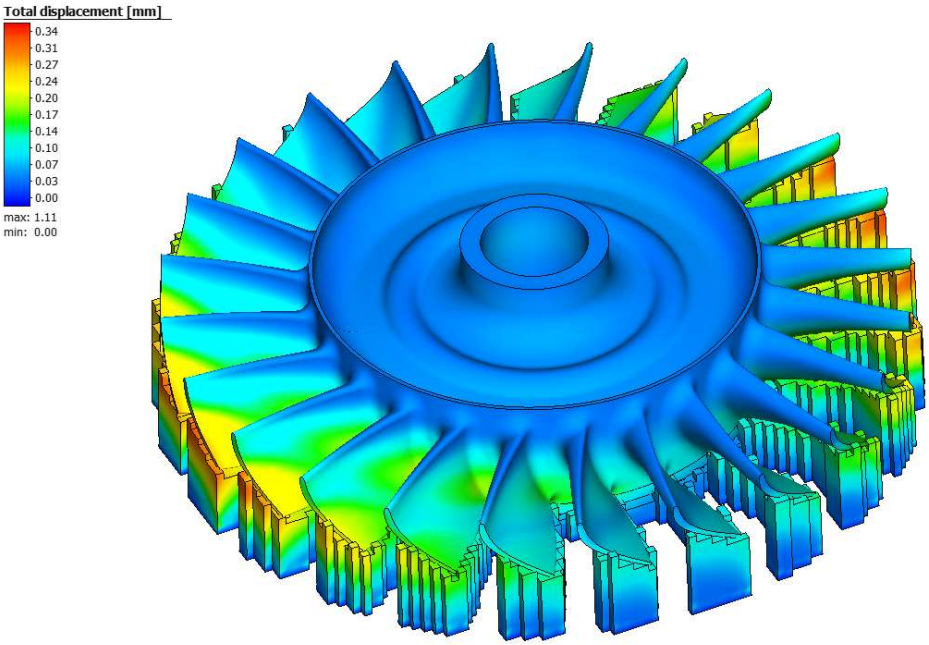


Figure 5.2: Displacement results of optimized part manufacturing simulation.

Solid metal supports were applied on the bottom surface according to the building direction where higher stress was expected after removing from the substrate (See Figure 5.3). The surface then machined to reach final geometry.

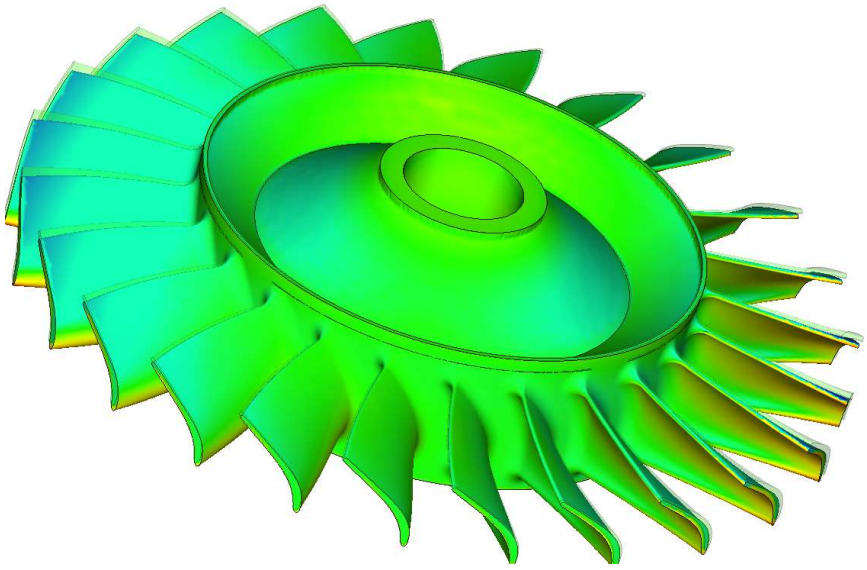


Figure 5.3: Bottom side of the manufacturing model.

5.2. Additive Manufacturing

The final design of the optimization part was additively manufactured with the EOS M290 SLM machine using Inconel 939 powder. Powder's particle size is ranging from 20 to 55 μm. During the operation default processing parameters were used according to the manufacturer.

Due to surfaces facing down should have a minimum angle of 35˚ with the building platform, the bottom geometry was supported with solid metal instead of support structures. This angle was taken into consideration to avoid break-ups and failed geometries. Necessary support structures added and final manufacturing model is presented in Figure 5.4.

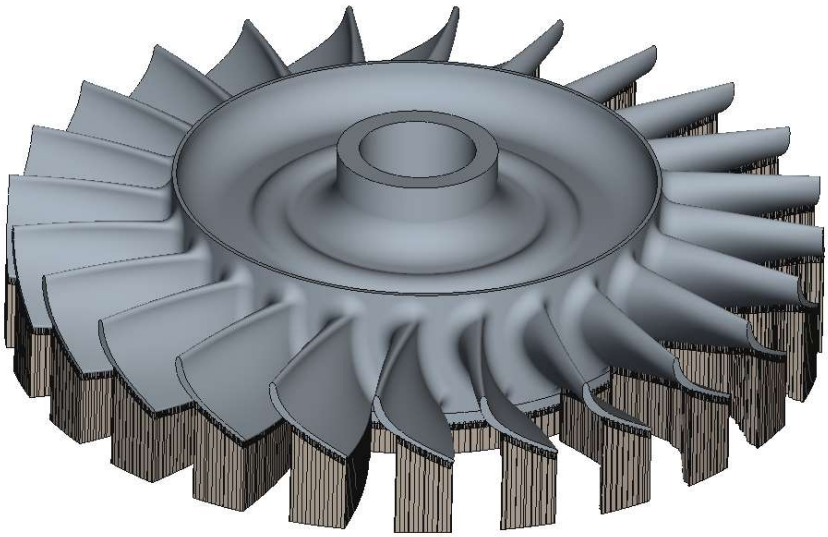


Figure 5.4: Manufacturing model of optimized part.

After manufacturing process, the part was cut from the manufacturing table with a wire Electrical Discharge Machining process, after thermal stress relieving with heating for about 2 hours. The manufactured final part after cutting from the manufacturing table is presented in Figure 5.5 below.

Figure 5.5: SLM manufactured optimized part.

5.3. Post Processes

After cutting the additively manufactured final part from the manufacturing table, the support structures on the bottom surface were removed with hand tools. As another post process, the assembly contact surfaces and solid support on the bottom side of the manufactured part were machined to achieve the required geometrical tolerances according to the engineering requirements. The final part after these post process steps is shown in Figure 5.6 below.

Figure 5.6: Machined & support removed final part.

Lastly, additively-manufactured final part from Inconel 939 powder consists of gamma phase (γ) and primary carbides as the as-built microstructure. Heat treatment process is required for the material to reach the desired microstructure and part properties through precipitation of the gamma prime (γ‘) strengthening phase [22]. Also, researches show that for SLM manufacturing process without heat treatment the fatigue life was reduced significantly due to pores in the micro structure [27]. From this point of view, heat treatment was performed with the parameters developed by the machine manufacturer.

The dimensional control of the optimized and manufactured part was completed with Altera 15.10.8 Coordinate Measuring Machine according to the manufacturing requirements by the means of surface quality, assembly feature locations. Deviations for measured values were within the tolerance values according to the drawing.

6. CONCLUSIONS AND FUTURE SCOPE

In the near future, with developing the current optimization software topology optimization will be a major tool for the design engineers to produce faster and reliable solutions to the major problems of the engineering industry with the help of developing additive manufacturing technology.

In this study, the design of a critical aerospace part for additive manufacturing with topology optimization is presented.

Reducing the weight of the turbine blisk seems to be possible while achieving design requirements with margins. By keeping the equivalent stress level under the ultimate strength value of the selected material, more than %14.5 of the structural mass of the blisk is reduced.

The activities carried out during this study have been presented that the use of topology optimization to re-design the current geometry, the application in additive manufacturing technologies to have a beneficial effect on weight reduction, while maintaining the structural engineering requirements.

The optimized part was successfully manufactured with SLM method on the machine EOS M290 and after being subject to post processes as support removal, machining, heat treatment and quality control, it was made ready for the single part/module rig tests or engine tests.

Further, with minor tricks in the optimization software it is indicated that the length of the current blisk along the engine direction could be reduced as well. However, additional design validation is necessary to confirm the new design whether the results are applicable or not.

For another future work, different optimization softwares can be used comparatively with widen optimization design space by the addition of design parameters into optimization process.

Moreover, component test, rig test, engine tests of additively manufactured aerospace component is needed for the qualification process in aerospace industry. Qualification of the new design also can be taken as a future work for industrial applications.

REFERANCES

[1] Liu, S., Li, Q., Liu, J., Chen, W., & Zhang, Y. (2018). A realization method for transforming a topology optimization design into additive manufacturing structures. Engineering, 4(2), 277-285.

[2] Christensen P, Anders K. (2008). An Introduction to Structural Optimization, Springer; ISBN 978-1-4020-8665-6.

[3] Thummar, D R. (2014), Truss Topology Optimization Using Modified Genetic Algorithm, Master of Technology in Machine Design, Department of Mechanical Engineering School of Engineering, RK University, Rajkot, Gujarat-360020

[4] Web 1, (2018), http://www.materialise.com/en/blog/using-topology-optimization-for-an-aircraft-engine-bracket, (Erişim tarihi: 25/01/2018)

[5] Web 2, (2018), http://analizsimulasyon.com/2015/01/06/yapisal-optimizasyon/, (Erişim tarihi: 25/01/2018)

[6] Poyraz, M. (2004). Bir kamyon şasisinin yapısal optimizasyonu, Yüksek Lisans Tezi, İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü.

[7] Palmer, P., & Nelson, E. (2011). Optimizing next-generation automotive structures using Altair OptiStruct. Plastics in lightweight and electric vehicles.

[8] Web 3, (2018), http://altairenlighten.com/in-depth/size-optimization/, (Erişim tarihi: 25/01/2018)

[9] Altair-Hyperworks. (2016). OptiStruct Optimization Concept and Fine-Tuning Design.

[10] Radman, A. (2013). Bi-directional evolutionary structural optimization (BESO) for topology optimization of material's microstructure. RMIT University.

[11] Wang, Y., Luo, Z., & Zhang, N. (2013) Design Optimization of Structures using A Nodal Density-Based SIMP Method.

[12] Brackett, D., Ashcroft, I., Hague, R., (2011), Topology Optimization For Additive Manufacturing," 24th Solid Freeform Fabrication Proceedings, Austin, Texas,US

[13] Santos, E. C., Shiomi, M., Osakada, K., & Laoui, T. (2006). Rapid manufacturing of metal components by laser forming. International Journal of Machine Tools and Manufacture, 46(12-13), 1459-1468.

[14] Thomas, C., Christopher, B. Williams, O., Banning, G. (2011) "Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing. strategic foresight" Initiative, October, 2011

[15] Hague, R. J. M., & Reeves, P. E. (2000). Rapid prototyping, tooling and manufacturing (Vol. 117). iSmithers Rapra Publishing.

[16] Lan, H., Ding, Y., Hong, J., Huang, H., & Lu, B. (2004). A web-based manufacturing service system for rapid product development. Computers in Industry, 54(1), 51-67.

[17] Şahin, K., & TURAN, B. O. (2018). ÜÇ BOYUTLU YAZICI TEKNOLOJİLERİNİN KARŞILAŞTIRMALI ANALİZİ. Stratejik ve Sosyal Araştırmalar Dergisi, 2(2), 97-116.

[18] Altuncu, E. (2020). Katmanlı İmalat İle Üretilen Parçalara Uygulanan Yüzey İşlemler. Sakarya Uygulamalı Bilimler Üniversitesi - SUMAR, 2-5.

[19] Drstvensek, I., Hren, N. I., Strojnik, T., Brajlih, T., Valentan, B., Pogacar, V., & Hartner, T. Z. (2008). Applications of rapid prototyping in cranio-maxilofacial surgery procedures. Int J Biol Biomed Eng, 1(2), 29-38.

[20] Web 4, (2021), https://www.eos.info/03_system-related-assets/system-related-contents/_pdf_system-data-sheets/eos_system_data_sheet_eos_m_290_en.pdf, (Erişim tarihi: 25/10/2021)

[21] "AMG Vanadium," AMG Vanadium, Inc, 2009. [Online]. Available: http://www.metallurgvanadium.com/cobaltpage.html.

[22] Web 5, (2021), https://www.eos.info/03_system-related-assets/material-related-contents/metal-materials-and-examples/metal-material-datasheet/nickelalloy-inconel/material_datasheet_eos_nickelalloy_in939_premium_en_web.pdf (Erişim tarihi: 25/10/2021)

[23] Web 6, (2021), https://nickelinstitute.org/media/1709/in_738alloy_preliminarydata_497_.pdf (Erişim tarihi: 18/09/2021)

[24] Norato, J. A., Bell, B. K., & Tortorelli, D. A. (2015). A geometry projection method for continuum-based topology optimization with discrete elements. Computer Methods in Applied Mechanics and Engineering, 293, 306-327.

[25] Zhang, S., Norato, J. A., Gain, A. L., & Lyu, N. (2016). A geometry projection method for the topology optimization of plate structures. Structural and Multidisciplinary Optimization, 54(5), 1173-1190.

[26] Zhang, S., Gain, A. L., & Norato, J. A. (2020). Adaptive mesh refinement for topology optimization with discrete geometric components. Computer Methods in Applied Mechanics and Engineering, 364, 112930.

[27] Zhao, X., Li, S., Zhang, M., Liu, Y., Sercombe, T. B., Wang, S., ... & Murr, L. E. (2016). Comparison of the microstructures and mechanical properties of Ti–6Al–4V fabricated by selective laser melting and electron beam melting. Materials & Design, 95, 21-31.

[28] Web 7, (2021), https://www.epsilonfea.com/wp-content/uploads/2019/05/ANSYS-Topology_Optimization_User_Meeting_020619.pdf, (Erişim tarihi: 18/09/2021)

[29] Dagkolu, A., Gokdag, I., & Yilmaz, O. (2021). Design and additive manufacturing of a fatigue-critical aerospace part using topology optimization and L-PBF process. Procedia Manufacturing, 54, 238-243.

[30] Witzel, J., Schrage, J., Gasser, A., & Kelbassa, I. (2011, October). Additive manufacturing of a blade-integrated disk by laser metal deposition. In International Congress on Applications of Lasers & Electro-Optics (Vol. 2011, No. 1, pp. 250-256). Laser Institute of America.

BIOGRAPHY

Fatih EKİNCİ Erzincan'da doğdu. Kariyerine otomotiv sektöründe Kalite Mühendisi olarak başladı. Havacılık sektöründe Uzman Mühendis olarak çalışmaktadır.