UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

PRODUCT REDESIGN BY TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING PROCESS

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WONGANI CLEMENT KIZITO SALIMA

A thesis submitted in fulfillment of the requirements for the degree of Master of Mechanical Engineering (Product Design)

Faculty of Mechanical Engineering

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2021

DECLARATION

I declare that this project entitled "Product Redesign by Topology Optimization for Additive Manufacturing Process" is the result of my own research except as cited in the references. The project report has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature :

Name : Wongani Clement Kizito Salima

Date : 14 August 2021

APPROVAL

I hereby declare that I have checked this project report and in my opinion, this project report is adequate in terms of scope and quality for the award of the degree of Master of Mechanical Engineering (Product Design)

Signature	:	
Supervisor Name	:	Dr Faiz Redza Bin Ramli
Date	:	14 August 2021

DEDICATION

To the service of God Almighty, my country and the world

ABSTRACT

This research evaluates an Alcoa bearing bracket commonly used on control surfaces of aircraft. The study seek to redesign the Alcoa bracket to minimize the weight while fitting in the same target design envelope and meeting the technical requirements and this is achieved by using the Topology Optimization (TO) technique. The objectives of this research are; to obtain the best TO model based on strength to weight ratio, von Mises stress, displacement, mass, and factor of safety by varying weight retentions between 10%-70% using solidThinking Inspire, then to optimize build orientation for the minimum amount of support structures using Fusion 360, and to obtain the required geometric compensations of the Alcoa bracket by using an Artificial Neural Network (ANN) tool in MATLAB to produce a more accurate bracket by controlling deformations occurring due to residual stresses after the Additive Manufacturing (AM) heating process. The methodology has three sections, the first section deals with pre-analysis and topology optimization, where three materials (15-5PH Steel, Ti6Al4V ELI-0406, and Ti-6Al-2Sn-4Zr-6Mo) were compared, and one material was selected for the design process based on material physical properties then topology optimization process was performed to obtain a design with excellent strength to weight ratio, von Mises stress, displacement, mass, and factor of safety. The second section deals with build orientation optimization in Fusion 360 to obtain the minimum amount of support structure during AM process. The third section deals with the ANN tool to make the required geometric compensations on the bracket which help to control deformation arising due to the AM heating process, a conformity check was conducted to validate and show the improvements achieved on the bracket after the ANN tool was implemented then the section finalizes with 3D printing of the bracket just to visualize the outcome of the TO process since the study's focus is entirely on computer simulations and not experiments. In the results, Ti-6Al-2Sn-4Zr-6Mo was selected as the material to use for the design process, the results also selected a 40% volume retention as the best model amongst the seven (7) iterations conducted, while the other results selected Rank 1 as the best-optimized build orientation amongst the thirteen (13) Ranks, while in the ANN results, it was found that before compensation, the conformity score of the deformed nodes after AM simulation was 76.312 for bracket with Cartesian mesh and 85.196 for bracket with Layered tetrahedral mesh while the conformity score after the AM simulation of the compensated bracket the conformity was 89.726 on Cartesian mesh bracket and 94.342 on Layered tetrahedral mesh bracket showing that there was an increase in conformity after the compensation. Finally, the TO model was printed by a 3D printer and it showed similar dimensions to the bracket's CAD model. In conclusion, the research selected a 40% volume retention using Ti-6Al-2Sn-4Zr-6Mo, also selected Rank 1 build orientation, and achieved 59.75% and 61.784% reduction in conformity error for Cartesian and Layered tetrahedral mesh respectively.

REKABENTUK SEMULA PRODUK DENGAN PENGOPTIMUMAN TOPOLOGI UNTUK PROSES PEMBUATAN TAMBAHAN

ABSTRAK

Penyelidikan ini menilai pendakap Alcoa yang kebiasaannya digunakan pada permukaan kawalan pesawat. Kajian ini bertujuan untuk merekabentuk semula pendakap Alcoa untuk meminimumkan berat sambil menyesuaikan sasaran rekabentuk serta memenuhi syarat-syarat teknikal dan ini dicapai dengan menggunakan teknik pengoptimuman topologi (TO). Objektif untuk penyelidikan ini adalah; untuk mendapatkan model TO terbaik berdasarkan nisbah kekuatan kepada berat, tegasan von Mises, sesaran, jisim, dan faktor keselamatan dengan mengubah pengekalan berat di antara 10% - 70% menggunakan solidThinking Inspire, kemudian untuk mengoptimumkan orientasi binaan bagi meminimumkan jumlah struktur sokongan menggunakan Fusion 360, dan untuk mendapatkan pampasan geometrik yang diperlukan oleh pendakap Alcoa menggunakan alat perisian rangkaian neural buatan (ANN) dalam MATLAB untuk menghasilkan pendakap yang lebih tepat untuk mengawal ubahbentuk disebabkan oleh tegasan baki selepas proses pemanasan Pembuatan Tambahan (AM). Metodologi ini terdiri daripada tiga bahagian, bahagian pertama melibatkan pra-analisis dan pengoptimuman topologi, di mana tiga bahan (Keluli 15-5PH , Ti6Al4V ELI-0406, dan Ti-6Al-2Sn-4Zr-6Mo) dibanding dan satu bahan telah dipilih berdasarkan sifat fizikal bahan dan kemudian proses pengoptimuman topologi telah dilakukan untuk mendapatkan rekabentuk yang mempunyai nisbah kekuatan kepada berat, tegasan von Mises, sesaran, jisim dan faktor keselamatan yang paling baik. Bahagian kedua melibatkan pengoptimuman orientasi binaan dalam Fusion 360 untuk meminimumkan jumlah struktur sokongan semasa proses AM. Bahagian ketiga melibatkan alat perisian ANN untuk mendapatkan pampasan geometrik yang diperlukan oleh pendakap bagi membantu mengawal peningkatan ubahbentuk disebabkan oleh proses pemanasan AM, semakan pematuhan telah dilaksanakan untuk mengesahkan dan untuk menunjukkan perubahan yang telah dicapai oleh pendakap selepas alat perisian ANN dilaksanakan dan bahagian ini diakhiri dengan pencetakan 3D pendakap hanya bertujuan untuk visualisasi hasil proses TO kerana kajian ini memfokuskan kepada simulasi komputer dan bukan kepada eksperimen. Dalam hasil penyelidkan, Ti-6Al-2Sn-4Zr-6Mo telah dipilih sebagai bahan yang digunakan dalam proses rekabentuk, hasil juga menunjukkan pengekalan isipadu 40% telah dipilih sebagai yang terbaik di antara tujuh (7) lelaran yang dilakukan, manakala Kedudukan 1 dipilih sebagai pengoptimuman terbaik orientasi binaan di antara tiga belas (13) kedudukan, manakala untuk keputusan ANN, ia telah didapati bahawa sebelum pampasan, skor pematuhan untuk ubahbentuk nod setelah simulasi AM adalah 76.312 untuk pendakap dengan jaringan Cartesian dan 85.196 untuk pendakap dengan jaringan tetrahedron berlapis sementara skor pematuhan selepas simulasi AM untuk pendakap dengan pematuhan pampasan adalah 89.726 pada pendakap jaringan Cartesian dan 94.342 pada pendakap tetrahedron berlapis yang mana ini menunjukkan bahawa terdapat peningkatan kepatuhan setelah pampasan. Akhir sekali, model TO telah dicetak menggunakan pencetak 3D dan ia menunjukkan dimensi yang sama berbanding model CAD pendakap. Kesimpulannya, kajian ini telah memilih pengekalan isipadu 40% menggunakan Ti-6Al-2Sn-4Zr-6Mo, juga Kedudukan 1 orientasi binaan, dan mencapai pengurangan ralat pematuhan sebanyak 59.75% dan 61.784% bagi jaringan Cartesian dan tetrahedral berlapis masing-masing.

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LIST OF ABBREVIATIONS

STA	-	Solution Treated & Aged
CS	-	Conformity Score
TO	-	Topology Optimization
PLA	-	Polylactic Acid
3D	-	Three Dimensional
ID	-	Identity
MSE		Mean Square Error
AM	-	Additive Manufacturing
DfAM	-	Design for Additive Manufacturing
ANN	-	Artificial Neural Network
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
SIMP	-	Solid Isotropic Material with Penalization
CAD	-	Computer-Aided-Design
ISE	-	Isotropic-Solid or Empty
SSD	-	Solid-State Drive
CPU	-	Central Processing Unit
UTS	-	Ultimate Tensile Strength
STL	-	Stereolithography
STEP	-	Standard for the Exchange of Product Data

LIST OF SYMBOLS

D,d	-	Diameter
kg	-	Kilogram
g	-	gram
N	-	Newton
m	-	Meter
K	-	Kelvin
mm	-	millimeter
MPa	-	Mega Pascal
GPa	-	Giga Pascal
lbf	-	Pound-force
^{O}C	-	Celcius

CHAPTER 1

INTRODUCTION

1.1 Background

Fuel economy improvement in aircraft is very important in reducing carbon emissions that negatively impact the environment as stated by Jankovics and Barari (2019). As regulations keep on tightening, the use of more lighter, non-traditional components is becoming a favorable option in meeting the targets. In aircraft, lighter materials not only improve fuel economy but also allows it to carry more load. Krishna and M G (2020) pointed out that a small reduction in the weight of each bracket will have a greater impact on the overall weight of the aircraft. But these components must comply with the safety regulations. There are several ways of achieving these compliant lighter components but this research will put much focus on using the Topology Optimization (TO) method and Additive Manufacturing (AM) in the design process.

Topology optimization refers to a form of the structural optimization process that is designed to obtain an optimal geometry based on a set of constraints. Jankovics and Barari (2019) explained that finite element analysis is used iteratively in determining the amount of material that should be kept in the current solid mesh and which amount of material should be set to void. This means that for a given design domain, the optimized component will use the least amount of material for the maximum stiffness. Even though topology optimization has the capability of creating compliant optimal structures for a given constraint and design domain, it does not take manufacturability into account because the structures it creates are often impossible to manufacture using traditional processes. Therefore, one way of avoiding these impossibilities or difficulties is using AM in the design process.

AM is a set of new fabrication technologies that overcome many limitations encountered in traditional manufacturing methods. It enables the creation of complex shapes from a single-step process than the many process steps from traditional processes where sometimes are not feasible in creating complex shapes. AM produces components directly from Computer-Aided-Design (CAD) data. The objects are created by adding layer upon layer, this is in contrast to the conventional manufacturing methods that remove material from the initial workpiece. During AM process, support materials are deposited during each layer and the support materials must be removed in the post-processing step. Support structures ensure successful printing of overhang structures as demonstrated by Vanek et al. (2014). Lalehpour and Barari (2016) as well pointed out that deposition speed is also affected by the support structures, the material is wasted and surface finish quality is also reduced.

Unda (2012) used topology optimization on engine accessory components with an objective to minimize the weight of a mounting bracket. The main parameter was the behavior of the bracket's shape. Stresses were computed for different shapes and compared to determine the best model under predetermined conditions. Deshmukh and Sontakke (2014) presented a static, model, harmonic response analysis of an engine mounting bracket using ANSYS 15.0 and the study showed that the proposed model of the bracket provided 12.5% weight reduction while maintaining an acceptable level of harmonic response and yield stress.

It is through these similar studies that it can be confirmed that topology optimization of components has a greater impact on the performance of the components as well as greater weight saving. Therefore, this research seek to redesign an existing Alcoa bearing bracket commonly used on control surfaces of various aircraft by means of topology optimization for minimum weight while fitting in the target envelope and meeting the technical requirements and various methods to allow for AM.

1.2 Problem Statement

Figure 1.1 shows the Alcoa bearing bracket understudy commonly used on control surfaces of various aircraft while Figure 1.2 is an example of a Landing gear door bracket (similar to the bracket understudy, but the bracket understudy in this paper is much smaller in size and weight).

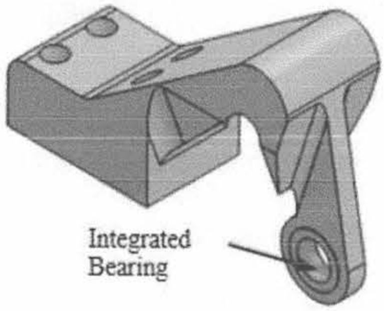

Figure 1.1 : Alcoa Bearing bracket

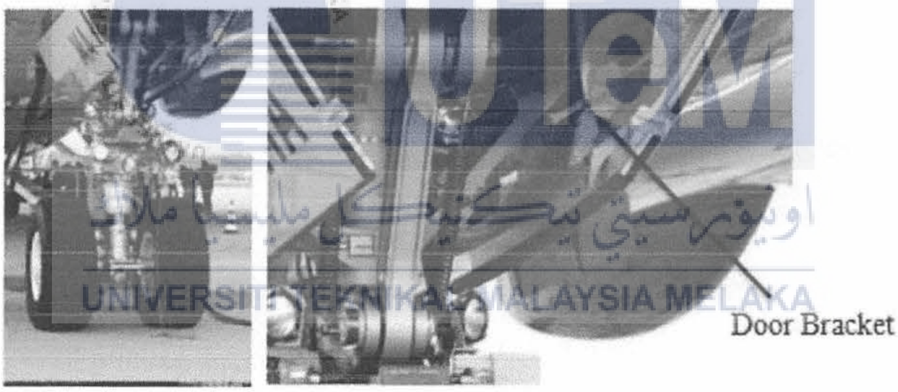

Figure 1.2 : A380 Landing Gear Door Bracket, (Divakaran et al. 2018)

Product development through advanced finite element analysis and structural optimization is a growing concern and focus in the aerospace industry. Reducing the weight of aircraft components has an impact on fuel usage, emission levels, and the amount of cargo that can be carried. In an attempt to optimize various aircraft components for minimum weight, Alcoa fastening systems engaged in various case studies, Figure 1.1 above shows one of the case studies with a challenge to redesign the existing bracket to minimize the weight from the total weight of 868g (Sammut-Bonnici and McGee, 2002) by topology optimization. Even though topology optimization has the capability of creating compliant optimal structures for a given constraint and design domain, it does not take manufacturability into account because the structures it creates are often impossible to manufacture using traditional processes. Therefore, one way of avoiding these impossibilities is by using AM in the design process.

In 2016 Alcoa organized a challenge through crowdsourcing with an objective to redesign the bearing bracket in such a way that its topology and shape are optimized for minimum weight while fitting in the target envelope and meeting the technical requirements. During the challenge, the submitted designs were evaluated via FEA and ranked based on their strength-to-weight ratio, mechanical performance, and the cost associated with the additional manufacturing operations like removing support structures (GrabCAD, 2016). The challenge received 301 entries and the winner managed to obtain a bracket with mass: 220.509 g, ultimate load:4968 lbf (22098.76 N), Strength/Weight: 22.53 lbf/g or (100.23 N/g). But in all the 301 entries, little is known on documented methodologies used, etc because the challenge demanded that the submissions should have: STEP files, any render or image files (JPEG, PNG, etc), and any calculations or considerations and schematic showing the desired printing direction.

Recently, some authors who were not part of the challenge re-worked on the same part, for example, Wang (2017) was interested in developing successful molds by integrating TO with design for casting and design for AM principles. The Alcoa bracket was one of the case studies, the redesigned part (mold) was successfully cast and demonstrated improvements in mechanical performance and weight reduction. Flavio Di Fede (2019) discussed the structural optimization methodology for AM of the Alcoa Bracket. The paper focused on methodology, it did not demonstrate and compare different weight reductions in order to choose the best design that had a good weight/stiffness ratio and this trend has been observed to be common in most literature reviewed.

Therefore, this research seek to redesign the same Alcoa bearing bracket by TO for excellent strength to weight ratio, von Mises stress, displacement, mass, and factor of safety while fitting in the same target design envelope and meeting the technical requirements.

1.3 Research Objective

The objectives of the research are:

a) To obtain the best TO model of the Alcoa bracket based on strength to weight ratio, von Mises stress, displacement, mass, and factor of safety by varying weight retentions between 10%-70% using solidThinking Inspire.

b) To optimize build orientation for the minimum amount of support structures using Fusion 360.

c) To obtain the required geometric compensations of the Alcoa bracket by using an Artificial Neural Network (ANN) tool in MATLAB to produce a more accurate bracket by controlling deformations occurring due to residual stresses after the AM heating process.

1.4 Scope of Research

This research covers the TO of an existing aircraft bracket by varying weight retentions between 10% - 70% of the total mass during simulation to obtain a design with the best strength to weight ratio, von Mises stress, displacement, mass, and factor of safety upon satisfying the design requirements. The CAD model of the bracket used in the TO process was obtained from GrabCaD (2016). Then the other part of the research seek to optimize the build orientation of the bracket during AM process to minimize the amount of support structures and finally due to deformations which normally occur due to residual stresses after the AM heating process an Artificial Neural Network tool was applied to control the deformations. It should be mentioned that this research work mainly focused on computer simulations and not experiments, the TO bracket model obtained was additively manufactured to only visualize the outcome of the TO process.

1.5 Thesis Outline

Based on the objectives presented previously and the proposed approach, this research is made up of five (5) chapters, which are summarized as follows:

- Chapter 1. Introduction. This chapter presents the background of the study, the research problem, objectives, and the research scopes.
- Chapter 2. Literature review. This chapter starts with a brief introduction of the Alcoa bracket, then it presents topology optimization approaches and methods. This chapter also presents a brief introduction of additive manufacturing technologies including the advantages and disadvantages. The chapter also introduces briefly the build orientation optimization. Another section discusses additive manufacturing deformations in order to understand the causes and possibility of controlling them. There is also a section discussing previous part compensation methodologies implemented in AM to identify gaps and to justify Artificial Neural Network as a better approach for this paper. Then the chapter closes with an overview of the Artificial Neural Network to counteract thermal deformations and a summary table of main literature reviewed.
- Chapter 3. Methodology. This chapter presents the methodology that has been developed in redesigning the Alcoa bracket by using the topology

optimization method, build orientation optimization, and the Artificial Neural Network methodology used to control thermal deformations.

- Chapter 4. Results and discussion. This chapter presents and discusses the results of the topology optimization process, build orientation results and the Artificial Neural Network results in counteracting thermal deformations.
- Chapter 5. Conclusion and recommendations. This chapter summarizes the main conclusions as well as achievements of the work undertaken in this research and suggests areas for future work.