THE INVESTIGATION OF MECHANICAL BEHAVIOR OF LIGHWEIGHT ALUMINIUM FOAM SANDWICH (AFS)

BY

NUR ASMAWIYAH BINTI IBRAHIM

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Kulliyyah of Engineering
International Islamic University Malaysia

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ABSTRACT

Demand and interest for the use of porous materials in various applications are rapidly growing by years. Several types of porous materials had been introduced in market todays and one of the well-known types is metal foam. Yet, metal foam itself is weak and to overcome the limitation, sandwich structure had been introduced which is aluminum foam sandwich (AFS). It has many advantages including excellent stiffness to weight ratio is, high energy absorption and most importantly lightweight. There is the need for lightweight material in structural parts for reducing used of energy and eventually reduce fuel consumption. The applications of AFS are automotive, aerospace, shipbuilding and architectural design industries. There were many researchers who had done an investigation on mechanical behavior of AFS. However, a few numbers did a research on open-cell aluminum foam and none of them identify the effect of skin to core thickness ratio, if any. Therefore, this research was conducted to identify the effect of skin to core thickness ratio on mechanical behavior of AFS when loaded under tension and three point bending experimentally with validation of simulation study. AFS specimens were made of open-cell aluminum foam as a core and attached with 6061-0 aluminum skin sheets using epoxy and hardener. Full factorial design of experiment (DOE) was used and repeated three times for each test. Three levels of skin thickness and three levels of core thickness had been used for tensile test. While for three-point bending test, DOE was developed using three levels of skin thickness and two levels of core thickness. Experimental results showed that by increasing skin to core thickness ratio, strength, force and deflection of AFS also increase for both tension and bending. Besides, results show that core thickness play an important role in effecting behavior of open-cell aluminum foam sandwich because of the percentage of porosity of the foam. Increasing foam thickness, will increase percentage of pore which will weaken the sandwich panels. Simulation study was conducted using LS-DYNA software and showed an agreement with experimental result of sandwich panel's deformation and force-displacement curve. Statistical analysis details show that both models of tensile and three-point test were significant and reliable with 'Prob > F' less than 0.05. The optimum skin to core ratio for tensile and three-point bending test were 0.1 and 0.12 respectively. Stiffness to weight ratio of AFS was increasing with higher core thickness. Lastly, stiffness of proposed porous material (open-cell foam) had better stiffness compared to other porous material with more than 40% higher stiffness.

خلاصة البحث

أثارت المواد المَسامِية الانتباه في السنوات الماضية وزادت نسبة طلبها عبر السنين مما أدى إلى ابتكار أنواع مختلفة منه وعرضها في السوق، أحد أشهر هذه الأنواع هي الرغوة المعدنية.جدير بالذكر أن الرغوة المعدنية في ذاتها ضعيفة، ولاجتياز هذا العَجز تم ادخال الهيكل المُسمّى بسندوتش رغوة الألومنيوم (aluminum foam sandwich). يتمتع هذا الهيكل بالكثير من المميزات كصلابته المناسبة لنسبة وزنه، و سُرعة امتصاصه للطاقة، والأهم من ذلك وزنه الخفيف. وجود هذا العنصر مُهم للتقليل من نسبة الطاقة المُستخدمة والحد من استهلاك النفط. يمكن تطبيق سندوتش رغوة الألومنيوم على التصاميم المعمارية الأرضية والجوية والبحرية.هناك العديد من الأبحاث التي أجريت على السلوك الميكانيكي لسندوتش رغوة الألومنيوم (AFS) ولكنَّ البحوث الخاصة بالخلايا المفتوحة لرغوة الألومنيوم تُعد نادرة جدًا، والقليل منها فقط من بَيَّن تأثير نسبة القشرة للنواة- إن وُجِد. لذلك، فإن هذه الدراسة قد أُجريت كي تُبيّن تأثير نسبة القشرة للنواة على السلوك الميكانيكي لسندوتش رغوة الألومنيوم عند تعرُّضه للضغط والثني ثُلاثي النقاط، كما تم التأكد من صحة النتائج بدراسة المُحاكاة. تم أخذ عيّنات من نواة لخلية مفتوحة لرغوة الألومنيوم مُعلقة ب 6061-0 شرائح لقشور الألومينيوم باستخدام الإيبوكسي. تم استخدام تصميم التجارب (DOE) كامل العوامل وإعادة التجربة ثلاث مرات لكل اختبار. كذلك تم استخدام ثلاث مستويات لسماكة القشرة وثلاث مستويات لسماكة النواة لاختبار الشد. أما بالنسبة لاختبار الثني ثُلاثي النقاط فقد تم استخدام ثلاث مستويات لسماكة القشرة ومستويَيْن لسماكة النواة.أظهرت النتائج أنه كلما زادت نسبة القشرة للنواة، كلما زاد إجهاد وقوة وإزاحة سندوتش رغوة الألومنيوم (AFS) لكلٍ من الضغط والثني. بجانب ذلك، أظهرت النتائج أن سُمك النواة يلعب دورًا مُهمًا في سلوك نواة الخلية المفتوحة لرغوة الألومنيوم بسبب النسبة المئوية لمسامية الرغوة، لذا فإن زيادة سُمك الرغوة، سيزيد من النسبة المئوية للمسامات والذي سيؤدي إلى إضعاف لوحات السندوتش.تم الاعتماد على برنامج ال.اس-دي واي ان إيه (LS-DYNA) لإجراء نموذج المُحاكاة، والذي دعمَت نتائجه التجربة العمليّة فيما يخص التغيير الشكلي للوحة الساندوتش ومُنحنى قوة الإزاحة. أظهرت النتائج الإحصائية أن كُلاً من اختبارَي الشد وثُلاثي النقاط موثوق ومُعتبر أخذًا في الاعتبار أن الاحتمالية أكبر من آف (Prob > F’) بنسبة تقل عن 0.05. كما أن المستوى الأمثل لكُلٍ من الاختبارَيْن هو 0.1 للشد، و 0.12 لثلاثي النُقاط و كلما زادت صلابة النواة كلما زادت نسبة الصلابة للوزن الخاصة بساندوتش رغوة الألومنيوم (AFS). وأخيرًا، فإن صلابة المواد المَسامِية المُقترحة (رغوة ذات خلية مفتوحة) كان لديها صلابة أفضل من المواد المَسامِية الآخرى التي تمتلك نسبة أعلى ب 40% من الصلابة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Manufacturing Engineering)

…………………………………..
Muataz Hazza Faizi Al Hazza
Supervisor

…………………………………..
Erry Yulian Triblas Adesta
Co-Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Manufacturing Engineering).

…………………………………..
Ahsan Ali Khan
Internal Examiner

…………………………………..
Mohd Amri Lajis
External Examiner

This thesis was submitted to the Department of Manufacturing and Materials Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Master of Science (Manufacturing Engineering).

…………………………………..
Mohamad Abd. Rahman
Head, Department of Manufacturing and Materials Engineering

This thesis was submitted to the Kulliyyah of Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Manufacturing Engineering).

…………………………………..
Erry Yulian Triblas Adesta
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Nur Asmawiyah binti Ibrahim

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Last but not least, I dedicate this writing to my late father, Allahyarham Haji. Ibrahim Mamat. May Allah S.W.T grant him happiness and Jannah. Amin.

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LIST OF ABBREVIATIONS

3D	Three Dimensional
3PB	Three Point Bending
AFS	Aluminium Foam Sandwich
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
EDM	Electric Discharge Machining
EDS	Energy Dispersive X-ray Spectroscopy
EXD	Energy Dispersive
FEA	Finite Element Analysis
JMP	JUMP Statistical Analysis Software
Kfile	Text files and can be open in any text editor
LS-DYNA	Livermore Software Finite Element Program
LS-Prepost	Livermore Software for Preprocessing and Post processing
OM	Optical Microscope
SEM	Scanning Electron Microscope
STW	Stiffness to weight ratio

LIST OF SYMBOLS

l	Length of sandwich beam (mm)
b	Width of sandwich beam (mm)
s	Support length (mm)
t	Skin thickness (mm)
c	Core thickness (mm)
F	Force (N)
d	Displacement (mm)
ρ	Density (kg/m^3)
W	Weight (kgf)
m	Mass (kg)
g	Gravity (mm/s^2)
ρ_f	Foam density (kg/m^3)
ρ_{fo}	Foam base material density (kg/m^3)
mm	Millimeter
mm/min	Millimeter per minutes
N	Newton
MPa	Mega pascal
E	Young’s modulus
E_{fo}	Young’s modulus of foam base material
PR	Poisson’s ratio
α, β	Dimensionless constants
γ	Kinematic hardening parameter
ε_D	Densification strain
$C_1, C_2,$ n	Material constants
σ_p	Density stress

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Demand and interest for the use of porous materials in various applications are rapidly growing by years. Porous material is a material containing pores and struts. Several types of porous materials had been introduced in market today such as foams, honeycomb and balsa wood. At the beginning of production of foam material, polymer-based foam had been introduced. However, polymer had limitation in heat resistant (Styles, Compston & Kalyanasundaram, 2005). Besides, there is an increasing in the amount of waste as increasing the used of polymer foam in shipbuilding industries (Crupi, Epasto, & Guglielmino, 2013). Thus, metal foam was developed and one of the famous metals foams with many industries applications is aluminum foam. Metal foam is also easier to recycle compared to polymer foam (Banhart, Schmoll & Neumann, 1998).

There are two categories of aluminum foam which is open-cell foam and closed-cell foam. Figure 1.1 below shows the different structure and porosity of both foam cell types.

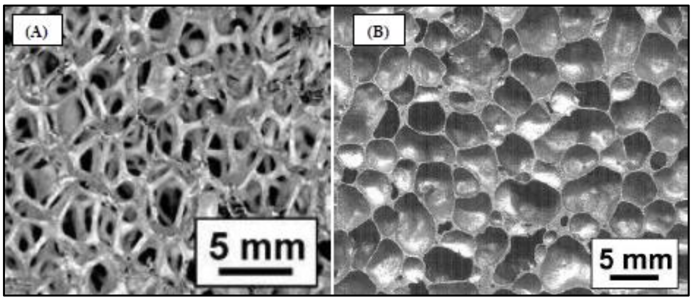

Figure 1.1 a) open-cell foam, b) closed-cell foam (Veale, 2010)

Open-cell metal foam had many advantages compared to closed-cell such as high interconnectivity, high moisture absorption and chemical leached. Closed-cell metal foam had disadvantage in term of closed-cell may contain undesired chemical. Aluminum foam can be different based material such as aluminum 6061 which produce by Banhart, Schmoll and Neumann (1998). They used powder metallurgical technology by using metal powder and foaming agent of TiH_2. Yet aluminum foam itself is weak, thus aluminum foam sandwich (AFS) were produced which consist of foam as core and thin solid material as upper and lower skin (Banhart, Schmoll & Neumann, 1998).

There were many advantages of sandwich panels with metallic foam cores. Crupi and Montanini (2007) stated that the properties of AFS was high energy dissipation, low specific weight, high damping, thermal insulation, and high strength impact. According to Banhart, Schmoll and Neumann (1998), the porous materials had grown in various application because of its excellent physical properties. This also supported by Styles, Compston & Kalyanasundaram (2005) who reported that metal foam has high impact energy absorption, good strength and stiffness to weight, electromagnetic wave absorption, good sound damping, non-combustibility and thermal insulation.

AFS geometries and physical properties can be varied according to each purpose such as core thickness, foam density, cellular morphology and face thickness (Crupi &

Montanini, 2007). Sandwich panels can be failing with different failure or collapse mode depending on their geometries, physical and mechanical properties. Li, Zheng, Yu, Qian and Lu (2014) mentioned that the possible failure modes of sandwich beams are core yielding and shear, face wrinkling and yielding and indentation. This is also supported by Crupi and Montanini, (2007) which stated that failure mode for bending can be face wrinkling, face yielding, indentation and core shear.

Nowadays, production in automotive industries are rapidly increased year by year. It is important for the industries to minimize the production cost but have high quality of product. Besides that, it is also important to have a product with longer life and durability. One of the essential parts of automotive industries that need to be enhanced and investigated in terms of weight, stiffness and energy absorption are the crash box. Crash box is the structural parts that placed behind the bumper of the vehicles. It is important for the crash box to have high energy absorption to withstand the impact during crash and lightweight to reduce the weight of the vehicle. Figure 1.2 below shows the sample of crash box.

Figure 1.2 Bumper with crash box (Belingardi, Beyene, Koricho & Martorana, 2015)

It is also stated by Banhart, Schmoll and Neumann (1998), the conventional steel used to make seat wall in car was replaced with sandwich panels and the results show that seat wall became lighter and ten times stiffer than conventional part. They also mentioned that, it is important to reduce the weight of parts for reducing the consumption of fuel and increasing the safety of passenger. The other well-known applications of sandwich panels were in shipbuilding, aerospace and architectural design.

Previously, there are several methods and techniques have been done by the previous researchers to identify mechanical behavior of the aluminum foam sandwich such as drop test (He et. al, 2016), quasi test (Jung, Pullen, & Proud, 2016), four-point bending test (An et. al, 2015) and impact test (Ismail et. al, 2015). All testing methods must be done by following the standard of ASTM and ISO standard. Although there were several reports on identifying mechanical behavior of sandwich structure, research of effect of skin to core ratio on sandwich structure has not been reported yet especially for sandwich panel with open-cell core, if any. In this study, a series of mechanical testing is proposed to investigate the effect of skin to core ratio on AFS using two approach of study which is experimental and simulation.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

The requirement of producing complex parts with advanced material properties and lighter weight are generally needed nowadays especially in structural parts in aerospace, automotive and marine industries. The parts were usually made by heavy and expensive material. To overcome the problem, researchers had generated a new technology of lightweight material which is aluminum foam sandwich. Shunmugasamy and Mansoor (2018) stated that AFS have been used as energy absorbers, acoustic dampers and weight saving members in automotive and aerospace structures. Besides, Crupi and Montanini (2007) mentioned that the aluminum foam sandwich has a lightweight structure with good dissipation of energy under impact and high mechanical strength. By reducing the weight of structural parts, energy consumption also will reduce which will lead to lessen oil consumption.

Although, many researches had been done by experimentally to investigate the mechanical behavior of aluminum foam sandwich but there is still a gap need to be fill, solve, and complete. This can be supported by An et. al (2018) who stated that many scholars have devoted time and energy to improve the mechanical properties of aluminum foams for a preferable application. Lehmhus, Busse, Chen, Bomas and Zoch (2008) also mentioned that there are still lacking on reliable data of mechanical performance of AFS. Besides, Nesic et al., (2012) stated data of material behavior from shear, bending and tensile were needed for contributing better understanding and general description on various types of foams. The data develop also can be used as metal foam design guidelines for future use. Other than that, there also a gap needs to be fill in term of parameters variation, and method of testing to develop a new reliable data as mentioned by Luna, Barari, Woolley and Goodall, (2014).

There are two types of foam available in the market which are open-cell and closed-cell foam. However, most of past researchers were focusing on determine behavior of closed-cell foam while least of them discuss on open-cell foam. None of them investigate skin to core ratio effect on mechanical behavior of open-cell aluminum foam sandwich.

Therefore, this research was conducted to compile new reliable data of mechanical behavior of open-cell aluminum foam sandwich in term of ultimate stress, force-displacement curve when loaded under tension and bending. Effect of skin to core ratio on mechanical behavior of AFS were determined experimentally and validate using simulation study. Furthermore, the research was continued by calculating the stiffness to weight ratio and strength to weight ratio for proving the lightweight of sandwich structure with foam as a core.

1.3 RESEARCH OBJECIVES

The objectives of the research are:

1. To investigate the effect of skin to core ratio on mechanical behavior and failure modes of aluminium foam sandwich using bending and tensile test.
2. To analyze lightweight properties of open-cell aluminium foam sandwich using stiffness to weight ratio through bending test.
3. To determine optimum values of core to skin ratio that maximize stress and force using desirability function methods.

1.4 RESEARCH METHODOLOGY

The proposed steps for completing this research will be divided into four categories which is fabrication method, experimental work, simulation modelling, data analysis and optimization. The fabrication of the sample was using adhesive bonding which consist of mixing epoxy resin and hardener. The samples were cut into desired shape following ASTM standard using electric discharge machine (wire cut). There are two types of mechanical testing conducted on samples which are tensile and three-point bending test. To validate the experimental results, simulation was run and material model were developed according to experimental work and previous research. The results were analyze based on stiffness to weight ratio, force-displacement curve and failure modes of sandwich beams. Lastly, ANOVA, scatter diagram, 3D plot surface