



## **Faculty of Manufacturing Engineering**

# **STAB RESISTANT ANALYSIS FOR BODY ARMOUR DESIGN FEATURES MANUFACTURED VIA FUSED DEPOSITION MODELING PROCESS**

**Chong See Ying**

**Master of Science in Manufacturing Engineering**

**2018**

**STAB RESISTANT ANALYSIS FOR BODY ARMOUR DESIGN FEATURES  
MANUFACTURED VIA FUSED DEPOSITION MODELING PROCESS**

**CHONG SEE YING**

**A thesis submitted  
in the fulfilment of the requirements for the degree of Master of Science  
in Manufacturing Engineering**

**Faculty of Manufacturing Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2018**

## **DECLARATION**

I declare that this thesis entitled "Stab Resistant Analysis for Body Armour Design Features Manufactured via Fused Deposition Modeling Process" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : .....

Name : .....

Date : .....

## APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.

Signature : .....

Supervisor Name : .....

Date : .....

## **DEDICATION**

To my beloved parents and family members

## ABSTRACT

Stab resistant body armour is a type of protective equipment worn to prevent from sustaining severe injuries caused by the sharp weapons. Despite many efforts have been devoted to enhance the protection and manoeuvrability of the body armour, current protective solutions continue to present a number of issues which has shown to affect the work performance of the wearers. Yet the application of additive manufacturing (AM) technology has potentially presented as an alternative solution to produce light weight body armour that able to provide adequate protection and performance characteristics due to the nature of AM build process. This research therefore attempted to investigate the feasibility to manufacture five designs of imbricate scale armour features for stab resistant application via Fused Deposition Modeling (FDM) process in order to meet the requirement of the knife resistance (KR) level one of the current HOSDB stab-resistant body armour standard with impact energy of 24 Joules. To do this, knife blades were fabricated in accordance with the international standard and securely installed to the Instron CEAST 9340 Drop Impact Tower which used to impact test on the test specimens. The test specimens were manufactured via Stratasys Fortus 400mc machine using two of the basis FDM filament materials including ABS-M30 and PC-ABS for a light weight stab resistant body protective armour. Prior to the experimental stab test, a preliminary study was performed via ANSYS which is a finite element analysis software to analyse stab resistance performance of these materials. Then, stab experimental test was conducted on both of the materials measured thickness ranging from 4.0 mm to 6.0 mm to ensure a proper material selection for stab resistance. By using the selected material, stab test was further conducted on the specimens measured thickness ranging from 7.0 mm to 10.0 mm to determine a minimum thickness resulted with a knife penetration through the underside which did not exceed the maximum penetration permissibility of 7.0 mm, as defined within HOSDB KR1-E1. The minimum thickness was then used to develop a series of designs incorporated with different imbricate scale-like features and stab tested to analyse their stab-resistant performance. Finally, one of the design which offered the highest knife penetration resistance was selected. Result obtained in the finite element analysis demonstrated the total deformation distributed in most of the PC-ABS specimens was lower than ABS-M30. This was also demonstrated in the stab experimental test of PC-ABS specimens which showed less shattering cases and lower overall knife penetration depth in comparison with ABS-M30. By using PC-ABS, further stab test demonstrated a minimum thickness of 8.0 mm can be used for the development of FDM-manufactured body armour design features. Lastly, the design feature of D5 has shown to exhibit the highest resistance to the knife penetration due to the penetration depth of 3.02 mm occurred in it was the lowest compared to other design features.

## ABSTRAK

*Perisai tubuh tahan tusukan adalah sejenis alat pelindungan yang dipakai bagi mencegah dari tusukan yang disebabkan oleh senjata tajam. Walaupun banyak usaha telah ditumpukan untuk meningkatkan perlindungan dan kebolehlengkapan perisai tubuh, perlindungan perisai tubuh semasa terus memberikan beberapa isu yang membawa kesan kepada prestasi kerja para pemakai. Namun demikian, aplikasi teknologi additive manufacturing (AM) berpotensi sebagai penyelesaian alternatif untuk menghasilkan perisai tubuh yang ringan dan dapat menyediakan ciri-ciri perlindungan dan prestasi yang mencukupi disebabkan oleh sifat proses pembuatannya. Oleh itu, penyelidikan ini menyiasat kebolehan proses Pemendapan Pemodelan Terlakur (FDM) untuk menghasilkan lima reka bentuk perisai tubuh bagi aplikasi tahan tusukan demi memenuhi keperluan HOSDB sebagai piawaian perlindungan perisai tubuh semasa dengan tenaga impak sebanyak 24 Joules pada tahap rintangan pisau (KR) yang pertama. Pisau-pisau telah disediakan dengan mematuhi piawaian tersebut dan dipasangkan pada mesin Instron CEAST 9340 untuk menjalankan eksperimen impak atas spesimen yang dihasilkan. Spesimen telah dihasilkan dengan mesin Stratasys Fortus 400mc dengan menggunakan dua bahan ABS-M30 dan PC-ABS bagi perisai pelindung tubuh badan yang ringan dan tahan tusukan. Kajian awal telah dijalankan melalui ANSYS yang merupakan perisian analisis unsur terhingga untuk melihat prestasi rintangan tusukan bahan-bahan tersebut sebelum menjalankan eksperimen menusuk. Seterusnya, eksperimen menusuk dijalankan pada kedua-dua bahan diukur dengan ketebalan 4.0 mm hingga 6.0 mm untuk memastikan pemilihan bahan yang sesuai. Dengan menggunakan bahan yang telah dipilih, eksperimen menusuk dijalankan pada spesimen yang diukur dengan ketebalan dari 7.0 mm hingga 10.0 mm untuk menentukan ketebalan minimum yang mengakibatkan penembusan pisau melalui bahagian bawah tidak melebihi kebenaran maksimum 7.0 mm, seperti ditakrifkan dalam HOSDB KR1-E1. Selepas itu, ketebalan minimum digunakan untuk menghasilkan beberapa ciri reka bentuk yang mengabungi ciri-ciri seperti skala imbricate dan diujikan untuk menganalisa prestasi tahan tusukan. Akhirnya, salah satu reka bentuk yang menawarkan rintangan penembusan pisau paling tinggi telah dipilih. Hasil yang diperolehi dalam analisa unsur terhingga menunjukkan jumlah deformasi terhasil pada kebanyakan spesimen PC-ABS adalah lebih rendah daripada ABS-M30. Hasil ini juga bersamaan dengan eksperimen menusuk bagi spesimen PC-ABS yang menunjukkan kes-kes pecah yang kurang dan kedalaman penetrasi keseluruhan yang lebih rendah berbanding dengan ABS-M30. Dengan menggunakan PC-ABS, eksperimen menusuk selanjutnya dengan ketebalan minimum 8.0 mm telah digunakan untuk pembangunan beberapa reka bentuk perisai tubuh. Akhir sekali, reka bentuk D5 telah menunjukkan rintangan tertinggi terhadap ancaman pisau disebabkan oleh kedalaman penembusan pisau yang berlaku di dalamnya iaitu 3.02 mm adalah paling rendah berbanding dengan ciri reka bentuk yang lain.*

## ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to express my deepest gratitude to my supervisor, Associate Professor Dr. Shajahan Bin Maidin who is one of the lecturer from the Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka (UTeM), for his essential supervision, patient guidance, support and encouragement upon the completion of this research.

I am very much thankful to Mr. Faizol and Mr. Mohd Faizal, the technicians from High Performance Testing Laboratory and Dynamic Laboratory of the Faculty of Mechanical Engineering and Mr. Hairudin and Mr. Fairol, the technician from Rapid Prototyping Laboratory and Advanced Manufacturing Centre, for their kind help and co-operation throughout my experimental test.

I would also like to extend my sincere thanks to the administration assistant, Mrs. Jamalindah binti Wahid and some other staffs from both Faculty of Manufacturing Engineering and Center of Graduate Studies for their patient guidance and assistance in processing some paper works and procedures related to this project.

My special thanks to UTeM for providing a high-quality learning platform and Zamalah scheme for the financial support during my research period.

Finally, my grateful thanks are extended to my dearest parents and family members for their love, support and concerns. Besides, it is also my privilege to thank my friends their constant encouragement throughout my research period.



## TABLE OF CONTENTS

	<b>PAGE</b>
<b>DECLARATION</b>	
<b>APPROVAL</b>	
<b>DEDICATION</b>	
<b>ABSTRACT</b>	<b>i</b>
<b>ABSTRAK</b>	<b>ii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>iii</b>
<b>TABLE OF CONTENTS</b>	<b>iv</b>
<b>LIST OF TABLES</b>	<b>vii</b>
<b>LIST OF FIGURES</b>	<b>viii</b>
<b>LIST OF APPENDICES</b>	<b>xiv</b>
<b>LIST OF ABBREVIATIONS AND SYMBOLS</b>	<b>xv</b>
<b>LIST OF PUBLICATIONS</b>	<b>xviii</b>
<b>CHAPTER</b>	
<b>1. INTRODUCTION</b>	<b>1</b>
1.1 Background	1
1.2 Problem Statement	3
1.3 Objectives	4
1.4 Scope of Research	4
1.5 Thesis Structure	5
<b>2. LITERATURE REVIEW</b>	<b>8</b>
2.1 Sharp Force Incident	8
2.1.1 Type of weapons	10
2.1.2 Injury Location	11
2.1.3 Principles of Stabbing and Protective Solutions	13
2.1.4 HOSDB Body Armour Test Standards	14
2.2 Overview of Armour	18
2.2.1 Biological Scale Armour	19
2.2.1.1 Placoid	21
2.2.1.2 Ganoid	22
2.2.1.3 Elasmoid	23
2.2.1.4 Osteoderms	26
2.2.1.5 Pangolin	28
2.2.1.6 Design Parameters of Scales	29
2.2.2 Historical Armour	33
2.2.2.1 Greek Armour	33
2.2.2.2 Roman Armour	34
2.2.2.3 Chainmail Armour	38
2.2.3 Modern Body Armour	40
2.2.4 Next-Generation Body Armour	44
2.2.4.1 Liquid-Based Armour	45
2.2.4.2 Bio-inspired Materials and Structures	48
2.2.5 Patent Review	50
2.2.5.1 Fabric-Based Armour	50
2.2.5.2 Rigid Armour	52

2.2.5.3	Scale-based Armour	54
2.3	Additive Manufacturing	57
2.3.1	Generic Process of Additive Manufacturing	58
2.3.2	Advantages and Limitations of AM Implementations	60
2.4	Additive Manufacturing Processes	62
2.4.1	Stereolithography Apparatus	63
2.4.2	Selective Laser Sintering	65
2.4.3	3D Printing	66
2.4.4	Fused Deposition Modeling	68
2.5	Additive Manufactured Textiles	69
2.6	FDM Materials and Enhancement Processes	73
2.6.1	FDM Process Parameters	73
2.6.2	Design Considerations for FDM	77
2.7	Finite Element Analysis Software – ANSYS	79
2.7.1	Explicit Dynamics	80
2.7.2	Steps in ANSYS	80
2.8	Summary	81
<b>3.</b>	<b>RESEARCH METHODOLOGY</b>	<b>86</b>
3.1	Overview Methodology	86
3.2	Preliminary Analysis	88
3.2.1	3D Modeling	89
3.2.2	Explicit Dynamics Analysis	91
3.2.3	Material Properties	92
3.2.4	Model Geometry	93
3.2.5	Boundary Conditions	95
3.3	Design and Preparation of Test Samples	96
3.3.1	Test Sample Geometry	96
3.3.2	Material Used	97
3.3.3	Creation of 3D Model	98
3.3.4	Manufacture of Test Samples	98
3.3.5	Build Parameters	100
3.3.6	Build Location	101
3.3.7	Build Operational Procedure	101
3.4	Stab Test Experimental Methodology	105
3.4.1	Drop Impact Test Tower	105
3.4.2	Backing Material	110
3.4.3	Test Knives	111
3.4.4	Test and Environmental Requirements	111
3.4.5	Recording Blade Penetration	113
3.4.6	Stab Experimental Procedure	114
3.5	Establishing Minimum Thickness for Stab Resistance	116
3.5.1	Experimental Methodology – Part A	116
3.5.1.1	Test Sample Geometry	117
3.5.1.2	Manufacture of Test Samples	117
3.5.1.3	Build Operational Procedure	117
3.5.1.4	Stab Experimental Test	118
3.5.1.5	Experimental Design for Stab Test	118
3.5.2	Experimental Methodology – Part B	119

3.5.2.1	Experimental Design for Stab Test	120
3.6	Design and Analysis	120
3.6.1	Design One	121
3.6.2	Design Two	125
3.6.3	Design Three	127
3.6.4	Design Four	129
3.6.5	Design Five	131
3.6.6	Experimental Methodology	133
3.6.6.1	Experimental Design for Stab Test	134
3.7	Summary	134
<b>4.</b>	<b>RESULT AND DISCUSSION</b>	<b>138</b>
4.1	Preliminary Test	138
4.1.1	Finite Element Analysis	139
4.1.2	Implication for Further Work	143
4.2	Establishing Minimum Thickness for Stab Resistance	144
4.2.1	Stab Resistance Performance of FDM Materials	145
4.2.2	Implication for Further Work	152
4.2.3	Minimum Thickness of FDM-printed Specimens	153
4.2.4	Implication for Further Work	155
4.3	Design and Analysis	156
4.4	Discussions	161
4.4.1	Comparison between Stab Resistance of FDM Materials	161
4.4.2	Minimum Thickness of FDM-printed Samples	162
4.4.3	Comparison between Design Features	164
4.5	Summary	166
<b>5.</b>	<b>CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH</b>	<b>168</b>
5.1	Conclusion	168
5.2	Recommendations for Future Research	171
	<b>REFERENCES</b>	<b>172</b>
	<b>APPENDICES</b>	<b>200</b>

## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Ballistic and Stab Resistant Body Armour Standards	15
2.2	Test Requirements of Knife Protection Level	16
2.3	Dermal Armours of Animals	83
3.1	Material Properties of Test Samples used in FEA	92
3.2	Model Geometries used in FEA	93
3.3	Build Parameters for ABS-M30 and PC-ABS Materials	100
3.4	Accessories of CEAST 9340 Drop Tower	107
3.5	Experimental Requirements of Stab Test at KR1-E1	113
3.6	Samples Order of Testing in Experiment - Part A	119
3.7	Test Sequence of PC-ABS Specimens in Experiment – Part B	120
3.8	Design Characteristic of Design One	123
3.9	Investigation of Assembly Angle at 10° - 20°	124
3.10	Test Sequence of Imbricate Scales Armour Samples	134
3.11	Comparisons of Five Different Design Features	136
4.1	Stab Test Result of ABS-M30 Test Specimens	145
4.2	Stab Test Result of PC-ABS Test Specimens	148
4.3	Knife Penetration Depth of PC-ABS Planar Specimens	153
4.4	Result Summary of the Stab Test of Sample Designs	156

## LIST OF FIGURES

<b>FIGURE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	US Law Enforcement Officers Killed in the Line of Duty 2006-2015	9
2.2	Various Accessible Knives	11
2.3	Mechanism of Knife Attack on Body Armour (a) Initial Penetration due to High Contact Loads, (b) Frictional Resistance to Continued Penetration, and (c) Resistance to Further Penetration	13
2.4	Examples of Stab Test Drop Towers (a) Guide-rail Tower and (b) NIJ Drop Test Fixture	17
2.5	UK HOSDB Standardised Engineering Knife Blade	18
2.6	Protection Behaviour of (a) Ballistic Fabric and (b) Dense Stab Resistant Woven Fabric	19
2.7	Placoid Scales from a White Shark (a) Scanning Electron Micrograph (SEM), (b) Side View, and (c) Top View	21
2.8	Example of Ganoid Scales in (a) Alligator Gar and (b) Scale Structure	22
2.9	Example of (a) and (b) Cycloid Scales, (c) and (d) Ctenoid Scales	24
2.10	Imbricate Scales of Arapaima Gigas	25
2.11	Example of (a) Armadillo and (b) Scales of Armadillo	27

2.12	An Illustration of (a) Osteoderms in Alligator and (b) Leatherback turtle	28
2.13	Example of (a) Pangolin and (b) Scales of Pangolin	29
2.14	Geometric Parameters of a Scale Assembly	30
2.15	Fish Scale Samples featuring Different Degree of Overlap and Overlapping Angle (a) Three Dimensional View and (b) Side View obtained from Digital Image Correlation (DIC) Camera	31
2.16	Dimensions of Scales with their Aspect Ratio	32
2.17	Example of (a) Bell Muscular Cuirass and (b) Reconstruction of Linen Cuirass	33
2.18	Roman <i>Lorica Squamata</i> Fragment	35
2.19	Example of <i>Lorica Plumata</i>	36
2.20	Example of (a) Roman Mail Shirt and (b) Fragment of Ancient <i>Lorica Hamata</i>	37
2.21	Example of (a) Reconstructed Roman <i>Lorica Segmentata</i> and (b) Its Inner Structure	38
2.22	Example of European Chainmail Armour	39
2.23	Example of (a) Explosive Ordnance Disposal (EOD) Suits and (b) Bullet Resistant Vest	41
2.24	Scanning electron micrographs (SEM) of (a) neat Kevlar, (b) Polyethylene, (c) Coextruded-Surlyn and (d) Surlyn Impregnated Fabrics	42
2.25	Example of (a) Complete Dragon Skin Body Vest and (b) Its Inner Structure	44

2.26	Behaviours of Particle Suspensions with Increasing Shear Rate	46
2.27	Behaviour of MR Fluid (a) Without Magnetic Field and (b) With Magnetic Field	48
2.28	Imbricated Hybrid Microstructures of Armour Provides a Balance between (a) Protection and (b) Flexibility	49
2.29	Example of (a) <i>Polypterus senegalus</i> and (b) Bio-Inspired Multi-Material Assembly	49
2.30	Protective Garment implemented (a) Multiple Components and (b) Inner Honeycomb Structure	51
2.31	Body Armour with Hard Spheres Mounted to Flexible Membrane (a) Before and (b) After Assaulted an Impact	52
2.32	Illustration of (a) A Flexible and Lightweight Compound Body Armour and (b) Mechanism of Protection against an Impact	53
2.33	Example of (a) Armour featuring Prismatic Tessellated Core and (b) Exploded View of the Armour Structure	53
2.34	Periodic Cellular Materials Comprise (a) Honeycomb and Corrugated Structure and (b) Lattice Structure made from Trusses	54
2.35	Example of (a) Flexible Armour featuring Disc-Shaped Plates and (b) Mechanism of Protection against an Impact	55
2.36	Example of (a) Protective Armour with Articulated Discs and (b) Its Inner Structure	56
2.37	Construction of (a) Flexlock Non-Textile Fabric and (b) Each Mating Element	56
2.38	AM Generic Process	59

2.39	Mechanism Diagram of Stereolithography	63
2.40	Schematic Diagram of SLS Process	65
2.41	Schematic diagram of 3D Printing Technology	67
2.42	Illustration showing the FDM Process	68
2.43	3D Conformal Additive Manufactured Textile Garment (a) Front and (b) Back View	70
2.44	Additive Manufactured Garment (a), (b) and (c) with Different Complicated Contours	71
2.45	Design Feature of Articulated Textile	72
2.46	(a) Build Orientation and (b) Tool Path Parameters	74
2.47	Example of (a) Cantilever Snap Fit Built in (b) Horizontal and (c) Vertical Directions	75
3.1	Flowchart of Research Methodology	87
3.2	Step of 3D Solid Model Creation	89
3.3	Stab Impact Loading of (a) Planar and (b) Imbricate Samples	90
3.4	Procedure of FEA Using ANSYS Software	91
3.5	Impact location of Textile Models	95
3.6	ANSYS Meshing for Stab Test Assembly of (a) Planar and (b) Imbricate Samples	95
3.7	(a) Support Removal Tank Filled with (b) WaterWorks Soluble Concentrate Solution	97
3.8	Stratasys Fortus 400mc Machine	98
3.9	Build Platen	99
3.10	Support Structures of (a) Imbricated Armour and (b) Planar	104



	Samples	
3.11	Instron CEAST 9340 Drop Tower Impact System	106
3.12	Data Acquisition System	109
3.13	A Steel Tray Filled with Roma Plastilina® No.1 Modelling Clay	110
3.14	Engineered Knife Blades Used for the Drop Impact Testing	111
3.15	Method of Measuring Blade Penetration of (a) Planar and (b) Imbricated Armour Specimens	114
3.16	Design One	122
3.17	Design Two	126
3.18	Design Three	128
3.19	Design Four	130
3.20	Design Five	132
4.1	Total Deformation Distributed in (a) ABS-M30 and (b) PC-ABS	140
	Test Samples	
4.2	Comparison between Maximum Total Deformations of ABS-M30 and PC-ABS	141
4.3	Deformation Region in Model 2	142
4.4	Stab Test Result of (a) 4.0 mm and 5.0 mm ABS-M30 Test Specimens and (b) 5.00/3 Test Specimen from Bottom View	146
4.5	Stab Test Result of (a) 6.0 mm ABS-M30 Test Specimens and (b) 6.00/3 Test Specimen from Bottom View	147
4.6	Stab Test Result of (a) 4.00/1, (b) 4.00/2 and 4.00/3 PC-ABS Test Specimens	149
4.7	Deformation Region in Both 6.0 mm Thick (a) PC-ABS and	150

	(b) ABS-M30 Specimens	
4.8	Force/Displacement Traces	150
4.9	Energy Absorption by Specimens Measured 6.0 mm Thickness	152
4.10	Mean Knife Penetration Depth per Thickness Group of PC-ABS Planar Specimens	154
4.11	Stab Test Result of (a) 10.00/1 and (b) 10.00/3 Test Specimen	155
4.12	Comparison of Mean Knife Penetration Depth of the Design Features	157
4.13	Stab Test Result of (a) D2/2 Test Specimen and (b) Its Underside Surface Condition	158
4.14	(a) Stabbed Region of D3 Specimen and (b) Fracture Occurred in D3/3 Specimen	159
4.15	Stab Test Result of D5 Specimen from (a) Bottom and (b) Side View	160
4.16	Stab Test Result of D4 Specimen from (a) Top and (b) Bottom View	160

## LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	HOSDB P1/B Blade Technical Drawing	200
B	Patents of Fabric-based Armours	201
C	Patents of Rigid Armours	203
D	Patents of Scale-based Armours	206
E	Material Data Sheet of ABS-M30	208
F	Material Data Sheet of PC-ABS	210
G	Sample of data generated from CEAST 9340 Drop Tower	212

## LIST OF ABBREVIATIONS AND SYMBOLS

$\theta$	-	Angle of scale relative to the tissue
$\phi$	-	Scale volume fraction
3D	-	Three Dimensional
3DP	-	Three-dimensional printing
ABS	-	Acrylonitrile Butadiene Styrene
AM	-	Additive manufacturing
ASTM	-	American Society for Testing and Materials
CAD	-	Computer aided design
CMB	-	Chromeleon backup archive
CO <sub>2</sub>	-	Carbon dioxide
d	-	Exposed scale length
D	-	Design
DAS	-	Data acquisition and analysis
E	-	Stab impact energy
$E_{ab}$	-	Energy absorption
EOD	-	Explosive ordnance disposal
FEA	-	Finite element analysis
FDM	-	Fused deposition modeling
g	-	Gravity = 9.81 m/s

HOSDB	-	Home Office Scientific Development Branch
h	-	Drop height
IGES	-	Initial graphics exchange specification
$K_d$	-	Degree of scale overlap
KE	-	Kinetic energy
KR	-	Knife-resistance
$L_s$	-	Total scale length
LS	-	Laser Sintering
m	-	Drop vehicle mass
MR	-	Magneto-rheological
MIT	-	Massachusetts Institute of Technology
NIJ	-	National Institute of Justice
PA	-	Polyamide
PC	-	Polycarbonate
PC-ABS	-	Polycarbonate-ABS
PE	-	Potential energy
PEEK	-	Polyetherketones
PLA	-	Poly lactide
PP	-	Polypropylene
PPSF/PPSU	-	Polyphenylsulfone
$R_a$	-	Scale aspect ratio
SLA	-	Stereolithography apparatus
SLS	-	Selective laser sintering
STF	-	Shear thickening fluid
STL	-	Stereolithography

$t_s$	-	Individual scale thickness
$t_d$	-	Scale-scale distance
UK	-	United Kingdom
US	-	United State
$v$	-	Drop velocity
$v_i$	-	Initial velocity
$v_f$	-	Final velocity

## LIST OF PUBLICATIONS

Maidin S. and Seeying C., 2016. Finite Element Analysis of Additive Manufactured Textile for Stab Resistant Application. *ARPJ Journal of Engineering and Applied Sciences*, 11(3), pp.1529-1535.

Maidin, S. and Seeying, C., 2015. Design and Analysis of Fused Deposition Modeling Textile Geometrical Features for Stab Resistant Application. *Jurnal Teknologi*, 77(32), pp.151-160.

# CHAPTER 1

## INTRODUCTION

This chapter introduces a general idea of the research by outlining the background, problem statement, objectives and scope of the study. This chapter also describes the thesis structure that briefly explain on the contents and purposes of each chapter. From these contexts, the entire overview of the project can be clearly seen.

### 1.1 Background

Body armour has been used for centuries to protect wearers against life threatening injuries during combat or other hazardous incidents (Ashcroft et al., 2001). Existing body armour are majority designed to resist handgun, rifle and ammunition threats with very little protection against low-speed stabs of piercing and cutting weapons (Levinsky et al., 2012). Despite direct applicable scientific work exists on stab resistant armour was relatively less when compared to the ballistic armour, the recent increasing number of stab assaults have led to an increase in the number of applications for body armour with stab protection (Horsfall, 2000; Decker et al., 2007). Stab resistant body armour has been increasingly used by the law enforcement and corrections officers in European and Asian countries where more likely involve violent knife crimes due to tight restrictions on gun ownership (Decker et al., 2007; Hilal et al., 2014). Traditionally, protective body armour are made of metal plates or ceramics which are heavy, inflexible, cumbersome, and uncomfortable to wear (Gong et al., 2014). In an effort to reduce these limitations, manufacture of stab resistant body armour