UNIVERSITI TEKNIKAL MALAYSIA MELAKA

## Faculty of Manufacturing Engineering

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

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**Master of Science in Manufacturing Engineering**

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

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

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**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.

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# 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 eskperimen 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, eskperimen 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, eskperimen 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, eskperimen 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.*

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## LIST OF ABBREVIATIONS AND SYMBOLS

| | | |
|---|---|---|
| θ | - | Angle of scale relative to the tissue |
| ϕ | - | 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 |
| $CO_2$ | - | 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 | - | Polylactide |
| PP | - | Polypropylene |
| PPSF/PPSU | - | Polyphenylsulfone |
| $R_a$ | - | Scale aspect ratio |
| SLA | - | Stereolithography apparatus |
| SLS | - | Selective laser sintering |
| STF | - | Shear thickening fluid |
| STL | - | Stereolithrography |

| | | |
|---|---|---|
| $t_s$ | - | 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. *ARPN 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