Establishing the performance requirements for stab resistant Additive Manufactured Body Armour (AMBA)

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Abstract

Body armour is worn to lessen the likelihood of sustaining a life threatening injury. Such protective solutions are used every day by law enforcement officers around the world, with strict guidelines governing their design and testing. These activities are monitored by government departments such as the Home Office Scientific Development Branch (HOSDB) within the United Kingdom (UK), and the National Institute of Justice (NIJ) within the United States.

Despite providing protection against significant levels of impact energy, a number of historical issues continue to be present with modern fibre-based soft body armour – which once addressed may demonstrate an enhancement wearer operational performance.

This paper therefore presents research highlighting such issues, and demonstrates how Additive Manufacturing (AM) technologies, particularly Laser Sintering (LS), could potentially be used to address such operational concerns whilst providing protection against a real-world threat.

Results documented within this paper demonstrate that 5.6 mm thick planar samples, Laser Sintered from a 50/50 mix of virgin and recycled PA 2200 successfully achieved penetration resistance to the UK HOSDB KR1 impact energy of 24 joules. These results therefore influenced the design, manufacture, and testing of a series of AM textile samples featuring an imbricated layout, which also demonstrated successful knife penetration resistance to the HOSDB KR1 level – thus developing stab resistant Additive Manufactured Body Armour (AMBA).

Introduction

Within the United Kingdom (UK) there are in excess of 144,000 police officers [1], and a further 765,000 sworn law enforcement officers within the United States (US) [2] – an occupation significantly at risk of encountering an assault within the workplace [3]. As part of their personal protective equipment, police officers are issued with body armour – the level of protection may vary depending on operational duties [4–6]. Body armour worn by these professionals can provide protection against a multitude of threats ranging from high-velocity ballistics to blunt-force and bladed artifacts, and are intended to lessen the likelihood of sustaining a life threatening injury as a result of a major incident [7,8]. Such armour can typically be placed into two categories [9–11]:

- Hard body armour – traditionally consisting of heavy ceramic plates encapsulated within a fabric carrier which fastens around its wearer, often used in military environments

- Soft body armour - typically manufactured from aramid-based fibres such as Kevlar™, where flexible armour panels are inserted into a fabric carrier, and are commonly used by the police. An example of which is shown in Figure 1.

Figure 1 – Soft Body Armour Example: Stab-Resistant Duty Vest carrier (L) and aramid-based insert (R)
Courtesy of Keltic Clothing [12]

One of the major risks facing police officers is that of sustaining a sharp force injury as a result of a bladed threat [5,13]. Soft stab resistant body armour worn by these individuals must adhere to strict performance and test requirements. These are defined in a series of closely related standards from the following UK and US government departments:

- UK: Home Office Scientific Development Branch (HOSDB) - Publication 39/07 [14]
- US: National Institute of Justice (NIJ) - Body Armour Standard 0110.01 [6]

Both HOSDB and NIJ standards aim to consider the various factors which can affect the severity of a sharp force incident, by defining the use of a standardised test procedure, drop-test impact rig, and standardised engineered blades. Additionally, these standards document the three levels of protection principle for the development of stab resistant body armour [14]:

- Knife Resistance Level One (KR1) – Armour for low risk patrolling environments which offer periods of maximum wear
- Knife Resistance Level Two (KR2) – General duty body armour providing a medium level of protection
- Knife Resistance Level Three (KR3) – Body armour providing a high level of protection, typically worn for short periods in high-risk situations

A breakdown of these test energies and over-test conditions for each protection level, as defined by the HOSDB and NIJ, are documented within Table 1.

Table 1 - HOSDB and NIJ Stab Impact Energy Protection Levels [6,14]

Energy Level		Strike Energy (J)	Velocity (ms^{-1})	Total Drop Vehicle Mass (kg)	Maximum Penetration (mm)
KR1	**E1**	24 +/- 0.5	5.0 +/- 0.05	1.9	7
	E2 - over test	36 +/- 0.6	6.2 +/- 0.05	1.9	20
KR2	**E1**	33 +/- 0.6	5.9 +/- 0.05	1.9	7
	E2 - over test	50 +/- 0.7	7.3 +/- 0.05	1.9	20
KR3	**E1**	43 +/- 0.6	6.7 +/- 0.05	1.9	7
	E2 - over test	65 +/- 0.8	8.3 +/- 0.05	1.9	20

Despite significant advances in technical fibre development and the implementation of HOSDB and NIJ standards, a number of historical issues continue to exist with many of the current protective solution. Such issues include:

- Restrictive and cumbersome use – impairing physical mobility [15,16]
- Poor fitting resulting in nerve and musculoskeletal injuries [15,16]
- Increased thermo-physiological loading, thus resulting in illness and reduced operational performance [17]

One area yet to be fully explored in an attempt to reduce such a burden on the wearer is that of Additive Manufacturing (AM). The unrivalled design freedom and ability to realise truly novel and highly complex functional assemblies via AM, specifically Laser Sintering (LS), may provide an opportunity to develop personalised Additive Manufactured Body Armour (AMBA) [18,19]. The utilisation of this technology may facilitate the incorporation of operational performance enhancing attributes which [16]:

- Maximise impact energy dissipation and freedom of movement
- Minimise impact deformation and penetration
- Provide enhanced fit and wearer comfort

However, to be considered as a viable solution, there is a need to assess the technical performance of AM body armour against existing body armour standards – beginning with the HOSDB and NIJ knife resistance standards previously documented.

Experimental Methodology

Four experiments were performed using a guide-rail drop test impact rig to the HOSDB KR1 impact energy of 24 joules (J). At this energy level, the maximum permissible penetration protruding through the underside of a test sample is 7.0 mm. All experiments used HOSDB specification ‘P1B’ engineered knives. To support the underside of each sample during testing, non-hardening, oil-based ‘Roma Plastilina® No. 1’ clay was used as backing material. The Plastilina backing material was packed into a 150 x 150 x 80 mm tray, open on its top face, and conditioned for three hours at a temperature of 35°C [8].

All test samples were manufactured from either 100% virgin or a 50/50 mix of virgin and recycled polyamide (PA 2200) supplied by EOS GmbH, and Laser Sintered using an EOS P100 Formiga system set to the following settings [8]:

- Layer thickness – 0.1 mm

- Build chamber temperature – 176.5°C
- Removal chamber temperature – 150°C
- Scan strategy – mechanic
- Contour laser power – 16W
- Contour scan power – 1,500 mms^{-1}
- Hatching laser power – 21W
- Hatching scan speed – 2,500 mms^{-1}

Two types of samples were tested across the four experiments. Experiments One to Three featured planar samples which were manufactured to the dimension of 80 x 80 mm. These samples were impacted tested to a centrally located strike zone identified on their top faces, as shown in Figure 2.

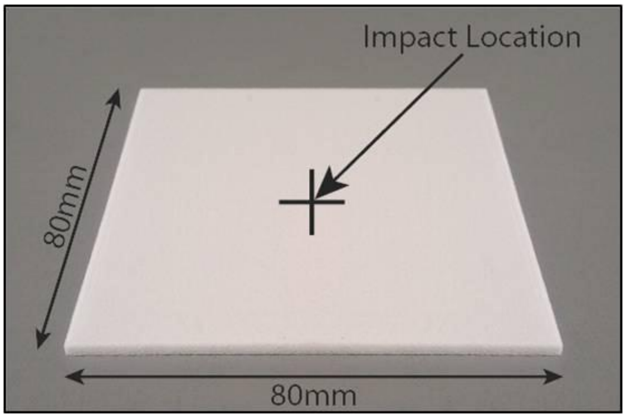

Figure 2 - Planar test sample highlighting the central impact zone

These samples ranged in thickness from 1-10 mm, with three samples tested at each thickness. An overview of these experiments is shown in Table 2.

Table 2 - Overview of Experiments One to Three

Sample Attribute	Experiment One	Experiment Two	Experiment Three
Design	Planar	Planar	Planar
Powder	100% virgin	50/50 virgin/recycled	50/50 virgin/recycled
Thickness Range	1-10 mm	1-10 mm	4.1-5.9 mm 5.1-5.9 mm
Thickness Increment	1.0 mm	1.0 mm	0.1 mm
Total Number of Samples	30	30	54

The results generated from the first three experiments were used to guide the generation of a series of novel articulated samples (AM textiles) which featured a scale link design within Experiment Four. These samples were manufactured via LS from a 50/50 mix of virgin and recycled PA 2200 to a dimension of 120 x 120 mm, and featured an individual scale thickness of 4.0 mm. Two strike zones were identified - directly on the top face of a centrally located scale, and in between two centrally located scales – as shown in Figure 3.

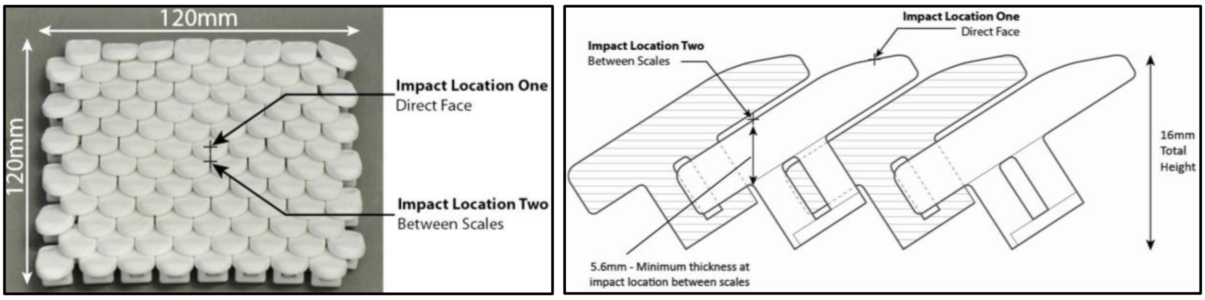

Figure 3 - Articulated test sample strike locations (L) and section view showing minimum material thickness (R)

The articulated samples featured a minimum material thickness of 5.6 mm in its thinnest region – as influenced by the planar sample test results from Experiments One - Three. The total height of the articulated samples when manufactured was 16 mm.

Experimental Results & Discussion

Experiment One

Test samples ranged from 1-10 mm thick in increments of 1.0 mm. This experiment demonstrated that when manufacturing samples from virgin PA 2200, a minimum sample thickness of 8.0 mm was required to consistently achieve an acceptable level of penetration resistance to the KR1 impact energy. Also noteworthy from this experiment is that 66% of the samples tested fractured into multiple pieces - as shown in Figure 4.

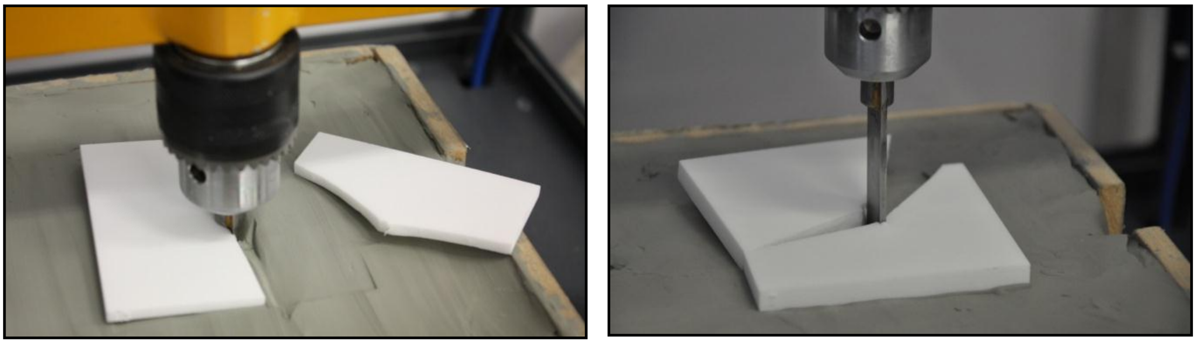

Figure 4 - Experiment One 4.3 mm (L) and 7.0 mm (R) thick virgin power shattered samples

In fact, 20 of the 21 samples tested prior to the 8.0 mm thick planar samples failed in this manner, thus prompting a further avenue of exploration – the use of a recycled and virgin mix of PA 2200.

Experiment Two

Samples were manufactured in thicknesses ranging from 1-10 mm in 1.0 mm increments using a 50/50 mix of virgin and recycled PA 2200. Impact testing demonstrated that a minimum sample thickness of 6.0 mm was required to consistently achieve penetration resistance below the 7.0 mm HOSDB KR1 permissible limit – as depicted in Figure 5.

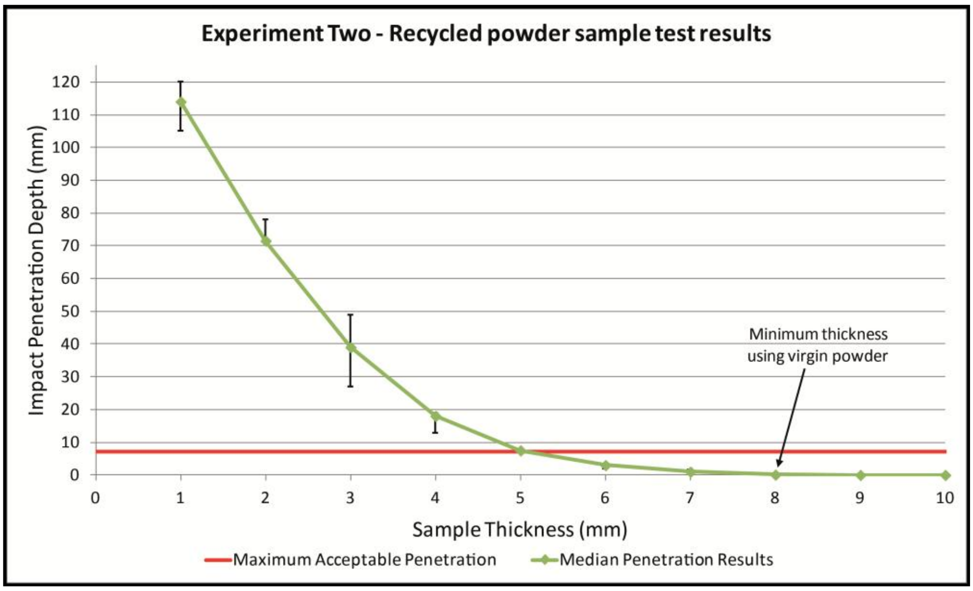

Figure 5 - Experiment Two recycled powder sample test results

Inconsistent penetration resistance within acceptable limits was also documented for 5.0 mm thick samples. This therefore prompted the need for further investigation of the impact penetration resistance of samples around 5-6 mm thick.

Experiment Three

Within this experiment samples manufactured from a 50/50 mix of virgin and recycled PA 2200 were tested. These ranged in thickness from 4.1-4.9 mm and 5.1-5.9 mm, increasing in 0.1 mm increments. The results from this experiment demonstrated that the 5.6 mm thick sample group were the first to consistently achieve penetration resistance within HOSDB and NIJ requirements for the KR1 impact energy of 24 J – as shown in Figure 6.

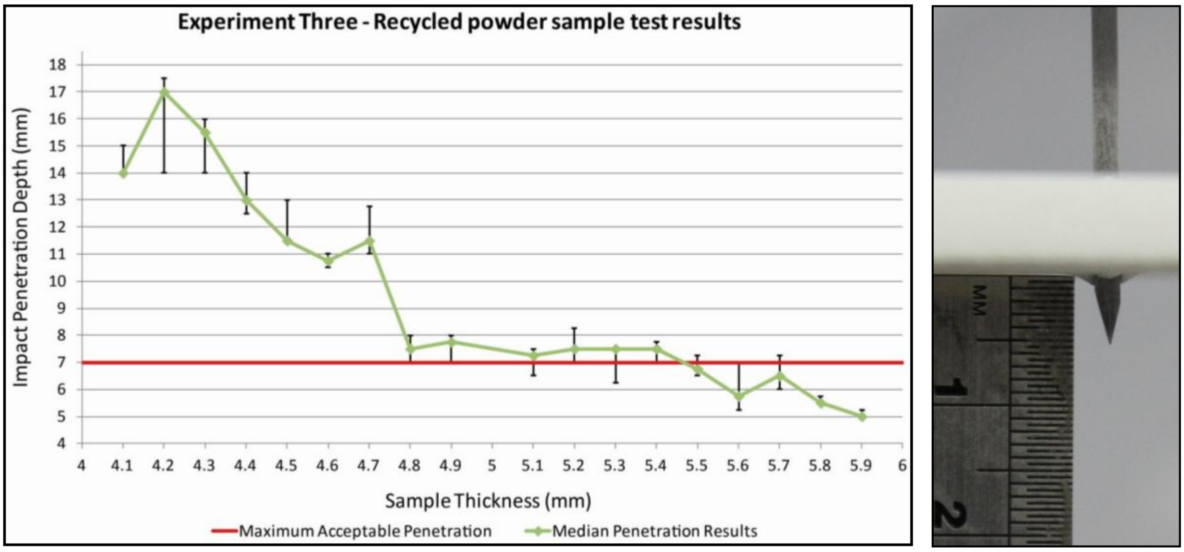

Figure 6 - Experiment Three Stab Test Results (L) and 5.6 mm thick planar sample (R)

Based on previous literature, the enhanced performance of 50/50 virgin and recycled PA 2200 mix samples may be attributed to an increase in the molecular weight due to the use of recycled powder. This powder had previously experienced temperatures in excess of

160ºC, causing the molecules to rearrange and pack more efficiently - thus increasing the tensile strength of the sintered parts [20]. Further investigation is required in order to verify whether this is the cause of enhanced penetration resistance.

Experiment Four

Results from the previous three experiments were used to drive the generation of a series of articulated AM textile samples, featuring a scale link based imbricated layout - manufactured from a 50/50 mix of virgin and recycled PA 2200. Samples were tested at both previously identified strike zones, with results demonstrating that all samples achieved penetration resistance within the acceptable limits as defined by the HOSDB and NIJ KR1 impact energy of 24 J. Impact testing of these samples is shown in Figure 7.

Figure 7 - Impacted articulated sample (L), maximum penetration demonstrated (M), and link failure (R)

Impacts directly on the top face of the scale links demonstrated no penetration, whilst a maximum knife penetration of 1.6 mm was experienced when the samples were stuck between a pair of scale links. This result was experienced on one test sample, and was likely due to a failure in the linkage mechanism. Due to the overlapping nature of the articulated samples, knife penetration was restricted and any failure within the design was contained within its structure.

Conclusions

Initial research into the feasibility of generating stab resistant AM textiles has successfully established a number of initial criteria that can be used to achieve stab resistance to the HOSDB KR1 impact energy of 24 J. Results from initial planar sample testing were used to design, manufacture, and test a number of articulated samples which demonstrated stab resistance significantly below the HOSDB and NIJ 7.0 mm permissible limit.

In addition to utilising AM technology to establish stab resistant requirements, the enhanced design and manufacturing freedom of AM solutions such as LS may now be used to begin investigating whether historical issues associated with wearing body armour could potentially be addressed. For example, using LS to develop AMBA solutions which reduce thermo-physiological loading on the wearer, or to generate individualised protective solutions.

To build on the initial results presented, research is now focused on establishing a series of additional criteria to enhance the performance of AMBA.

Further Work

Further work is being performed as part of PhD research within Loughborough University to investigate methods of enhancing the protective performance of stab resistant AMBA. A series of planar samples manufactured from PrimePart DC powder are currently being tested to the KR1 impact energy of 24 J to determine their knife resistance performance. Additionally, samples manufactured from the 50/50 mix of virgin and recycled PA 2200 are also being tested to the KR1 over-test impact energy of 36 J – where a maximum 20 mm penetration is permissible. It is anticipated that the results from this over-test condition will provide an indication as to the requirements to attain protection against the enhanced KR2 impact energy of 33 J, where the maximum permissible penetration is 7 mm - thus establishing a medium level of protection as defined by both the HOSDB and NIJ.

Research is also focused on using graphical generative algorithm solutions for the design and development of scale links that incorporate features to enhance strike energy dissipation and assembly flexibility, whilst minimising scale geometry – a number of examples of which are demonstrated in Figure 8.

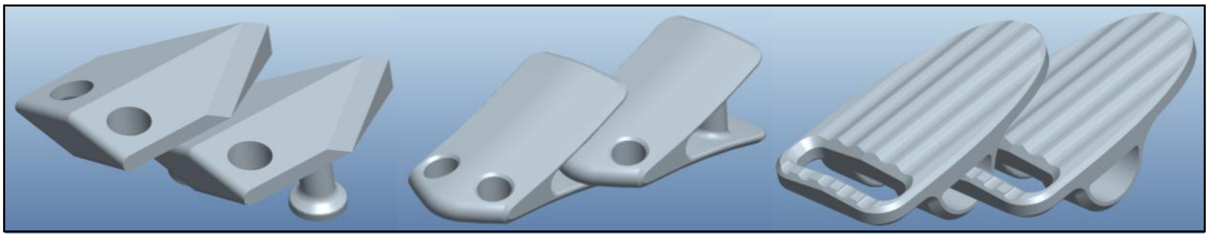

Figure 8 – Examples of scale design features

Features currently being explored in order to further enhance the protective performance of stab-resistant AMBA include:

- Investigating the cross-sectional design of the scale link
- Disturbing strike incidence through the incorporation of disruptive design features
- Enhancing the linkage mechanism between scales to encourage and maximise impact energy dissipation

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