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Laser sintered body armour – establishing single layer stab protection

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Laser sintered body armour – establishing single layer stab protection

Purpose:

The purpose of this research was to establish the minimum thickness required to provide stab protection in accordance with the United Kingdom Home Office Scientific Development Branch (HOSDB) standards while testing a series of Laser Sintered planar specimens using instrumented test apparatus.

Design/methodology/approach:

Planar test specimens were Laser Sintered in single layer thicknesses ranging from 1.00 to 15.00 mm in four material powder categories – Duraform® virgin; Duraform® 50/50 mix, Duraform EX® virgin; and Duraform EX® 50/50 mix. All specimens were tested using instrumented drop test apparatus and were impacted with established Stanley Tools 1992 trimming blades to the UK HOSDB KR1-E1 stab impact energy.

Findings:

The research demonstrated that a minimum single planar specimen thickness of 11.00 mm, manufactured from Duraform EX® 50/50 mix powder, was required to provide protection against the HOSDB KR1-E1 level of stab impact energy. The alternative powder mixes tested within this experiment demonstrated poor levels of stab protection – with virgin powder specimens demonstrating no protection up to 15.00 mm, while Duraform® 50/50 mix specimens demonstrating inconsistent performances.

Originality/Value:

This paper enhances on existing literature surrounding the manufacturing and testing of Additive Manufactured stab resistant armour by adding further rigor to the testing of such specimens. In addition this research establishes key foundation characteristics which could be utilised for the future development of bespoke next-generation body armour garments realised via Laser Sintering.

Keywords:

Laser Sintering; body armour; stab protection; 3D printed textiles; protective clothing

1. Introduction

The primary aim of any body armour garment is to minimise the likelihood of its wearer sustaining life threatening injuries (Ashdown 1909). Throughout history this aim has been achieved using a range of techniques including the use of animal hide, highly decorated cuirass assemblies, or more recently through the use of aramid fibre panels and Polycarbonate plates (Scott 2005; Ffoulkes 1909). Despite modern armour providing protection to stringent protective standards established by the United Kingdom Home Office Scientific Development Branch (HOSDB) (Croft & Longhurst 2007a; Croft & Longhurst 2007c), their fundamental design have been shown to hinder the operational manoeuvrability and thermal regulation of its wearer (Dempsey et al. 2013).

Additive manufacturing (AM) technologies are being utilised in an increasing number of novel applications - from customised wrist splints and industrial grade gripping solutions, to high performance stab resistant textiles manufactured via Laser Sintering (LS) (Paterson et al. 2015; SCHUNK GmbH & Co. 2015; Johnson et al. 2013). By utilising the inherent design freedom provided by such technologies, there is a growing opportunity to manufacture highly protective body armour that also begins to address historical concerns relating to wearer manoeuvrability and thermal comfort (Dempsey et al. 2013).

Previously published research has investigated the use of AM technologies for the manufacture of body armour, including the development of monolithic solutions via Laminated Object Manufacturing (LOM), bio-inspired and multi-layered AM armour, and the analysis of material extruded modelled stab resistant links (Klosterman et al. 1999; Rudykh et al. 2015; Johnson et al. 2015; Maidin & Seeying 2016). In addition, previous research has established that a minimum Laser Sintered single planar thickness of 8.00 mm was required to successfully provide stab protection within HOSDB guidelines - with specimens manufactured from Polyamide (PA) 2200 using a 50:50 mix of virgin and recycled powder. However, it should be noted that all experimental tests performed within this original proof-of-concept body of work used an in-house manufactured drop test impact rig and in-house manufactured HOSDB P1/B specification blades (Johnson et al. 2013).

More recently the stab performance of the HOSDB P1/B blade was assessed against the Stanley 1992 trimming blade – arguably a more credible real-world and readily available threat (Johnson 2014). Results from this recent investigation determined that when stab tested against HOSDB KR1 certified body armour specimens, the Stanley 1992 trimming blades demonstrated greater levels of blade penetration than the P1/B blades at the same impact energy of 24 Joules (Johnson 2014).

Whilst recognising the limitations experienced within the original outlined proof-of-concept research, this body of work advances knowledge relating to the stab resistant performance of single thickness planar specimens through the utilisation of established instrumented test apparatus. The primary objective of this experiment was therefore to assess the stab resistant performance of single thickness LS test specimens manufactured from two common polymer materials using both virgin and a commonly refreshed powder mixture, against the Stanley 1992 trimming blade.

2. Experimental methodology

2.1. Specimen materials

Two common PA based materials purchased from 3D Systems™ were used for the manufacture of test specimens:

- Duraform® (3D Systems 2013)
- Duraform EX® (3D Systems Corporation 2008)

Test specimens were manufactured from both 100% virgin, and a 50/50 mix of virgin and recycled powder using both Duraform® and Duraform EX® materials. In total four builds were performed using an EOS P100 Formiga LS machine:

- Group one: Virgin Duraform® powder
- Group two: 50/50 Duraform® powder
- Group three: Virgin Duraform EX® powder
- Group four: 50/50 Duraform EX® powder

The recycled constituents of the Duraform® and Duraform EX® powders were generated from any non-sintered powder from the build volume along with any pre-warmed powder within the build chamber and hopper system. Previous research has established that powder that has been used for less than 20 hours build time or 200 mm build height, is of good quality to be used in a refresh/recycled format (Dotchev & Yusoff 2009).

2.2. *Test specimen geometry*

The main body of each specimen measured 60 x 60 mm in length and width, and ranged in thickness from 1.00 to 15.00 mm in 1 mm increments. Three specimens were manufactured per thickness, with each featuring an identification tab. In total 45 test specimens were manufactured per material group, with 180 tested across this experiment overall.

2.3. *Test specimen manufacture*

All test specimens were manufactured by the Additive Manufacturing Research Group (AMRG) at Loughborough University using an EOS P100 Formiga LS machine, as shown within Figure 1.

Figure 1. EOS P100 Formiga Laser Sintering machine (A), Empty build chamber (B), LS build bed applied (C) & Powder tumbler (D)

2.4. *Build parameters*

Previously established processing parameters for each of the four material groups were used – these parameters have been optimised to ensure the successful manufacture of specimens for testing, and are outlined within Table 1 (Johnson 2014).

Table 1. Laser sintering process parameters

Table 1 highlights that a number of parameters, most notably part bed temperature and warm-up time were greater when using Duraform EX® powder. This was due to the material processing window for the Duraform EX® powder (Polyamide 11 based) being much smaller than that of the Duraform® powder (Polyamide 12 based), and was consequently more susceptible to changes in temperature (Goodridge et al. 2012). Therefore by increasing the temperature and pre-heating the machine and powder for a longer period, previous literature demonstrated that Polyamide 11based sintered parts were less prone to failure during the build process (Goodridge et al. 2012).

2.5. Build location and orientation

To minimise the likelihood of any potential performance effects as a result of part positioning within the build volume, the placement of each specimen was randomised across six positions on eight different layers - this is shown within Figure 2. In addition, the numbering scheme shown within Figure 2 designates the thickness of each specimen along with its sample number. For example, a designation on layer one of '6/1' indicates a specimen of 6 mm thick of which it is the first of three related to that particular thickness.

Figure 2. Experimental build layout

In line with established literature, test specimens were orientated to ensure the dimension for specimen thickness was perpendicular to the build platform, thus ensuring densities and fracture strengths were maximised (Caulfield et al. 2007; Gibson & Shi 2007). In addition, specimens were centered on the 200 x 250 mm build platform of the EOS P100 Formiga LS machine. A powder base layer of 3.00 mm was applied to the build platform during preparation, with an additional 2.00 mm of powder was applied during the warm up phase. A 5.00 mm spacing between each sample in X and Y-directions was maintained, while a 3.00 mm spacing between specimens in the Z-direction was established. To complete the build and to assist with controlled cooling, a 5.00 mm thick layer of powder was applied on top of the completed sintered parts – establishing a total build height of 99 mm.

2.6. Build procedure

A detailed operational procedure for preparing the CAD build files, the steps taken to initiate each LS build, and for the post-process of specimens to remove any residual powder were established (Johnson 2014).

2.7. Stab testing experimental design

Each stab tests used a virgin Stanley 1992 trimming blade. In total 180 specimens were tested across four material groups – with 45 tests per group. The order in which samples were tested was randomised to minimise the effects of any uncontrollable variables. Backing material trays were used for one test before being rotated – with the backing material being reformed between each test to ensure trays maintained thermal conditioning.

2.8. Stab test methodology

2.8.1. Drop tower apparatus

All stab tests were performed using an 'Instron 9250HV' instrumented drop tower, as shown within Figure 3.

Figure 3. Instron 9250HV drop tower

The total mass of the drop weight assembly, including blade chuck was calibrated at 6.50 kg. Velocity detecting apparatus was also used to validate the performance of each drop test and ensure the desired impact energy was reached.

2.8.2. Backing material

Roma Plastilina® No. 1 clay was used as the backing material for all tests, and was housed within a set of three steel fabricated trays – as shown within Figure 4.

Figure 4. Roma Plastilina® No. 1 clay backing tray

Prior to experimentation, each backing tray was thermally conditioned at 30°C for a period of three hours using an Alpha 190 H temperature chamber – in line with UK HOSDB body armour standards (Croft & Longhurst 2007b; Green 1978). During testing the backing trays were temporarily secured to the bed of the drop tower.

2.8.3. Test and environmental requirements

All drop tests were performed to the UK HOSDB KR1-E1 impact energy of 24 J, were performed in an ambient environment within a temperature range of 21°C +/-6, and a relative humidity range of 30-70% as defined by the HOSDB (Croft & Longhurst 2007c). The experimental test requirements used on the Instron 9250HV drop tower are outlined within Table 2.

Table 2. Stab test experimental requirements

Test specimens demonstrating no blade penetration through their underside, or a level of blade penetration at or below 7.00 mm is identified as providing a successful level of stab protection within the UK HOSDB standards.

2.8.4. Test blades

All tests performed within this body of work featured use of the Stanley Tools 1992 trimming blade – one of the most common utility blades currently available. A summary of the specification of the Stanley blade and view of the blade assembly is shown within Figure 5 and Figure 6 respectively.

Figure 5. Stanley Tools 1992 Trimming Blade Specification

Figure 6. Stanley 1992 Trimming Blade Assembly

Within Figure 6, the jig component was used to orientate the blade to ensure the double sided cutting edges of the blade contacted the strike surface of the test specimen.

2.8.5. Recording blade penetration

Blade penetration through the underside of test specimens were directly measured using digital callipers (Johnson 2014) – as demonstrated within Figure 7.

Figure 7. Measuring blade penetration

2.8.6. Detailed manufacturing and test procedures

Detailed procedures relating to the manufacture of all test specimens and operation of test apparatus were established. Further information relating to these can be found within PhD thesis – "Establishing design characteristics for the development of stab resistant Laser Sintered body armour" (Johnson 2014).

3. Experimental results

Results from this experiment are presented in the following sub-sections by material category.

3.1. Duraform® - Virgin

Specimens manufactured using virgin Duraform® powder in thicknesses ranging from 1.00 to 15.00 mm proved ineffective at providing stab protection against the Stanley 1992 trimming blade threat to the UK HOSDB KR1-E1 impact energy of 24 Joules. An overview of the measured blade penetration depths are presented within Table 3.

Table 3. Blade penetration depth of each material test group

As documented, 37 of the 45 samples manufactured across all thicknesses within the virgin Duraform® material group demonstrated the maximum 30 mm of blade penetration through the underside of the specimens. In 92% of these cases the test samples fractured or shattered, as shown within Figure 8.

Figure 8. Virgin Duraform® 2.00/3 test specimen

The eight positive results were found in specimens ranging in thickness from 8.00 to 15.00 mm, with no single thickness group demonstrating a consistent level of blade penetration resistance across all three test specimens. Of the positive results, only four demonstrated stab penetration resistance where the test sample did not fracture or shatter, while the remaining four specimens shattered – as demonstrated in Figure 9.

Figure 9. Virgin Duraform® 8.00/3 specimen (left) and 10.00/1 test specimen (right)

When stab testing the 8.00/3 test specimen, the blade shattered before penetrating the underside of the test sample. However, the result from testing the 10.00/1 specimen showed that the test blade caused a significant level of damage to the sample - enough to cause it to fracture before the blade failed. Such blade failure occurred in all eight of the positive results documented. This failure was a likely result of the need to transfer kinetic energy away from the drop vehicle once impacted with the test sample – therefore shattering the test blade offered the path of least resistance.

In summary, the stab resistive performance of test specimens manufactured from the virgin Duraform® material group was poor and offered no consistent stab resistant thickness.

3.2. Duraform® - 50/50

The results from the stab testing of specimens manufactured from a 50/50 mix of virgin and recycled Duraform® are also presented within Table 3.

Test specimens ranging in thickness from 1-10 mm demonstrated inadequate stab resistance – with all specimens shattering or fracturing, to allow full blade penetration. The 11.00 mm thick test specimen group was the first to demonstrate a consistent level of stab protection, with no blade penetration registered across all three samples - as shown in Figure 10.

Figure 10. 11.00 mm thick test specimens manufactured from 50/50 mix Duraform®

Two of the three positive results within this thickness group not only demonstrated test blade failure, but also featured the shattering of the test specimen. The first thickness group to demonstrate a consistent and positive level of blade penetration resistance without specimen failure was that of the 15.00 mm group, as shown in Figure 11.

Figure 11. 15.00 mm thick test specimens manufactured from 50/50 mix Duraform®

All three 15.00 mm thick specimens shown within Figure 11 registered zero blade penetration – successfully demonstrating stab resistance. Instead, the Stanley 1992 trimming blades shattered.

3.3. Duraform EX® - Virgin

When manufactured from virgin Duraform EX® powder all specimens in thicknesses below 11.00 mm failed to demonstrate penetration resistance within the 7.0 mm HOSDB limit. Six of the 15 specimens between 11-15 mm thick provided appropriate levels of penetration resistance, however, no single thickness group demonstrated a consistent level of stab protection across all three test specimens. A summary of results from this material group are documented within Table 3.

When compared against the results previously obtained from testing Duraform® samples, the results document that specimens ranging in thickness from 1-3 mm prevented full penetration of the blade to be reached – suggesting they demonstrate some resistance. This is illustrated within Figure 12.

Figure 12. Failure mode comparison between 3.00 mm thick virgin Duraform EX® (left) and virgin Duraform® (Right) specimens

Instead of shattering like the previously tested virgin Duraform® samples, the 3.00 mm thick virgin Duraform EX® test specimen appeared to have absorbed a degree of the stab impact energy – causing the specimen to deform on its underside and begin to fracture. This resistive behaviour however did not extend beyond the 3.00 mm thick specimens – with those above failing via a shattering mode.

3.4. Duraform EX® - 50/50

The final material group to be tested was that of specimens manufactured from a 50/50 consistency virgin and recycled Duraform EX®. The results from the stab testing of these specimens are outlined within Table 3.

Positive results were demonstrated with a number of the samples in the 9.00 and 10.00 mm thickness groups. These results were however not consistent until the specimen thickness increased to 11.00 mm – with all succeeding samples within the test group also showing positive results. Stab protection achieved with 11.00 mm thick 50/50 Duraform EX® specimens is shown within Figure 13.

Figure 13. 11.00/1 test specimen manufactured from 50/50 mix Duraform EX®

Within these positive results, the Stanley test blade shattered, resulting in the tip of the blade left residing within the strike surface of the test specimens. All of the specimens which demonstrated a positive result showed no signs of fracturing on either their strike or underside surfaces.

It should also be noted that when testing 50/50 mix Duraform EX® specimens, the mode of failure for those up to and including 6.00 mm thick was a puncturing mode, while test specimens beyond this thickness demonstrated fracturing and shattering failure modes. When compared to the results from stab testing virgin and recycled Duraform®, and virgin Duraform EX®, this mode of failure occurred up to a greater thickness than in previous experiments – suggesting the material is more suitable at absorbing stab impact energy.

4. Conclusions

All tests were performed to the UK HOSDB KR1-E1 stab impact energy of 24 Joules using Stanley Tools 1992 trimming blades. A summary of test results, highlighting minimum single thickness requirements are outlined within Table 4.

Table 4. Summary of single thickness stab resistant minimum requirements

The results from this investigation demonstrate an increase in the minimum thickness is required to provide stab protection to the UK HOSDB KR1-E1 impact energy of 24 Joules - in comparison to previously published proof-of-concept research (Johnson et al. 2013). Although such is the case this research has demonstrated a significant step towards the development of stab resistant AM body armour through the utilisation of established instrumented test apparatus, rather than in-house manufactured apparatus as used in previous proof-of-concept research.

No virgin powder test specimens were successful with single thicknesses up to 15.00 mm. However, the test results do suggest that stab resistance is achieved when using 50/50 mix powder across both Duraform® and Duraform EX® material groups – albeit inconsistent performance when using Duraform®. The only material group to demonstrate a consistent level of stab protection at and above 11.00 mm thick was that of the Duraform EX® 50/50 mix group. This enhanced mechanical performance may be attributed to the increased molecular weight as a result of prior thermal loading of the recycled powder within the Duraform EX® 50/50 mix (Zarringhalam et al. 2006; Gibson et al. 2010).

It should be recognised that a number of limitations are apparent with this research. For example, the experimental test procedure utilised within this body of work is based on world leading and established HOSDB stab test procedures relating to the testing of traditional aramid-fibre and polycarbonate armour systems. Modifications were required to ensure the instrumented drop test apparatus was suitable for testing additive manufactured specimens. In addition, as previously stated stab testing was performed using the more potent Stanley 1992 trimming blade rather than the identified HOSDB P1/B blade. By successfully demonstrating stab protection against the more severe blade, there are high levels of confidence that successful stab protection would also be achieved using the less severe HOSDB P1/B blade within any body armour certification testing.

By successfully establishing a LS single layer thickness that provides stab protection, there is the potential to the drive the development of the next-generation of protective body armour via the utilisation of LS technologies. The results of which may influence the development of protective solutions that provide high levels of protection without restricting the operational manoeuvrability of its wearer.

5. Further work

Based on the results obtained from this experiment, further research investigating the development of stab resistant AM body armour should be focused on the use of 50/50 mix Duraform EX® powder over the alternatives used within this experiment.

In addition, the results obtained from this experiment have highlighted a number of areas which if investigated could further advance the development of stab resistant AM body armour. Such areas include:

(1) The potential development of thinner layers arranged to create multi-layered specimens. Initial results in the outlined experiments suggested that thinner specimens offered some degree of resistance; therefore multiple thin layers may demonstrate a reduced total thickness required to achieve stab protection.
(2) A detailed investigation between the ratio of virgin and recycled powder to determine whether a greater level of recycled powder enhances stab protective performance.
(3) The potential to explore further LS materials such as metal-filled and ceramic-filled polymers.
(4) An opportunity to explore the protective performance of AM armour featuring composite and/or cellular based internal structures.
(5) Using all established design characteristics for the design, manufacture, and testing of articulated textiles.
(6) Assessment of established AM/LS armour against blunt force and ballistic threats.

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Figure 1. EOS P100 Formiga Laser Sintering machine (A), Empty build chamber (B), LS build bed applied (C) & Powder tumbler (D)
Figure 1
135x107mm (150 x 150 DPI)

Table 1. Laser sintering process parameters

Parameter	Duraform®	Duraform EX®
Layer thickness	0.1 mm	0.1 mm
Part bed temperature	172.5°C	178.5°C
Laser Power	18 W	22 W
Scan Speed	1,500 mm/s	3,000 mm/s (3.0 m/s)
Warm-up time	150 minutes	300 minutes

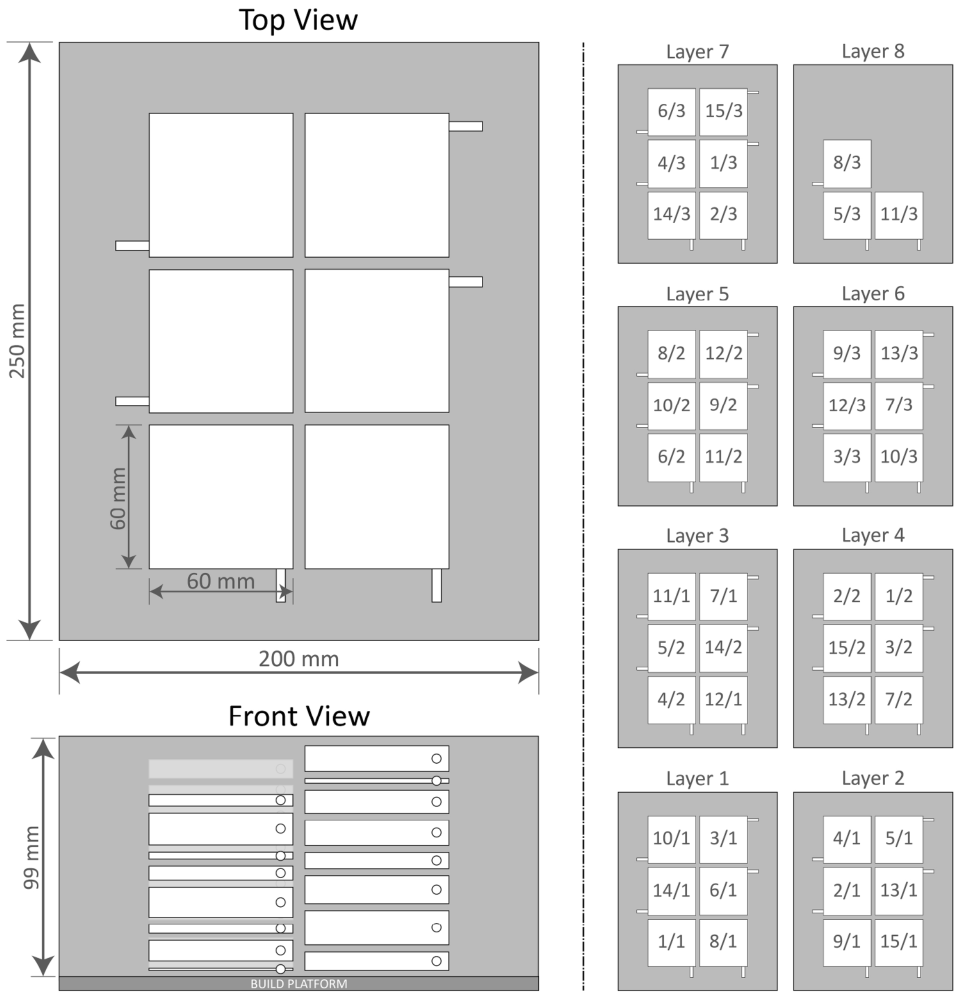


Figure 2. Experimental build layout
Figure 2
451x469mm (150 x 150 DPI)

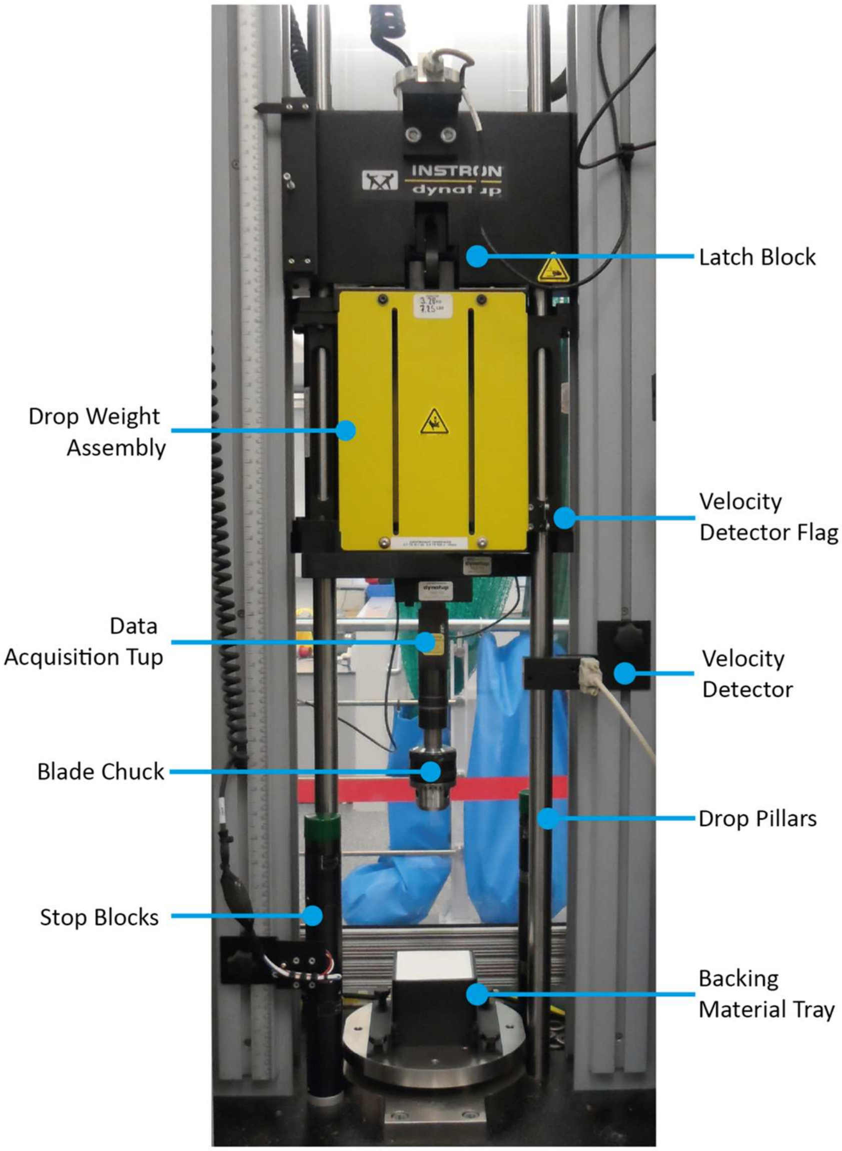
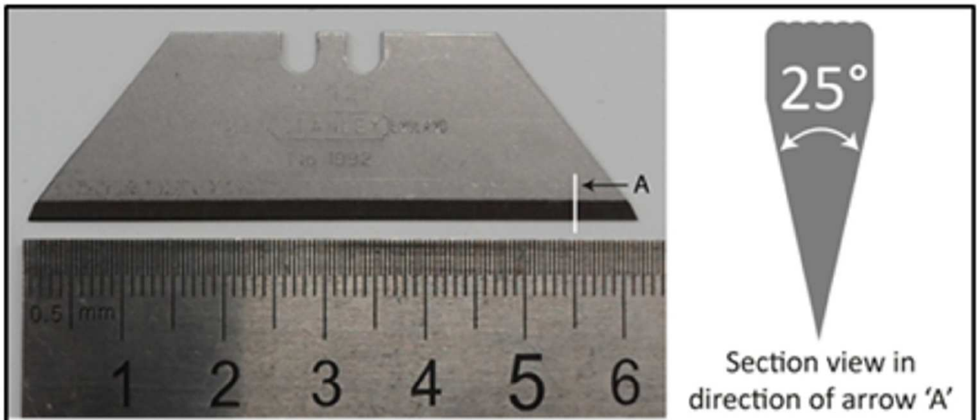


Figure 3. Instron 9250HV drop tower
Figure 3
187x255mm (150 x 150 DPI)

Figure 4. Roma Plastilina® No. 1 clay backing tray
Figure 4
118x71mm (150 x 150 DPI)

Table 2. Stab test experimental requirements

Energy Level	Stab Energy (Joule)	Drop Mass (kg)	Drop Height (m)	Drop Velocity (m/s)	**Maximum Blade Penetration (mm)**
KR1-E1	24 +/- 0.5	6.50	0.376	2.716	7.00



	1992 Trimming Blade
Length (mm)	62.00
Height (mm)	19.00
Thickness (mm)	0.65
Mass (g)	3.80
Angle between cutting edges (°)	25
Material	Polished steel (grade unknown)
Manufacturer	Stanley Black & Decker UK Ltd

Figure 5. Stanley Tools 1992 Trimming Blade Specification
Figure 5
130x142mm (150 x 150 DPI)

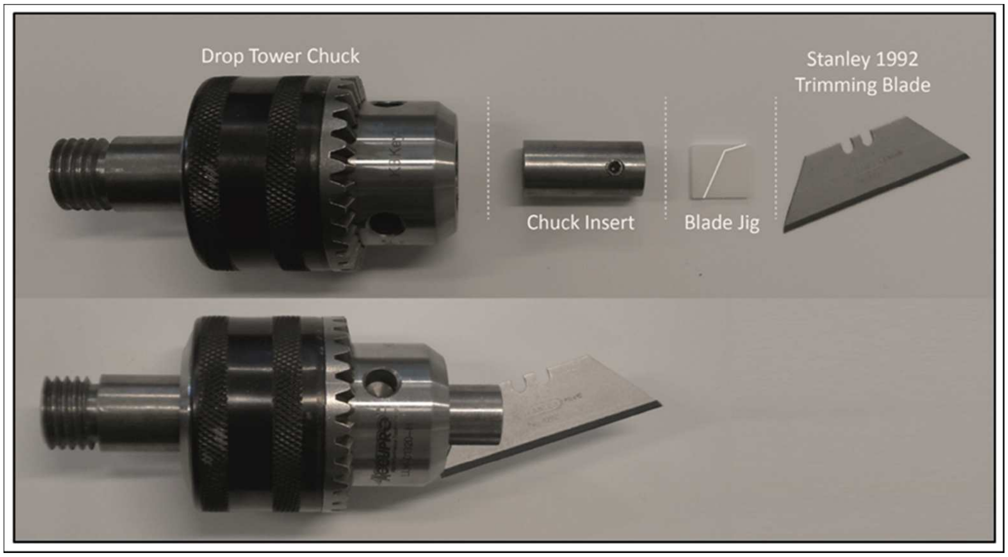


Figure 6. Stanley 1992 Trimming Blade Assembly
Figure 6
169x93mm (150 x 150 DPI)

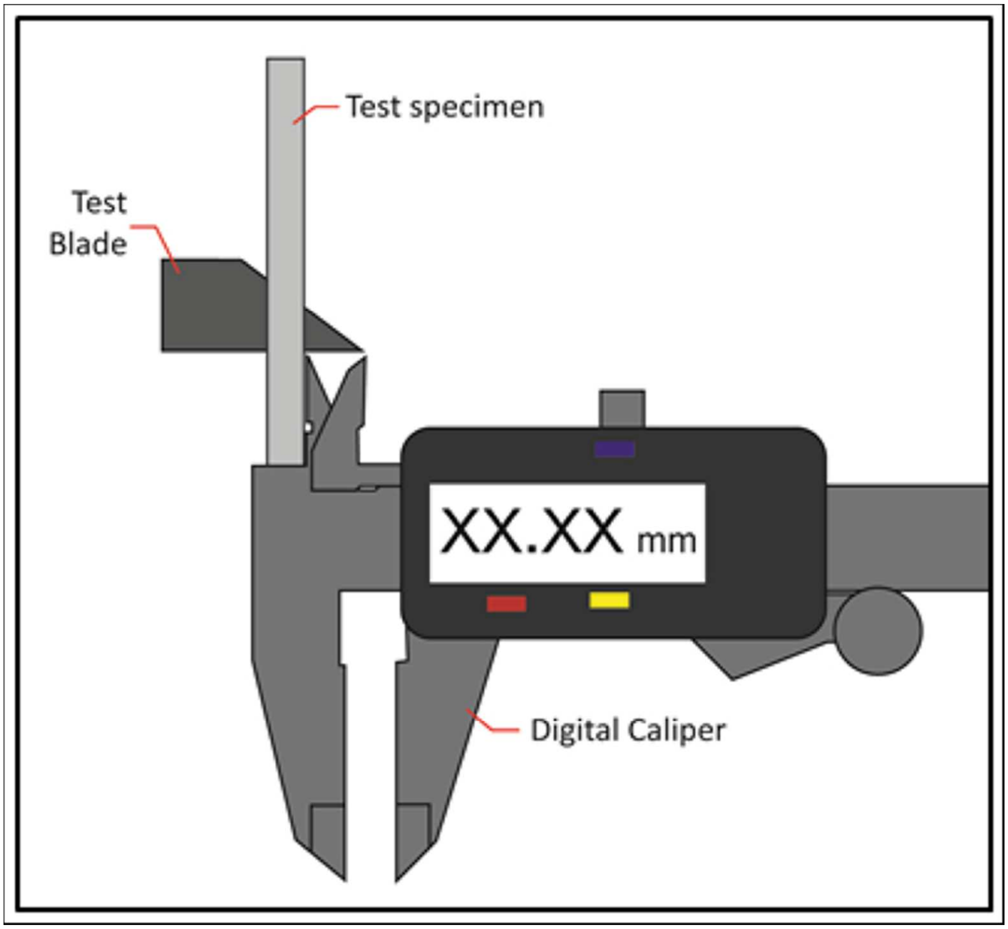


Figure 7. Measuring blade penetration
Figure 7
124x114mm (150 x 150 DPI)

Table 3. Blade penetration depth of each material test group

		Blade Penetration Depth (mm)			
No.	**Specimen ID**	Duraform® Virgin	Duraform® 50/50 mix	Duraform EX® Virgin	Duraform EX® 50/50 mix
1	01.00/1	30.00	30.00	30.00	30.00
2	01.00/2	30.00	30.00	27.84	30.00
3	01.00/3	30.00	30.00	29.82	30.00
4	02.00/1	30.00	30.00	29.91	28.67
5	02.00/2	30.00	30.00	28.93	29.74
6	02.00/3	30.00	30.00	28.04	30.00
7	03.00/1	30.00	30.00	30.00	29.54
8	03.00/2	30.00	30.00	28.21	30.00
9	03.00/3	30.00	29.97	30.00	30.00
10	04.00/1	30.00	30.00	30.00	30.00
11	04.00/2	30.00	30.00	30.00	30.00
12	04.00/3	30.00	30.00	30.00	30.00
13	05.00/1	30.00	30.00	30.00	30.00
14	05.00/2	30.00	30.00	30.00	30.00
15	05.00/3	30.00	30.00	30.00	28.08
16	06.00/1	30.00	30.00	30.00	30.00
17	06.00/2	30.00	30.00	30.00	30.00
18	06.00/3	30.00	30.00	30.00	30.00
19	07.00/1	30.00	30.00	30.00	30.00
20	07.00/2	30.00	30.00	30.00	30.00
21	07.00/3	30.00	30.00	30.00	30.00
22	08.00/1	30.00	29.55	30.00	29.00
23	08.00/2	30.00	30.00	30.00	30.00
24	08.00/3	0.00	30.00	30.00	30.00
25	09.00/1	30.00	30.00	30.00	28.65
26	09.00/2	30.00	30.00	30.00	0.00
27	09.00/3	30.00	30.00	30.00	30.00
28	10.00/1	2.36	30.00	30.00	0.00
29	10.00/2	30.00	30.00	30.00	24.38
30	10.00/3	30.00	30.00	30.00	0.00
31	11.00/1	0.00	0.00	30.00	0.00
32	11.00/2	30.00	0.00	0.00	0.00
33	11.00/3	5.53	0.00	30.00	0.00
34	12.00/1	30.00	5.98	30.00	0.00
35	12.00/2	30.00	30.00	30.00	0.00
36	12.00/3	0.00	2.20	5.83	0.00
37	13.00/1	1.89	0.00	30.00	0.00
38	13.00/2	30.00	14.16	0.00	0.00
39	13.00/3	30.00	0.00	0.00	0.00
40	14.00/1	0.00	0.00	30.00	0.00
41	14.00/2	30.00	0.00	14.30	0.00
42	14.00/3	30.00	11.71	30.00	0.00
43	15.00/1	0.00	0.00	30.00	0.00
44	15.00/2	30.00	0.00	3.55	0.00
45	15.00/3	30.00	0.00	0.00	1.56
Mean Impact Energy (J)		23.70	23.66	23.65	23.66
Mean Impact Velocity (m/s)		2.70	2.70	2.70	2.70

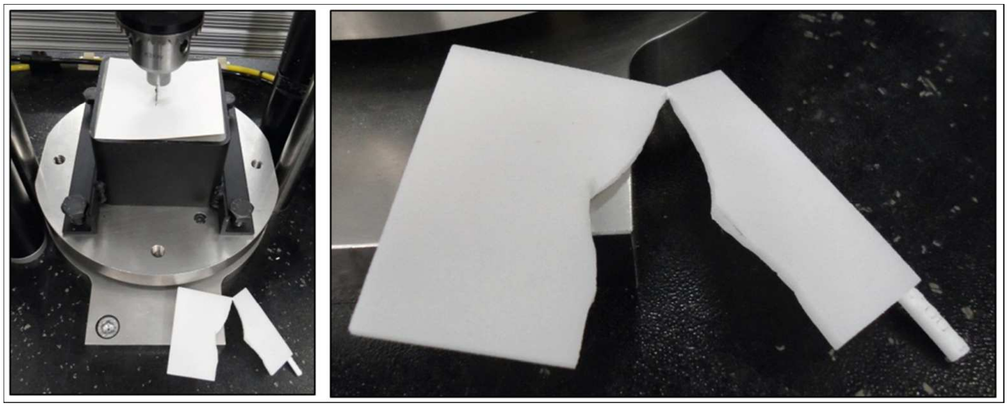


Figure 8. Virgin Duraform® 2.00/3 test specimen
Figure 8
234x93mm (150 x 150 DPI)

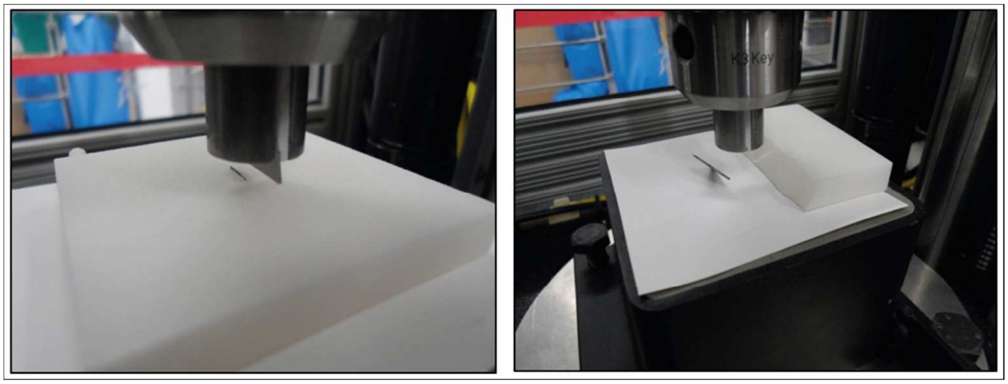


Figure 9. Virgin Duraform® 8.00/3 specimen (left) and 10.00/1 test specimen (right)
Figure 9
237x89mm (150 x 150 DPI)

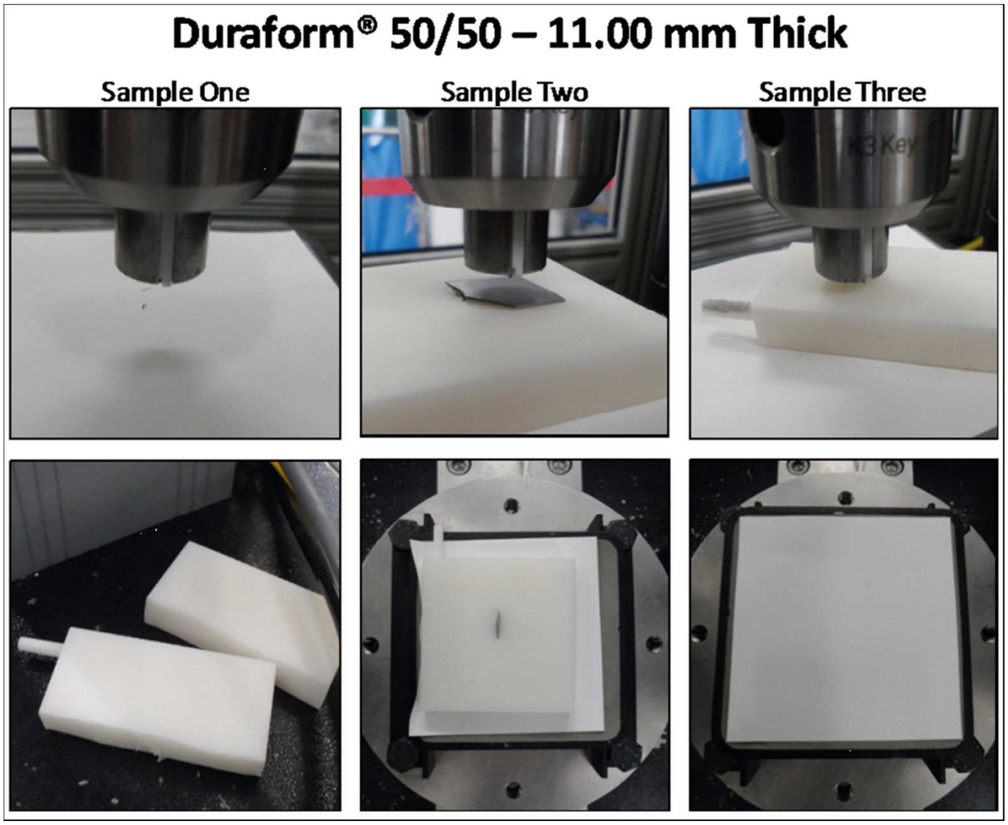


Figure 10. 11.00 mm thick test specimens manufactured from 50/50 mix Duraform®
Figure 10
187x153mm (150 x 150 DPI)

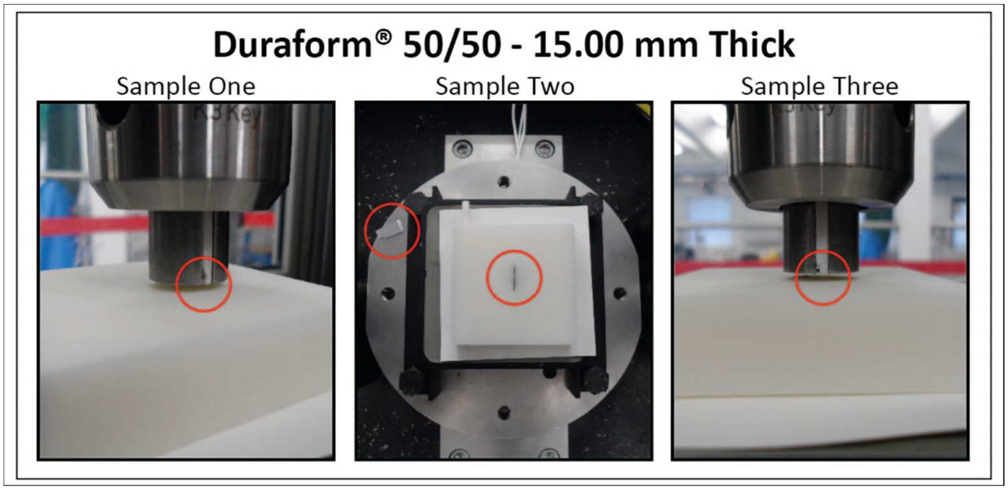


Figure 11. 15.00 mm thick test specimens manufactured from 50/50 mix Duraform®
Figure 11
240x116mm (150 x 150 DPI)

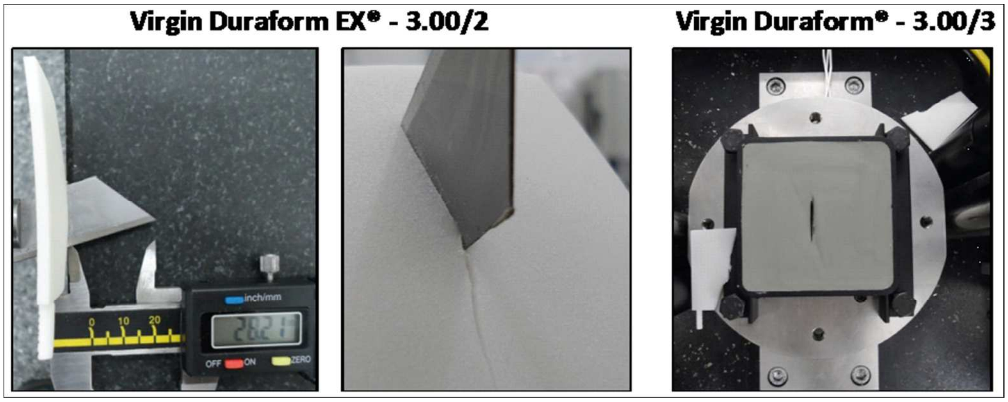


Figure 12. Failure mode comparison between 3.00 mm thick virgin Duraform EX® (left) and virgin Duraform® (Right) specimens
Figure 12
238x94mm (150 x 150 DPI)

Figure 13. 11.00/1 test specimen manufactured from 50/50 mix Duraform EX®
Figure 13
224x86mm (150 x 150 DPI)

Table 4. Summary of single thickness stab resistant minimum requirements

Material	Minimum thickness
Duraform® Virgin	No minimum achieved
Duraform® 50/50 mix	Initial 11.00 mm (Inconsistent at greater thicknesses)
Duraform EX® Virgin	No minimum achieved
Duraform EX® 50/50 mix	11.00 mm