Direct 3D Printing of Polymers onto Textiles: Experimental Studies and Applications

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1.1 Entry-Level 3D Printers

The Additive Manufacturing (AM) industry has had an impressive double-digit growth for the last 17 years (Wohler's report, 2014). There has been a strong demand for Entry-Level 3D Printers (EL3DPs) or low-cost desktop AM systems that are proliferating the market (Pei et al, 2011). Many of these are based on Fused Deposition Modelling (FDM) that uses the extrusion of molten thermoplastics. Other processes including Stereo-Lithography Apparatus (SLA), Digital Light Processing (DLP), Selective Heat Sintering (SHS) and Selective Laser Sintering (SLS) are gaining traction in the entry-level market. A key reason for the increasing popularity is that key patents such as those for FDM technologies have expired and the open-source movement is aligned with Arduino and Raspberry Pi micro-controllers that support universal access via free licensing. EL3DPs are often sold in a kit form, requiring basic tools and skills as compared to commercial machines that are enclosed and assembled (Marlone and Lipson, 2007). It has been recognised that the Fab@Home was the first open-source 3D printer that was specifically catered for the entry-level market, developed by Hod Lipson at Cornell University in 2006 and early models utilised a syringe-based deposition method (Fab@Home, 2014). Closer to the United Kingdom, the Rapman was developed by Adrian Bowyer from the University of Bath in 2009 (Jones et al, 2011). A key difference between the two systems was that the commercial version of the Rapman used a coiled filament that was cleaner and more cost effective (Lotz, Pienaar and de Beer, 2012). The first filament material that was developed for 3D printing was ABS (Acrylonitrile Butadiene Styrene). Although it comes in a variety of colours and is lightweight to transport, fumes of Acrylonitrile are produced, leading to health concerns (Stephens, et al 2013). In recent years, Poly-Lactic Acid (PLA) has been a more popular choice as it is bio-degradable, has a lower melting point and more dimensionally stable as compared to ABS. Today, a wide plethora of filament materials are available including Nylon, High Impact Polystyrene (HIPS), Polycarbonate (PC), flexible Thermo-Plastic Elastomers (TPE), Polyvinylchloride (PVC), Polyethylene terephthalate (PET) and wood-based Bio-linen filaments. It is expected that as FDM technology matures, better understanding of polymer science will lead to newer materials such as Graphene.

1.2 3D Printed Textiles and Novel Applications

The use of AM supports freedom of manufacture that enables complex geometry to be produced with fewer build constraints than conventional fabrication processes. Taking advantage of this benefit, fashion designers Jiri Evenhuis and Janne Kyttanen from Freedom of Creation were one of the pioneers to utilise AM to create textiles and bespoke clothing using patterns ranging from interlocking structures to tightly woven meshes (Chua, 2010). Some of their notable pieces include the 3D Glove that was printed using SLS with Polyamide (Taylor and Unver, 2014). Julia Koerner and Iris van Herpen worked with Materialise to create a web-woven dress made from Laser-Sintered plastic (TPU 92A-1) that is flexible, durable and machine washable (Koerner, 2013). Stratasys and Neri Oxman produced a range of organic garments that were fabricated using two different materials containing hard and soft sections with Polyjet technology (Oxman, 2012). Taking a step further, Hudson (2014) pushed the boundaries of 3D printed textiles by developing a needle felting print head with an embedding technique that combines the use of soft fibres (wool and wool blend yarn) on a printed nylon mesh to form a functioning arm of a teddy bear.

Academic research in 3D printed textiles has grown exponentially over the last decade with the majority of work focusing on optimising the modelling of Three-Dimensional (3D) Computer-Aided-Design (CAD) data for conformal AM textiles (Godazandeha et al, 2010), as well as looking at understanding the mechanical properties of complex structures in AM textiles (Crookston et al, 2008). Nervous System (2013), a Massachusetts-based design studio led by Jessica Rosenkrantz and Jesse Louis-Rosenberg developed the Kinematics software that tessellates and splits the CAD model into triangles and then links the individual parts together with hinges. The digital model is computationally folded to compress itself into the smallest possible volume to maximise the limited space within the 3D printer (Pei, 2014).

According to Bingham et al (2007), AM textiles can only be considered to be a true fabric if it has free movement and drape characteristics. The use of AM is advantageous because it can create free-moving assemblies at a micro-level within a single manufacturing process. However, AM textiles will not replace conventional fibre-based production for simple pieces of garment and will instead cater for niche markets such as high-performance wear. There are surmountable challenges that must be overcome. For example, it is time consuming to ensure that each link within the assembly is properly connected, as well as finishing processes, durability, duration of print and the costs involved before AM textiles can become mainstream (Brown 2003; Taylor and Unver, 2014).

1.3 Direct Deposition of Polymers onto Fabrics

Due to the fact that AM textiles are still not widely accepted, a growing number of researchers have investigated the potential of printing polymers directly onto fabrics as a means of achieving hard surfaces yet still allowing free movement of the fabric (Figure 1). Campbell (2009) investigated polymer deposition on textiles to achieve a three-dimensional effect. Using a FDM printer, samples of cylindrical tubes in rigid Nylon were produced. Their work highlighted the limitations concerning support structures that were impossible to remove unless dissolvable lattices were used. Whittow et al. (2014) investigated the technical challenges of inkjet printed dipole antennas on textiles for wearable communications. They found that although it is difficult to inkjet print onto textiles because of the surface roughness, this can be overcome by adding a coated layer for better bonding to polyester cotton fabric. Melnikova et al (2014) recognised that direct printing on textile hugely depends on the compatibility of the materials and the printer. In their work, they utilised FDM and SLS systems to create a variety of structures, showing that features such as weft knitted structures require a minimum material thickness for strength and the distance between stitches is important. They also noted issues with fine support structures and observed undesirable clots in FDM-printed parts. Their work also examined the use of multi-materials, combining hard and soft sections within a single print.

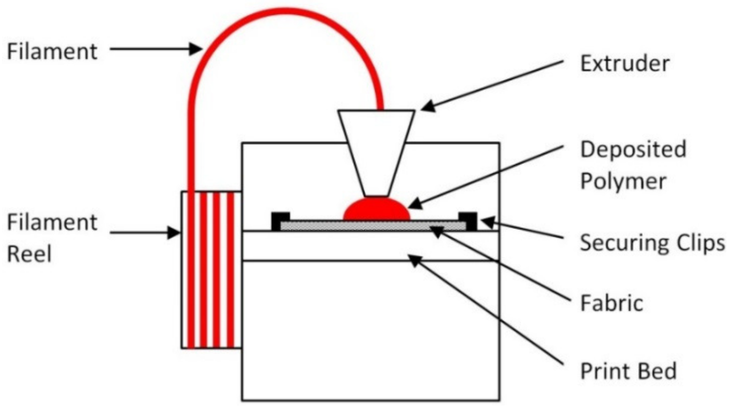


Figure 1: Direct deposition of polymers onto fabrics

Brinks et al (2013) defined "3D polymer deposition" as a technology concerning the build-up of three-dimensional polymers onto a surface in a programmed way. They noted that the free-movement nature of the textile and fibres made interconnection of printed surfaces difficult. In line with Melnikova et al (ibid), they highlighted that it is important to understand the bonding process of polymers with textiles and factors that influence the polymer melt. The polymer should penetrate into the fabric for firm adhesion. Their tests found that for molten polymers with high viscosities, pressure is required for better penetration. It is proposed that future work in this area will overlap the boundaries of 4D printing where material properties are assigned to predefined regions during the design and fabrication process of AM. Functionally graded printed parts will allow physical variations of the design to be achieved, such as areas for stiffness or flexibility (Tsai and Oxman, 2013; Oxman, et al. 2011).

From the literature, it can be summarised that three areas must be explored for effective deposition of polymers onto fabrics. First, the binding and adhesion phenomena of polymer material deposited onto fabrics must be understood. The adhesion of the polymer is dependent on the contact area so that the bonding energy can be spread across a larger surface area. Second, printed parts should not influence the drape of the fabric so as to allow for free movement. For example, it is important to carefully select positions that coincide with intended folds and stitches. Third, the polymer and fabric must withstand deformation and recover when it is subjected to forces occurring as part of daily wear, such as twisting and stretching. The parts should retain its structure and shape when exposed to the environment (Holmes, 1999).

The aim of this research is to investigate the adhesion of polymer materials printed directly onto fabrics using an entry-level FDM machine. A series of functional and decorative parts were designed to explore the limitations and to identify potential applications. Examples include medical braces where the flex and breathability of the textile will provide comfort, and the rigid structures of the polymer will provide support. This area opens up avenues for customisation where products can be designed for specific purposes. Decorative features such as textures or logos, or specially engineered foot insoles and functional clips can also be produced.

2.1 Filament Material

The Ultimaker 1 used for this research is an open-source, single-extruder FDM printer that ranks well among other desktop machines in terms of speed and accuracy of prints. The key variables for this study include the fabric and the polymer being used. The print settings such as the extrusion temperature, speed, fill amount, layer height and print density were kept consistent. ABS, PLA and Nylon filament materials were used for the experiments (Table 1). Although ABS is widely available and has good strength, warping has been a major concern (Pei et al, 2011). Therefore, the purpose of using ABS was to ascertain whether warping would still occur when being deposited onto fabrics. PLA was chosen due to its growing popularly and the advantage of being biodegradable and more flexible than ABS which is brittle. Nylon 645 was also used as it has a combination of strength and flexural properties, bringing the benefits of both PLA and ABS. Nylon is hard wearing and can be dyed which is an advantage.

Properties	ABS	PLA	Nylon 645
Chemical name / Blend	Acrylonitrile Butadiene Styrene	Poly-Lactic Acid	Co-Polymer of Nylon 6/9, 6 & 6T
Supplier	Form Futura	Ultimaker	Taulman
Cost	32.95Eur/kg	31.50Eur/kg	39.95Eur/kg
Diameter	2.85 mm	2.85 mm	2.85 mm
Opacity	Opaque	Opaque	Transparent
Density	1010 kg/m³	1240 kg/m³	930 kg/m³
Print Temperature	200-250°C	180-220°C	230-265°C
Melting Temperature	105° C	65°C	194°C
Impact Strength:	16 KJ/m2	7.5 KJ/m2	N.A.
Tensile Modulus:	2000 Mpa	3310 Mpa	114 MPa

Table 1: Filament materials and their properties

2.2 Fabric Material

Two fibres dominate the world market - Cotton as a natural fabric and Polyester as a synthetic fabric based on Polyethylene Terephthalate. Cotton, polyester and other popular fabrics such as Polypropylene, Nylon, Soy and Polywool will be used in this research (Table 2).

Weave Structure	Type	Textile
woven	Polymer Base	Polypropylene
woven	Polymer Base	Polyester
woven	Polymer Base	Nylon (Thick)
woven	Polymer Base	Light Polyester
woven	Blend	Polyester Wool Polywool
woven	Natural	Cotton
knit	Polymer Base	Soy
knit	Polymer Base	Nylon

Table 2: Types of fabric used

The properties of the fabric depend on the fibre, the weave structure, thread packing, yarn crimp, stitch density and length of weft knit (Holme, 1999; Taylor, 1985). In general, fabrics are produced through a weaving or knitting process. Woven textiles are tighter because multiple yarns are looped at right angles to form the fabric. Although they crease easily, they are easier to sew. In contrast, knitted fabrics are produced by continuously looping yarn in rows and they can be stretched along the width. Compared to natural textiles, Polypropylene fabric has excellent stain resistance, durable, absorbs little moisture and has good mechanical properties. Polyester fabric was chosen as it has a higher melting point (260°C) than Polypropylene fabric (165°C), giving it better heat resistance and it can be dyed. Nylon fabric has a high strength to weight ratio, possesses good elasticity and does not shrink after washing. Depending on the type of construction, Nylon fabric can retain heat; or allowed to breathe. Polyester Wool (Polywool) fabric is a blend of synthetic and natural fibres. Because of its combination, the material possesses good strength yet being light, suitable for making suits and pants. Lastly, Soy and natural Cotton fabrics were used for the experiments. Soy is a synthetic protein fabric derived from the soybean cake. It has a smooth touch and possesses excellent drape. The material has the same moisture absorption as Cotton, but with a higher breaking strength than Wool, Cotton or Silk. Cotton is a widely used natural fabric that has good moisture absorbency and possesses a soft feel. It has been used to produce clothing and padding for home furnishing. It is sometimes coated with a water resistant finish where the coating extends the functional performance and adds value to the product.

2.3 Complex Structures

A series of shapes and structures of objects were designed to evaluate whether complex parts could be directly 3D printed onto the surface of fabrics. The complexity of shapes and structures have been described by scholars in several ways such as geometry, interaction of parts, use of external references; as well as repetition and differentiation of the structure (Corning, 1998; Simon, 1996; Salingaros, 2000; Chase and Murty, 2000). Sukumar et al (2008) defined levels of complexity through perception using psychophysical studies, grouping complex features according to surface variation, symmetry, large part count, part decomposability, intricate details and topology. For the experiments, four sets of geometric shapes were designed (Table 3).

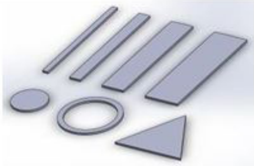
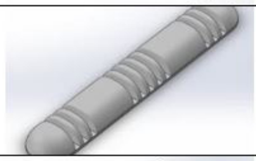
Set	Structure	Image	Dimensions (mm)	Description
Set 1	Parallel strips		50 x 15 x 1, 50 x 10 x 1, 50 x 5 x 1, 50 x 2.5 x 1	A set of 4 parallel strips to evaluate aspects of parallelism and repetition
	Circle		Ø15 x 1	Solid shapes and circularity
	Ring		Ø 25.75 x 1, inner Ø 21.3	Shapes with cavity
	Triangle		31mm each side x 1	Sharp corners
Set 2	Text		128.5 x 58 x 7.5	Thin details, closely spaced
	Braille characters			Small details, pattern arrangement
Set 3	Articulated part		96 x 16 x 7	Flexural strength tests
Set 4	Functional latch and hook		89 x 92 x 10	Flexural strength and interconnection of parts and assemblies

Table 3: Complexity of CAD structures

2.4 Experimental Studies

According to Singha (2012), good adhesion on textile surfaces depends on the compatibility of the material, the nature of the fibre surface, the presence of natural or added impurities and the physical and chemical process. The purpose of Set 1 was to ascertain which polymer-fabric combination would be the most promising. The set is tested with different types of filament material: Set 1A for ABS, Set 1B for PLA and Set 1C for Nylon. The extrusion temperature was based on the melting point of the polymer according to the manufacturer's guide (Table 11 in Appendix). The results of each print was then visually analysed by all authors and a Likert scale rating from 1 to 10 was used. A better print quality results in a higher score. The 0 value represents the worse, and 10 represents excellent according to four areas: w for warping (1 = most warping, 10 = least warping); q for bonding (1 = no bonding; 10 = excellent bonding); p for print output (1 = poor; 10 = excellent print); and f for flex (1 = poor; 10 = good flexural strength).

The results from Set 1A printed with ABS is tabulated in Table 4. The combination of ABS with light Polyester fabric and woven Polywool fabric had the best overall results where warping was minimal and good adhesion. Although woven Polypropylene fabric offered the best bond, warping was high and the print quality was very low (Figure 2).

Set 1A (Strips, Circle, Triangle)	Warping (w)	Bonding (b)	Print (p)	Total	Average
ABS with woven Polypropylene	7	9	4	20	6.7
ABS with woven Polyester	4	5	5	14	4.7
ABS with woven Nylon	3	2	6	11	3.7
ABS with light Polyester	7	6	10	23	7.7
ABS with woven Polywool	8	8	7	23	7.7
ABS with woven Cotton	3	6	9	18	6
ABS with knit Soy	6	7	0	13	4.3
ABS with knit Nylon	2	8	2	12	4

Table 4: Results from Set 1A

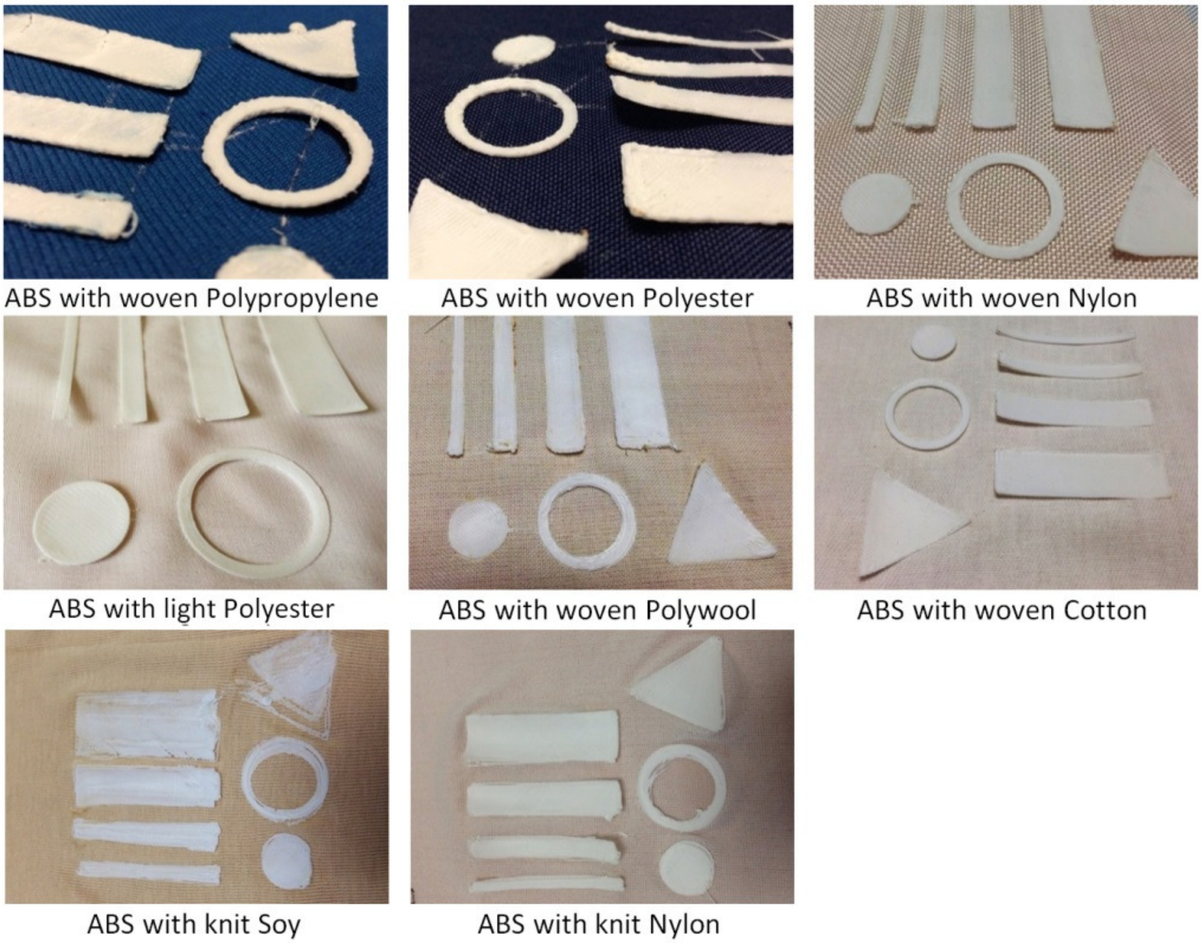
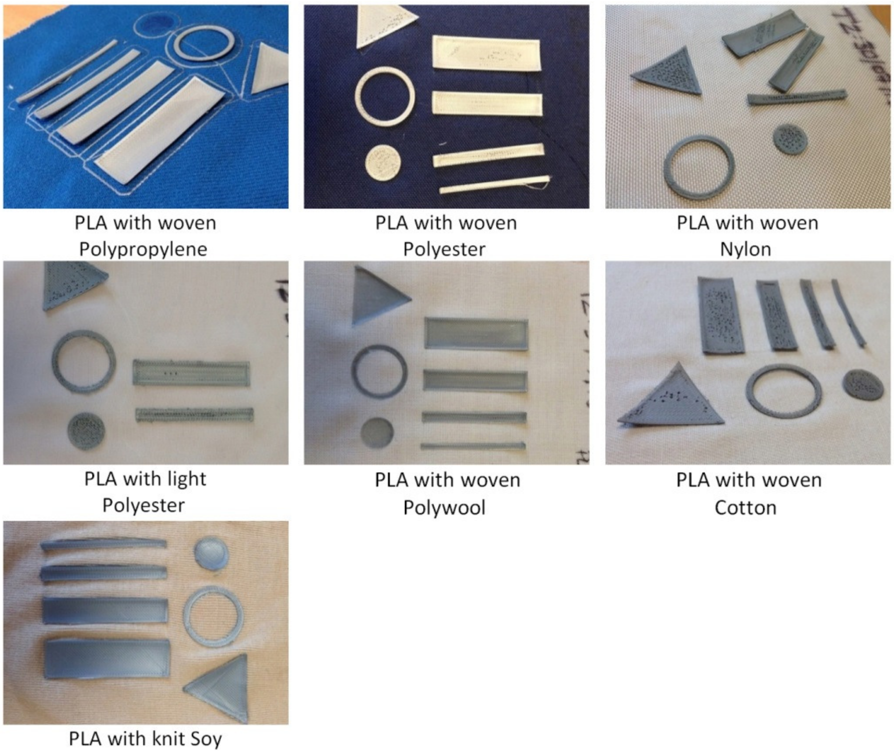


Figure 2: Photographs of samples from Set 1A for printing of ABS on different fabrics

The results from Set 1B is summarised in Table 5 where PLA with woven Polywool fabric had the best results, similar to the outcome when using ABS. Although woven Polypropylene fabric and knit Soy fabric had high overall scores, the bond between PLA fabric and knit Soy fabric was excellent with little warping (Figure 3).

Set 1B (Strips, Circle, Triangle)	Warping (w)	Bonding (b)	Print (p)	Total	Average
PLA with woven Polypropylene	9	3	10	22	7.3
PLA with woven Polyester	7	1	6	14	7
PLA with woven Nylon	5	1	4	10	5
PLA with light Polyester	7	1	6	14	7
PLA with woven Polywool	9	8	10	27	9
PLA with woven Cotton	9	7	4	20	6.7
PLA with knit Soy	7	7	8	22	7.3
PLA with knit Nylon	0	0	0	0	0

Table 5: Results from Set 1B



PLA with woven Polypropylene; PLA with woven Polyester; PLA with woven Nylon; PLA with light Polyester; PLA with woven Polywool; PLA with woven Cotton; PLA with knit Soy

Figure 3: Photographs of samples from Set 1B for printing of PLA on different fabrics

The results from Set 1C is summarised in Table 6 where Nylon with woven Polywool fabric, woven Cotton fabric and knit Soy fabric had the best results with low warping, good adhesion and good quality of prints (Figure 4).

Set 1C (Strips, Circle, Triangle)	Warping (w)	Bonding (b)	Print (p)	Total	Average
Nylon with woven Polypropylene	10	4	1	15	5
Nylon with woven Polyester	10	6	6	22	7.3
Nylon with woven Nylon	6	3	6	9	3
Nylon with light Polyester	8	7	8	23	7.7
Nylon with woven Polywool	10	8	8	26	8.7
Nylon with woven Cotton	10	8	8	26	8.7
Nylon with knit Soy	10	9	7	26	8.7
Nylon with knit Nylon	8	7	7	22	7.3

Table 6: Results from Set 1C

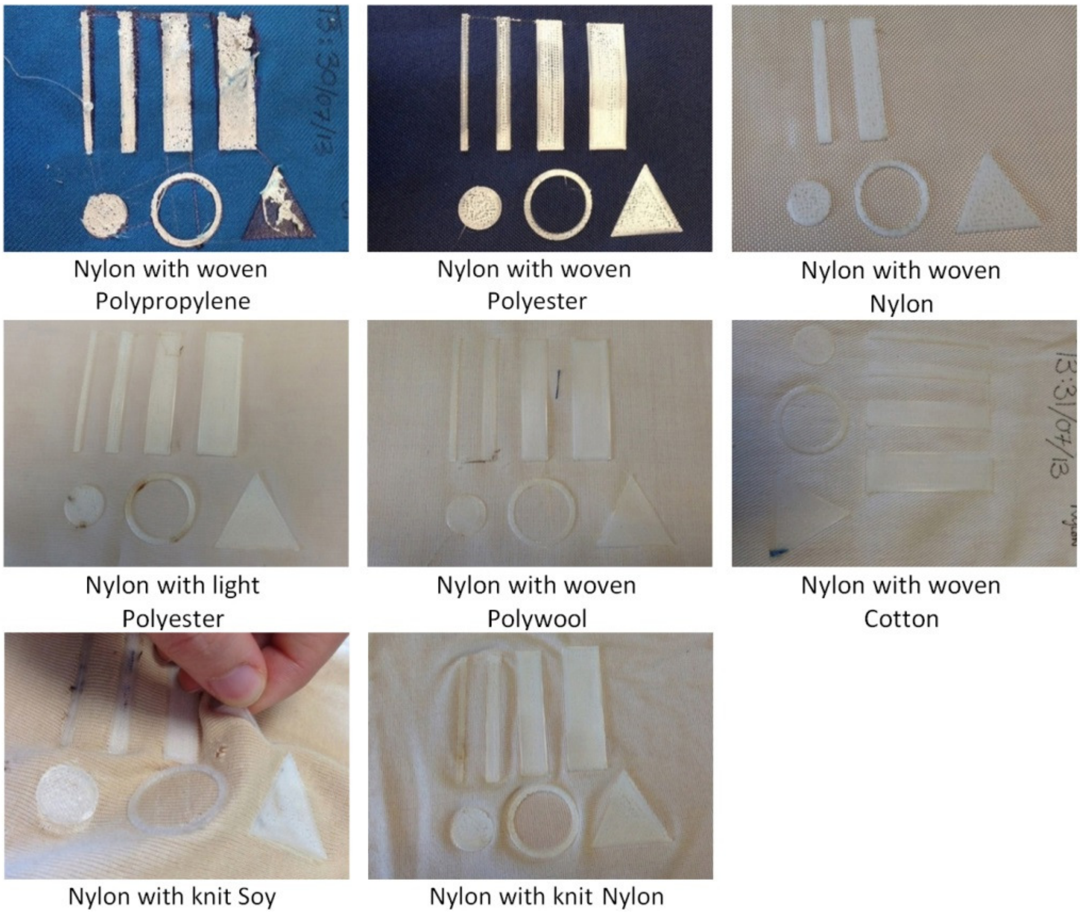


Figure 4: Photographs of samples from Set 1C for printing of Nylon on different fabrics

For efficiency, it was decided that only the best combinations from Set 1A, 1B and 1C would be used for subsequent experiments. Table 7 shows the highest scores from the three sets of experiments. Although the combination of ABS and Polyester fabric achieved good prints, there were warping issues and bonding was poor. Therefore, woven Polypropylene fabric, woven Polywool fabric, woven Cotton fabric and knit Soy fabric would be used for the further tests.

Best Combination from Set 1	Warping (w)	Bonding (b)	Print (p)	Total	Average
ABS with light Polyester	7	6	10	23	7.7
ABS with woven Polywool	8	8	7	23	7.7
PLA with woven Polypropylene	9	3	10	22	7.3
PLA with woven Polywool	9	8	10	27	9
PLA with knit Soy	7	7	8	22	7.3
Nylon with woven Polywool	10	8	8	26	8.7
Nylon with woven Cotton	10	8	8	26	8.7
Nylon with knit Soy	10	9	7	26	8.7

Table 7: Summary of results from Set 1

Set 2 comprised of a line of text and braille characters. The purpose is to ascertain whether intricate details could be printed on different textiles using the 3 polymers. The print settings were identical to the ones used for Set 1 (Table 11 in Appendix). The results from Set 2 is summarised in Table 8 where PLA with woven Cotton fabric had the best result, achieving excellent adhesion and print quality; following which PLA with woven Polywool fabric and PLA with knit Soy fabric had good results in terms of material adhesion and print quality (Figure 5).

Set 2 (Braille text & characters)	Warping (w)	Bonding (b)	Print (p)	Total	Average
ABS with woven Polypropylene	6	4	4	14	4.7
ABS with woven Polywool	6	5	6	17	5.7
ABS with woven Cotton	9	8	7	24	8
PLA with woven Polywool	10	9	7	26	8.7
PLA with knit Soy	10	8	8	26	8.7
PLA with woven Cotton	10	10	9	29	9.7
Nylon with woven Polywool	10	0	2	12	4
Nylon with knit Soy	10	10	2	22	7.3
Nylon with woven Cotton	10	8	3	21	7

Table 8: Summary of results from Set 2

ABS with woven Polypropylene | ABS with woven Polywool | ABS with woven Cotton

PLA with woven Polywool | PLA with knit Soy | PLA with woven Cotton

Nylon with knit Soy | Nylon with woven Cotton | Nylon with woven Polywool

Figure 5: Photographs of samples from Set 2

The design of Set 3 comprised of a single articulated part measuring 96 x 16 x 7 mm and the same combination of materials and print settings from Set 2 was used (Table 11 in Appendix). This purpose of this test was to ascertain the flexural strength of the articulated part when bonded to the textile and to observe how well the printed part would work. The results from Set 3 is summarised in Table 9. Similar to Set 2, PLA with woven Cotton fabric had the best result, achieving excellent adhesion and print quality and good flex. The following results were also identical to those from Set 2 where PLA with woven Polywool fabric and PLA with knit Soy fabric had good results in terms of material adhesion and print quality. Although Nylon had very good bonding and little warping, the print quality was poor and therefore the flex function did not perform well (Figure 6).

Set 3 (Articulated part)	Warping (w)	Bonding (b)	Print (p)	Flex (f)	Total	Average
ABS with woven Polypropylene	3	5	6	8	22	5.5
ABS with woven Polywool	10	7	7	10	34	8.5
ABS with woven Cotton	10	9	8	10	37	9.25
PLA with woven Polywool	10	9	9	10	38	9.5
PLA with knit Soy	10	8	10	10	38	9.5
PLA with woven Cotton	10	10	10	10	40	10
Nylon with woven Polywool	10	10	5	7	32	8
Nylon with knit Soy	10	10	3	3	26	6.5
Nylon with woven Cotton	10	8	1	1	20	5

Table 9: Summary of results from Set 3

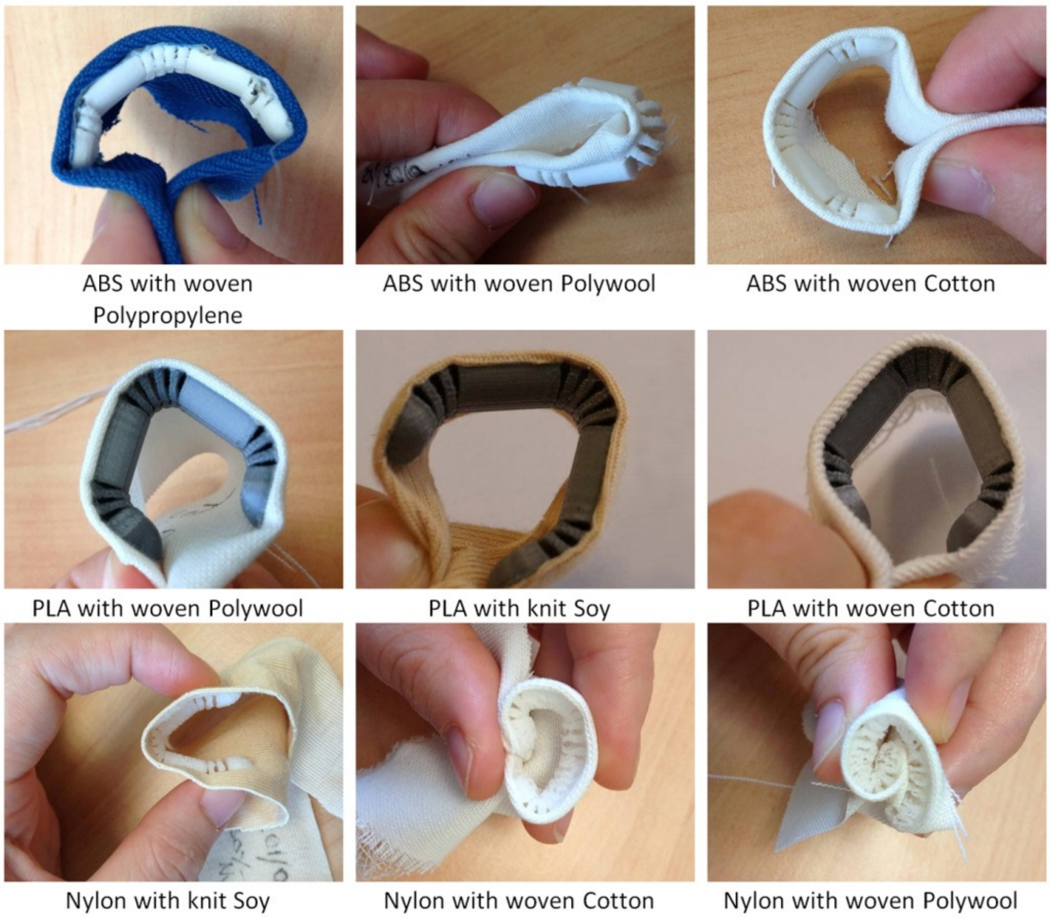


Figure 6: Photographs of samples from Set 3

Set 4 comprised of a series of functional latch and hook parts made up of complex geometries, articulated sections and assemblies (Figure 7). The parts were printed used the same build settings (Table 11 in Appendix). The ABS parts bonded well with the textiles and the parts achieved some flex on the prints with the most successful being the articulated latch and snap fit. The hook and hoop parts were less successful as some areas were thinly produced. Although the ABS material was strong, it soon became evident that the material was brittle and snapped easily. The PLA parts had extremely good print quality, consistent with those from the previous tests. The articulated latch was the strongest piece among the other shapes and the material had more flexibility than ABS. The hook and hoop parts were too thin to be used functionally. Due to the extremely poor print quality of Nylon, it was decided that the material would not provide good results and was omitted from the experiment. In summary, PLA with woven Cotton fabric had the best overall score and performed well in terms of bonding, print quality and flexural strength. However, PLA with knit Soy fabric and ABS with woven Cotton fabric also performed relatively well in terms of the surface adhesion, print quality and flexural strength (Table 10).

Set 4 (Latch & Hook)	Warping (w)	Bonding (b)	Print (p)	Flex (f)	Total	Average
ABS with woven Polypropylene	10	8	6	5	29	9
ABS with woven Polywool	10	7	7	7	31	7.8
ABS with woven Cotton	10	9	7	8	34	8.5
PLA with woven Polywool	10	9	7	7	33	8.3
PLA with knit Soy	10	10	7	8	35	8.8
PLA with woven Cotton	10	10	8	8	36	9

Table 10: Summary of results from Set 4

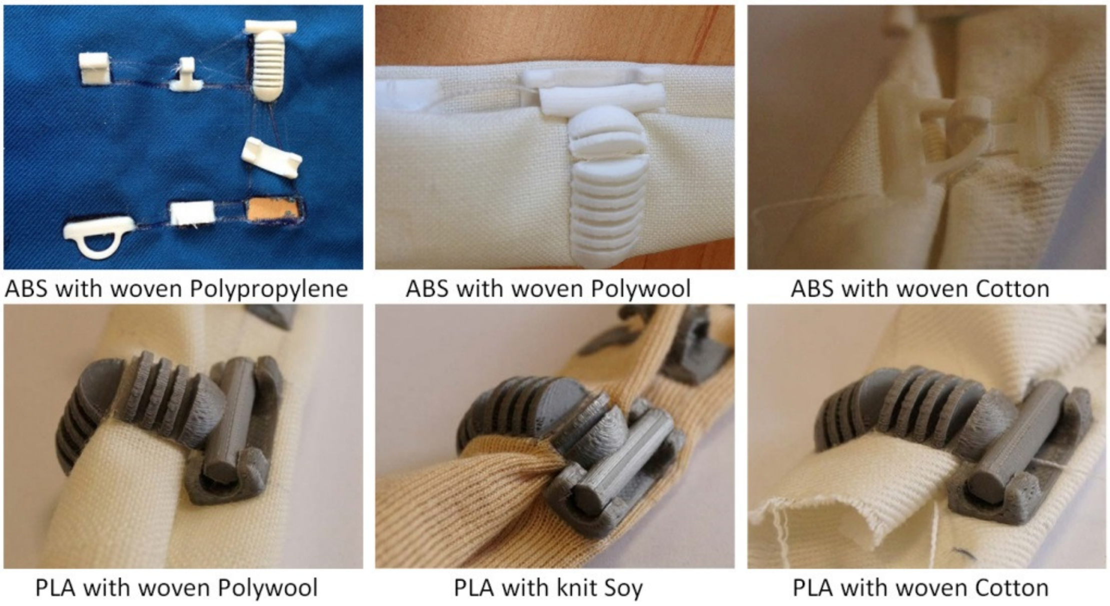


Figure 7: Photographs of samples from Set 4

3.1 Discussion

The experiments have enabled a better understanding of polymer materials being printed directly onto fabrics using an entry-level FDM machine. Figure 8 showed that PLA had better overall results as compared to ABS and Nylon which had a relatively similar outcome. It is also interesting to note that woven Cotton and woven Polywool fabrics showed good compatibility with all 3 types of polymers.

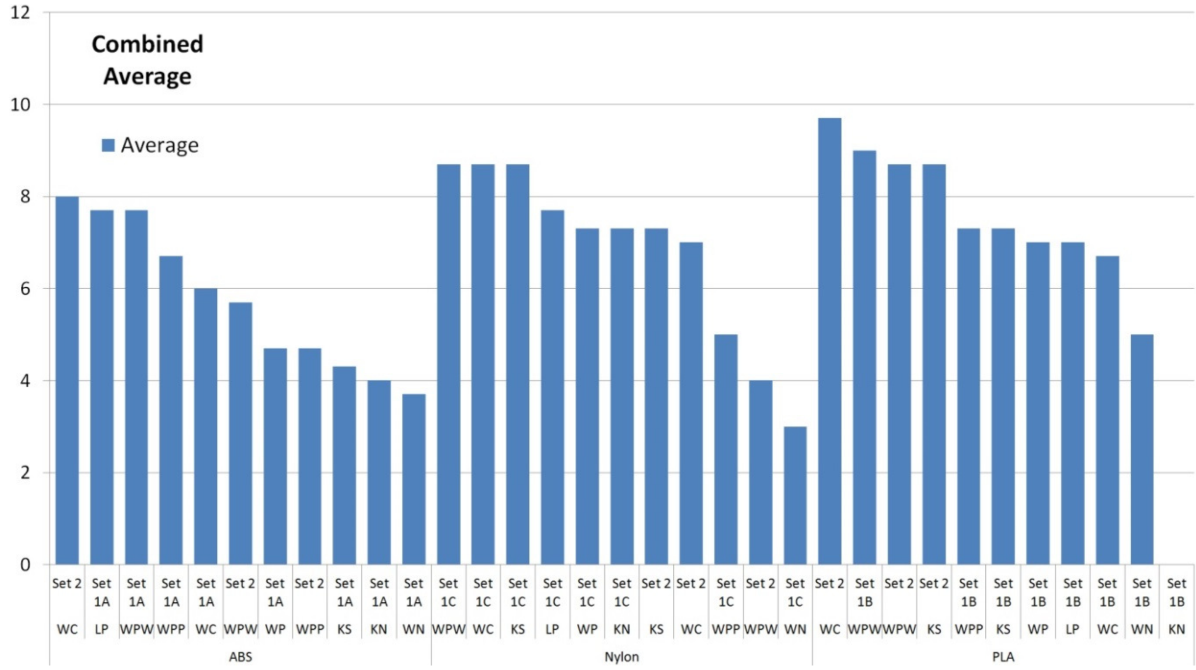


Figure 8: Average rating based on Overall Combination

In terms of warping, a higher rating meant that the polymer parts had less warp and material distortion. Figure 9 showed that Nylon and PLA had fewer warping issues when compared with ABS. Among the textiles, woven Polywool, woven Cotton, knit Soy and woven Polypropylene fabrics had generally good compatibility with the 3 polymers and showing little warping. Knit Nylon and woven Nylon fabrics had poor performance with severe warping encountered.

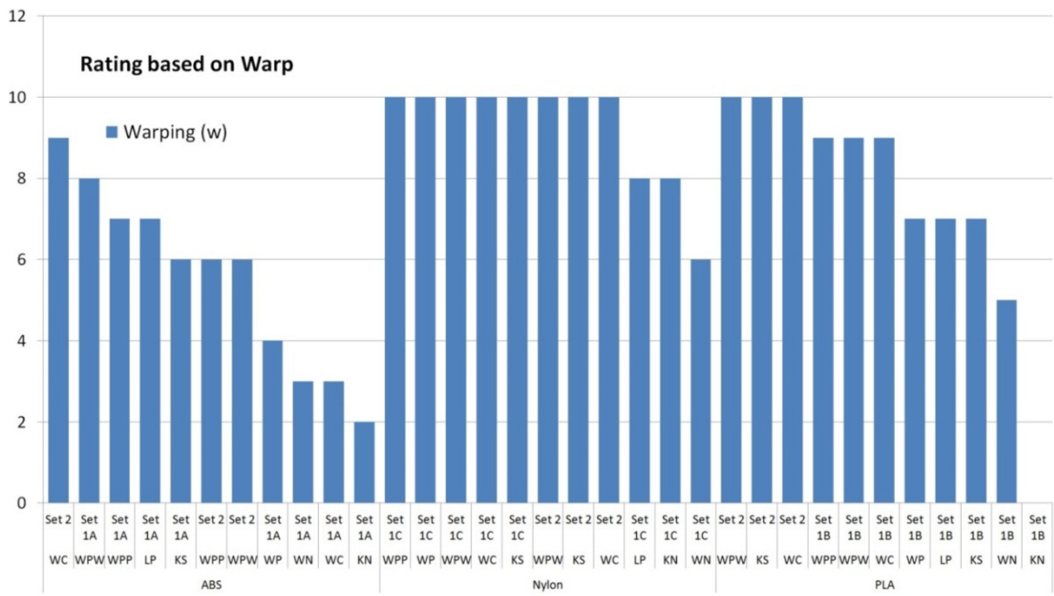


Figure 9: Rating based on Warp

The results showed that the adhesion between woven Polywool, woven Cotton and knit Soy fabrics performed the best with the 3 polymers (Figure 10). Although woven Polypropylene fabric had good bond with ABS for Set 1A, it performed badly for the other tests. The strong adhesion between the polymer parts and Cotton, Soy and Polywool fabrics could be due to the free-standing fibres that enabled stronger adhesion as the other fabrics had a smoother surface finish which did not enable good surface adhesion. From prior research, it was expected that polymers would bond most effectively with synthetic fabrics because both plastics would melt and adhere together, whereas natural fibre would burn. It was also expected that having both polymer-based parts and textiles, such as Nylon printed onto a Nylon sheet would make it ideal for end of life recycling. Unfortunately, the combination of Nylon polymer with Nylon fabric was very poor.

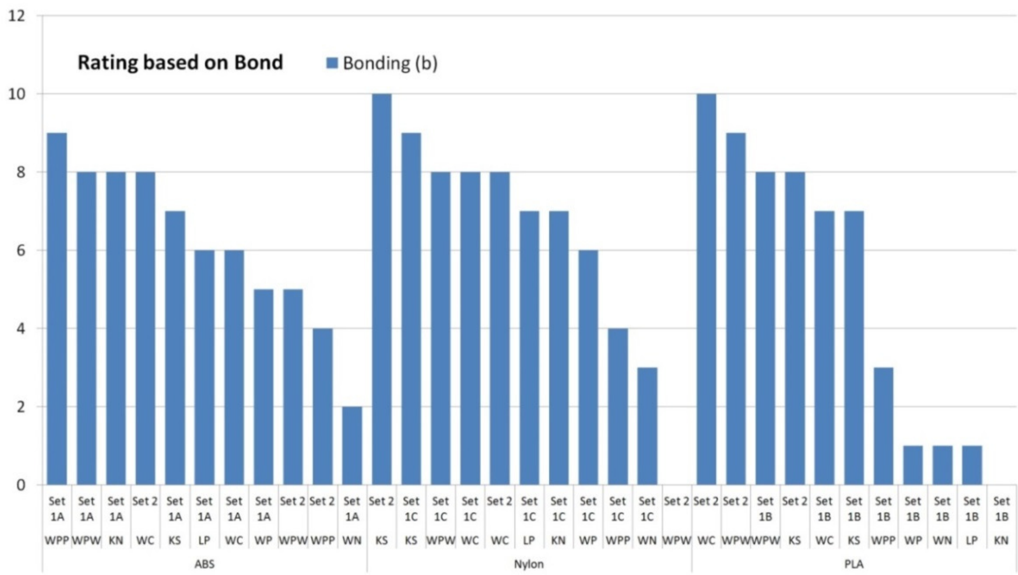


Figure 10: Rating based on Bond

For print quality, PLA in general produced far better results as compared to ABS or Nylon. It is also interesting to note that there were mixed results when comparing which combination had better print definition, although woven Polywool fabric and woven Cotton fabric had good print output (Figure 11).

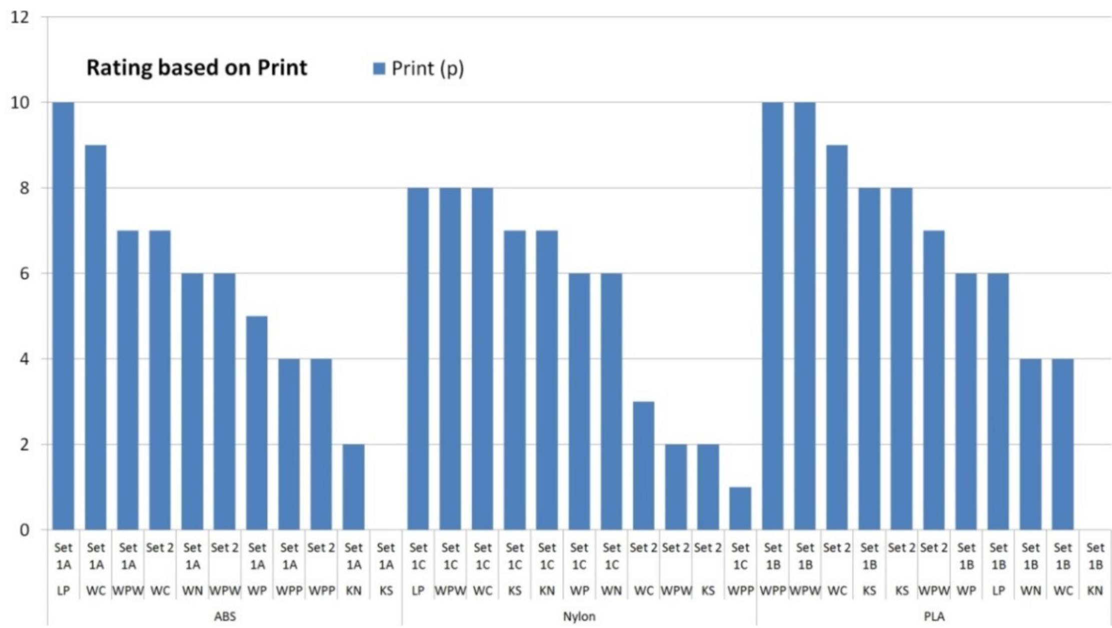


Figure 11: Rating based on Print Quality

In terms of flexural strength, only the results from Set 3 and 4 were used as it included articulated parts. From the graph (Figure 12), woven Polywool fabric performed the best for all 3 polymers. Good results were also achieved when ABS and PLA were printed on woven Cotton fabric but was less than ideal when Nylon was used. There was no data for Nylon for Set 4 due to the fact that the material had poor print definition and was not included.

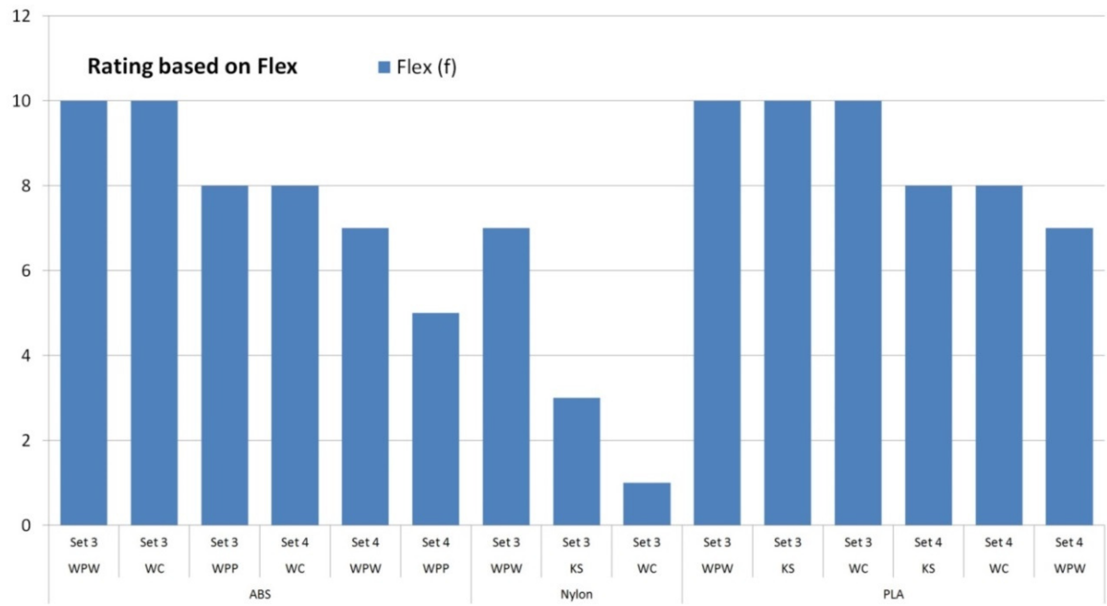


Figure 12: Rating based on Flex

4. Conclusion

Polymer deposition onto textiles covers aspects of material science, material compatibility, polymer-textile adhesion and material deposition technology. The fact that textiles comprise a wide variety of different materials with different constructions and cloth architecture, understanding of the interface phenomena with polymers has been a challenge. This paper has contributed to new knowledge by providing a better understanding of polymer materials being printed directly onto fabrics using entry-level FDM machines. This work supports on-going research on wearable electronics by integrating comfortable textiles with hard wearing parts without compromising on quality and fit; and combining additive manufacturing processes with textiles to maintain the drape characteristics of the fabric. Polymer-textile deposition will contribute to new applications and functional products such as orthopaedic braces for medical use, or for decorative features such as buttons and trimmings for garments.

Apart from material compatibility, the next stage for wide-spread use depends on manufacturing processes on an industrial scale. Future work should investigate the method of deposition to minimise tensions of the fabric that may lead to distortion or stretch (Singha, 2009). In line with Holmes (1999), for the polymer to bond effectively, it must be compatible with the fibre substrate and in contact with the substrate at all points to develop the maximum adhesive bond strength. Future work should also cover a wider range of polymers, textiles and incorporating more functional features for testing. This may include modifying the fibre surface through mechanical or chemical means to achieve a more efficient adhesion with the fibre, and examining the deposition process in terms of temperature, pressure and build density. It is also expected that future work should consider the use of mechanical testing according to standardised methods. For example, Mikkonen et al. (2013) subjected the use of elongation and the breakage force according to SFS-EN ISO 3934-1 to determine how flexible materials (produced by an Objet Connex 350 printer) with different print directions of plain, parallel and orthogonal patterns would behave in the context of wearable garments.

Among the 3 polymers, PLA had the overall best results, followed by Nylon and ABS when printed on the various types of fabrics. PLA had extremely good adhesion with little warp, and still displaying a high quality of print with good flexural strength. Although, PLA is water-soluble and not sufficiently durable for long term wear, the material is still suitable for producing prototypes and for short-term use. In terms of adhesion, woven Polywool, woven Cotton and knit Soy fabrics performed the best when used with the 3 types of polymers. At this time of writing, a new material, Bendlay was tested which had promising results. The Butadiene-based material offers transparency, good flexibility with a shore hardness of D65, and can be dyed. Future work will also include wash tests involving different water temperatures, spin cycles, drying and also colouration to investigate whether the parts retain their form and if the adhesion remains intact.

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5. Appendix

Set	Textile	Polymer	Extrusion Temperature	Extrusion Speed	Fill Amount	Layer Height	Packing Density
Set 1A	woven Polypropylene	ABS	250°C	45mm/s	50%	0.1mm	0.85
	woven Polyester	ABS	250°C	45mm/s	50%	0.1mm	0.85
	woven Nylon	ABS	250°C	45mm/s	50%	0.1mm	0.85
	woven light Polyester	ABS	250°C	45mm/s	50%	0.1mm	0.85
	woven Polywool	ABS	250°C	45mm/s	50%	0.1mm	0.85
	woven Cotton	ABS	250°C	45mm/s	50%	0.1mm	0.85
	knit Soy	ABS	250°C	45mm/s	50%	0.1mm	0.85
	knit Nylon	ABS	250°C	45mm/s	50%	0.1mm	0.85
Set 1B	woven Polypropylene	PLA	210°C	45mm/s	50%	0.1mm	0.85
	woven Polyester	PLA	210°C	45mm/s	50%	0.1mm	0.85
	woven Nylon	PLA	210°C	45mm/s	50%	0.1mm	0.85
	woven light Polyester	PLA	210°C	45mm/s	50%	0.1mm	0.85
	woven Polywool	PLA	210°C	45mm/s	50%	0.1mm	0.85
	woven Cotton	PLA	210°C	45mm/s	50%	0.1mm	0.85
	knit Soy	PLA	210°C	45mm/s	50%	0.1mm	0.85
	knit Nylon	PLA	210°C	45mm/s	50%	0.1mm	0.85
Set 1C	woven Polypropylene	Nylon	250°C	75mm/s	50%	0.1mm	0.85
	woven Polyester	Nylon	250°C	75mm/s	50%	0.1mm	0.85
	woven Nylon	Nylon	250°C	75mm/s	50%	0.1mm	0.85
	woven light Polyester	Nylon	250°C	75mm/s	50%	0.1mm	0.85
	woven Polywool	Nylon	250°C	75mm/s	50%	0.1mm	0.85
	woven Cotton	Nylon	250°C	75mm/s	50%	0.1mm	0.85
	knit Soy	Nylon	250°C	75mm/s	50%	0.1mm	0.85
	knit Nylon	Nylon	250°C	75mm/s	50%	0.1mm	0.85
Set 2	woven Polypropylene	ABS	250°C	75mm/s	100%	0.1mm	0.85
	woven Polywool	ABS	250°C	75mm/s	100%	0.1mm	0.85
	woven Cotton	ABS	250°C	75mm/s	100%	0.1mm	0.85
	knit Soy	PLA	210°C	75mm/s	100%	0.1mm	0.85
	woven Polywool	PLA	210°C	75mm/s	100%	0.1mm	0.85
	woven Cotton	PLA	210°C	75mm/s	100%	0.1mm	0.85
	knit Soy	Nylon	250°C	75mm/s	100%	0.1mm	0.85
	woven Polywool	Nylon	250°C	75mm/s	100%	0.1mm	0.85
	woven Cotton	Nylon	250°C	75mm/s	100%	0.1mm	0.85
Set 3	woven Polypropylene	ABS	250°C	75mm/s	100%	0.1mm	0.85
	woven Polywool	ABS	250°C	75mm/s	100%	0.1mm	0.85
	woven Cotton	ABS	250°C	75mm/s	100%	0.1mm	0.85
	knit Soy	PLA	210°C	75mm/s	100%	0.1mm	0.85
	woven Polywool	PLA	210°C	75mm/s	100%	0.1mm	0.85
	woven Cotton	PLA	210°C	75mm/s	100%	0.1mm	0.85
	knit Soy	Nylon	250°C	75mm/s	100%	0.1mm	0.85
	woven Polywool	Nylon	250°C	75mm/s	100%	0.1mm	0.85
	woven Cotton	Nylon	250°C	75mm/s	100%	0.1mm	0.85
Set 4	woven Polypropylene	ABS	250°C	75mm/s	100%	0.1mm	0.85
	woven Polywool	ABS	250°C	75mm/s	100%	0.1mm	0.85
	woven Cotton	ABS	250°C	75mm/s	100%	0.1mm	0.85
	knit Soy	PLA	210°C	75mm/s	100%	0.1mm	0.85
	woven Polywool	PLA	210°C	75mm/s	100%	0.1mm	0.85
	woven Cotton	PLA	210°C	75mm/s	100%	0.1mm	0.85

Table 11: Print settings used for the experiments