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MATERIALS ENGINEERING | REVIEW ARTICLE

Textile additive manufacturing: An overview

Edmund M. Keefe[1], Jack A. Thomas[1], Gary A. Buller[1] and Craig E. Banks[1]*

Abstract: Additive manufacturing (3D-printing) is a rapidly emerging technology grouped under the heading of Industry 4.0 and revolutionises the way products are created. One emerging area is textiles (apparel) where additive manufacturing allows the rapid fabrication of products that are not easily produced using traditional manufacturing approaches. In this review, we provide an overview of recent developments in textile additive manufacturing highlighting this exciting and rapidly growing research area and offer insights into the future perspectives of this promising and innovative technology.

Subjects: Material Science; Composites; Industrial Textiles; Polymers & Plastics; Textile Manufacturing

Keywords: Textiles; additive manufacturing; 3D-printing; fabrics; apparel

1. Introduction

Additive Manufacturing is a digital process enabling the rapid production of three-dimensional parts via layering and is now rapidly finding widespread utilisation in a plethora of scientific areas. Initially the media use the term “3D Printing” as a synonym for all Additive Manufacturing processes, but there are many individual processes varying in their methodology of layer manufacturing. Each individual process differs, depending on the material and machine technology used the resultant prints will display isotropic strength and bond (*e.g.*, stereolithography) or anisotropic (*e.g.*, Fused Filament Fabrication) which will dramatically influence the resulting additive manufactured structures and their applications. Additive manufacturing continues to grow due to its inherent advantages over conventional manufacturing, which include: 1) eliminating design constraints (*e.g.*, no stencils/screens or moulds); 2) flexibility in design, removing expensive tooling requirements; 3) dimensional accuracy; 4) wide range of available materials; 5) ability to manufacture high-value replacement and repair parts; 6) small manufacturing footprint and continually shrinking equipment costs; 7) green manufacturing, where additive is reported to reduce waste over than of subtractive; 8) on-demand manufacturing, on-site reducing the transportation of parts and reducing CO_2 footprints; and last, 9) the ability to additive manufacture parts with complex geometries that cannot be made via traditional manufacturing approaches. Potential limitations are as follows: limitation on the range and diversity of materials that can be additive manufactured, lack of data for end-use uptake and regulations, and last, limited to relatively small parts/low volume manufacturing. Indeed, as the field

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PUBLIC INTEREST STATEMENT

Additive manufacturing (3D-printing) is an emerging industrial technology that is used in a plethora of areas allowing bespoke parts with complex geometries and little wastage to be realised. One area of recent interest is the additive manufacturing onto textiles and textiles themselves. This paper provides an overview of the recent developments in textile additive manufacturing increases, such issues will be overcomes. For example, the issue of volume can be overcome as additive manufacturing machines can now rapidly manufacture tens/hundreds of thousand parts, economically and rapid, and this can be further increased via additive manufacturing "print farms"; the outputs of additive manufacturing machines will clearly grow. As such, it should be considered on a case-by-case basis to uptake mass production via additive manufacturing over traditional manufacturing (*e.g.*, injection moulding).

One key application of additive manufacturing is in the area of textiles, termed *Textile Additive Manufacturing* which is changing the value chain in the apparel industry through digital manufacturing (Chakraborty & Biswas, 2020; Kabir et al., 2020; Valtas & Sun, 2016). The process can be envisaged as starting from scanning the body to ensure made-to-measure apparel is produced with the data allowing an avatar to be created allowing online testing and checking fit, style, etc., using virtual reality and then rapid manufacturing using additive manufacturing that could be localised to the person ordering the apparel reducing shipping costs, time and environmental impacts (reduced CO_2). In terms of textile additive manufacturing, generally, there are two key approaches, direct additive manufacturing upon textiles/fabrics and additive manufacturing of textiles/fabrics themselves. This has obvious applications in fashion, which can not only create aesthetically pleasing designs allowing individualisation or change mechanical properties but saves the labour and time-consuming process of having to sew them in using traditional methods, but also creating tensile structures, unusual shapes and functional additions, and also potential electrical and mechanical applications. Some recent applications include smart textiles such as electronic components on textiles (Grimmelsmann et al., 2016) ankle braces (Pattinson et al., 2019) thermal regulation textiles (Chatterjee & Ghosh, 2020) e-skin for tactile sensing through triboelectric effects (Chen et al., 2021) much more. In this review, we will overview approaches of additive manufacturing onto textiles and textiles/fabrics themselves and summarise recent exciting developments and highlight potential future developments of *Textile Additive Manufacturing*.

2. Additive manufacturing onto textiles

Figure 1 shows exciting examples of additive manufacturing onto textiles where using thermoplastic polyurethane (TPU) additively manufactured via Selective Laser Sintering (SLS), a standalone dress has been designed and fabricated in collaboration with Iris van Herpen, Julia Koerner and the company Materialise. Clearly the ability to be able to rapidly prototype ideas has significant benefit allowing new designs with added functionality, which is clearly of huge interest and advantage. The use of additive manufacturing onto textiles can be traced back as early as 2013 (Passlack et al., 2013) with (Sabantina et al., 2015) additive manufacturing floral patterns via Fused Filament Fabrication (FFF) onto cotton, wool, viscose fabric and polyester nets, with the authors noting that textiles nets give rise to sufficient connection with that of the additive manufactured printed layers, and noting that the approach has potential for utilisation in garments (Richter et al., 2015; Sabantina et al., 2015) used FFF to fabricated PLA and NinjaFlex (flexible thermoplastic polyurethane) into 3D structures with carbon and PMMA fibres trapped between print layers.

It is clear that there are many parameters that can affect the quality of textile additive manufacturing which include, but not limited to: 1) the choice of the additive manufacturing material, usually plastic and its composition; 2) additive manufacturing printer settings, dependent upon the choice of the technology being utilised, for example, for a FFF printer, the print settings, *e.g.*, layer height, printing speed, extrusion width, extruder settings, distance between the nozzle and the print bed, the print bed type and temperature, adhesion of the apparel to the print bed; 3) the textile material, its composition, type, thickness and physicochemical properties/surface properties and any pre-treatments. All these need to be fully understood for the field of textile additive manufacturing to progress further.

A key issue related to points 1–3 above, for textile additive manufacturing to significantly grow, is the issue of adhesion of the printed material onto the chosen apparel. For example, one can envisage bespoke fitting joint support bandages that are fitted to individuals via scanning and creating an appropriate workflow which can be additively manufactured but their practical uptake

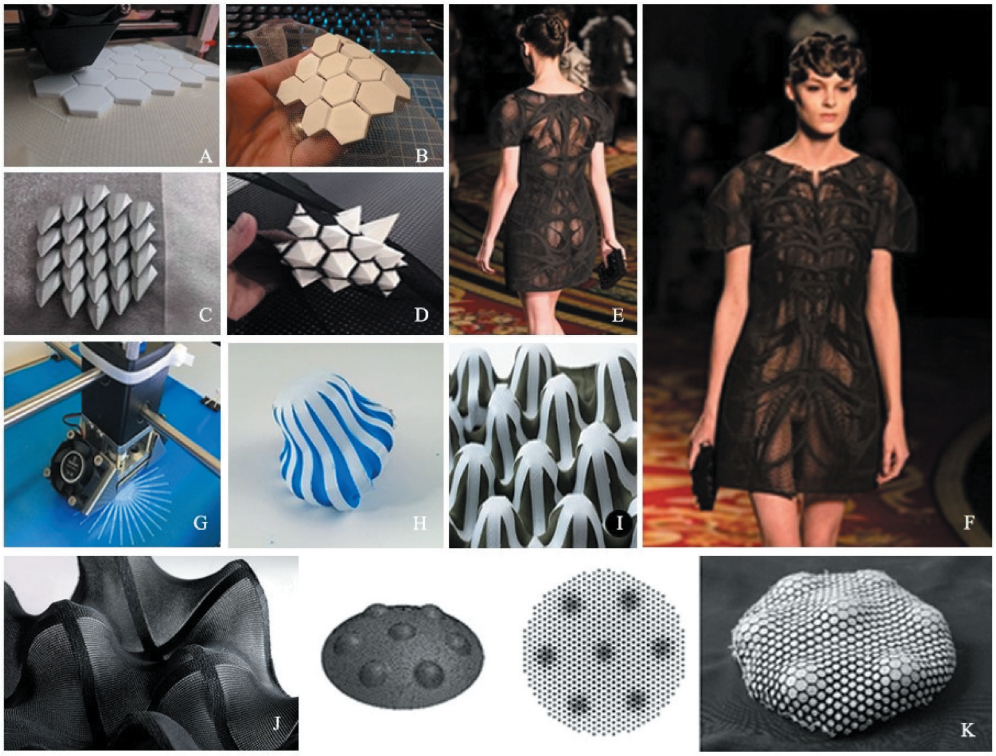

Figure 1. Some exciting examples of how additive manufacturing can be integrated with textiles/fabrics. (a), (b): Hexagons; image from: (DrainSmith**)** (c): Dragon scales; Image from: (Shorey**)** (d): Hexagonal pyramids; image from: **https://www.geeetech.com/blog/2018/02/3d-printing-on-fabric-is-easier-than-you-think/** (e), (f): TPU additive manufactured (via Selective Laser Sintering) standalone dress (left and middle images) made in collaboration with Iris van Herpen, Julia Koerner and the company Materialise; Image from: **https://www.materialise.com/en/cases/iris-van-herpen-debuts-wearable-3d-printed-pieces-at-paris-fashion-week** (g), (h): Self-forming structures on stretched fabric showing intrinsic curvature. After additive manufacturing plastic onto a textile surface, the resultant print forms a 3D object reminiscent of a jellyfish; Image from: (Gabe Fields) (i), (j) Regions of alternately positive and negative Gaussian curvature. Image from: (Gabe Fields, XXXX, YYYY, XXXX**)** (k): CAD model, that is used to generate the pattern to print onto fabric and then the resulting stricture with intrinsic curvature; Image from: (Gabe Fields).

is limited by the adhesion between the polymer and the fabric. There are many endeavours in exploring how to improve this adhesion. Additive manufacturing textiles are tested via adhesion tests (mechanical peel testing) in-line with standards (*e.g.*BS EN 28510–1 Zhang, Liu, Ji, Banks, Zhang et al., 2011a) where the 180 degree peel strength can be calculated from the average load to separate the textile from the additive manufactured printed objects. Other useful measurements, where appropriate to assist researchers to benchmark their additive manufactured textiles include: Tear strength, bending length measurements, (Zhang, Liu, Ji, Banks, Zhang et al., 2011b) abrasion testing (Tiwari et al., 2014) and the effect of washing (Zhang et al., 2014). It is clear that the material type is critical to obtaining sufficient adhesion between the additive manufactured polymer/plastic and chosen textile, where net-like fabrics provide the upmost adhesion since the molten polymer/plastic permeate through the pores of the fabric enclosing the threads and yarns. Other approaches involve the creation of bi-material 3D printed objects, where the textile is trapped between printed layers (Richter et al., 2015). The issue of poor adhesion arises with textile fabrics that are "closed" such as common woven fabrics (Meyer et al., 2019; Pei et al., 2015).

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. It is necessary to study the adhesion/bonding of substrates that vary in terms of solid, fluid, molten, powder and so on. Adhesion strength of additive manufactured flexible polymers is influenced by form-locking connection of the molten polymer with that of the textile substrate (Korger et al., 2016). Second, printed parts should not interrupt the drape of the fabric so as to allow for free movement. The drape can be influenced by the additive manufacturing embellishment but cannot overly restrict drape/flow otherwise the garment would become functionless. It is important to carefully select positions that coincide with intended folds and stitches and manoeuvre 3D elements around them to not interrupt garment construction. Drape has been found to be significantly influenced by additive manufacturing onto textiles and especially by the free spaces between the additively manufactured areas as well as the overall areal weight of the fabric; depending on the arrangement of the patterns, different effects could be included (Spahiu et al., 2017). 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 (Holme, 1999).

Pei and co-workers (Pei et al., 2015) explored the use of FFF with ABS, PLA and Nylon 645 onto a range of different textiles, namely, polypropylene, polyester, Nylon, Polyester wool, soy and cotton with different weave structures (woven and knit) and explored printer parameters (*e.g.*, extrusion temperature and speed, fill amount, layer height and packing density) and printed forms (*e.g.*, warping, bonding and flex). The authors reported that PLA had the best results overall followed by Nylon and ABS when printed on the various types of fabrics. PLA had extremely good adhesion with little warp and still displayed a high quality of print with good flexural strength (Pei et al., 2015). The authors noted that 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 Polyester wool, woven cotton and knit soy fabrics performed the best when used with the three types of polymers. (Grimmelsmann et al., 2018; Pei et al., 2015) extended the study of Pei and co-workers (Pei et al., 2015) to demonstrate that the z-distance, defined as the distance between nozzle and printing bed, was found to be a crucial parameter for the adhesion. Using FFF technology, the authors explored the additive manufacturing of PLA, ABS and PA 6,6 upon woven and non-woven polyester, wool and cotton textiles. The authors found the effect of the z-distance was most pronounced for PLA additive manufacturing on polyester but smaller for ABS and Nylon as well as wool or wool/polyester textile substrates; adhesion forces were shown to coincide with polymer layer thickness. (Grimmelsmann et al., 2018)

The parameters of the additive manufacturing machine obviously have a profound effect upon the adhesion of the printed plastic with that of the textile. For example, Spahiu and co-workers (Spahiu et al., 2018) reported that the z-distance, *i.e.* the distance between the nozzle and the printing bed is a critical parameter showing that as the distance is decreased, the adhesion forces increases until a minimum distance is reached which presses the additive manufactured polymer with higher forces into the open pores of woven fabric. The authors also noted that the printing bed and nozzle temperatures are important, with higher temperatures decreases the viscosity for the molten plastic during printing. (Eutionnat-Diffo et al., 2020; Spahiu et al., 2018) studied the wear resistance of conductive PLA, additive manufacturing via FFF onto PET fabrics. Abrasion resistance was measured according to ASTM D4966-12 and it was concluded that the weave type (or pattern), the weft density and the print bed temperature were the most importance parameter in controlling the abrasion resistance. Additionally, the electrical conductivity of the additive manufactured conductive PLA was significantly impacted by the abrasion process, clearly an area to be researched to overcome such limitations.

Meyer et al. (2019) explored the influence of a polymeric coating (5% PMMA) on a range of textile fabrics (linen, cotton, coarse silk and polyester) from additive manufacturing soft and hard PLA. The authors found that coating with PMMA increases the adhesion significantly for the hard PLA while the soft PLA adhered better on some materials without additional coating with their study highlighting that a necessary prerequisite for high adhesion is high inter-fibre friction. Meyer et al. (2019) Thermal after-treatment *e.g.*, using ironing (Ehrmann et al., 2020) as a post-processes approach has also been reported to increase the adhesion of the additive manufacturing of plastics upon textiles for the case of FFF, (Ehrmann et al., 2020) but in other studies, no significant difference (Kozior et al., 2018). While prior work has focused upon increasing the adhesion forces between additive manufactured components and textile fabrics through careful choice of each, for example, (Kozior et al., 2018) have demonstrated that the pre-treatment of the textile surface can change its hydrophobicity resulting in significant modifications of the adhesion forces. The authors also show that this adhesion is influenced by the infill orientation, with an orientation of 90° being significantly advantageous compared to 0° (Kozior et al., 2018). Figure 2 shows how the infill orientations are derived and their effect upon adhesion forces where PLA is additive manufactured upon cotton; PLA was chosen due to prior work reporting it to be a superior material to ABS or nylon in terms of adhesion to textile surfaces (Grimmelsmann et al., 2018). Interestingly, while surface roughness was also shown to depend on the infill angle, no significant differences of the tensile strength or the elongation at break were observed. Figure 2b shows the adhesion forces versus the contact angles prior to additive manufacturing. The authors point out that most of the samples do indeed follow the (Korger et al., 2016) which is, the more hydrophilic a sample is, the higher the adhesion force is, and vice versa. The authors noted that below a contact angle of approximately 60°–80° the adhesion forces seem to saturate, while for increasing contact angles the adhesion forces constantly decrease (Kozior et al., 2018). In comparison of the highest and lowest contact angles, adhesion forces changed by a factor of 2, showing the significance of taking into account the fabric pre-treatment effects. Figure 2c shows the surface roughness of the prints have been explored for the first time by Kozior and co-workers (Kozior et al., 2018) with respect to infill orientations of the additive manufactured samples showing the average roughness Ra, the root mean squared roughness Rq, and the average distance between the highest peak and the lowest valley in each sampling length Rz. A trend toward higher roughness for angles around 90° was observed and additionally, the roughness of the first layer is higher than that of the second layer, attributed to the influence of the underlying rough textile structure. Kozior et al. (2018) have overview the current state of the art of experimental research on the adhesion of additive manufactured polymers upon textiles (Kozior et al., 2020). The authors commented that wetting, coating and pressure are critical parameters with printing speed and after-treatment need to be studied further as no direct trends have been found.

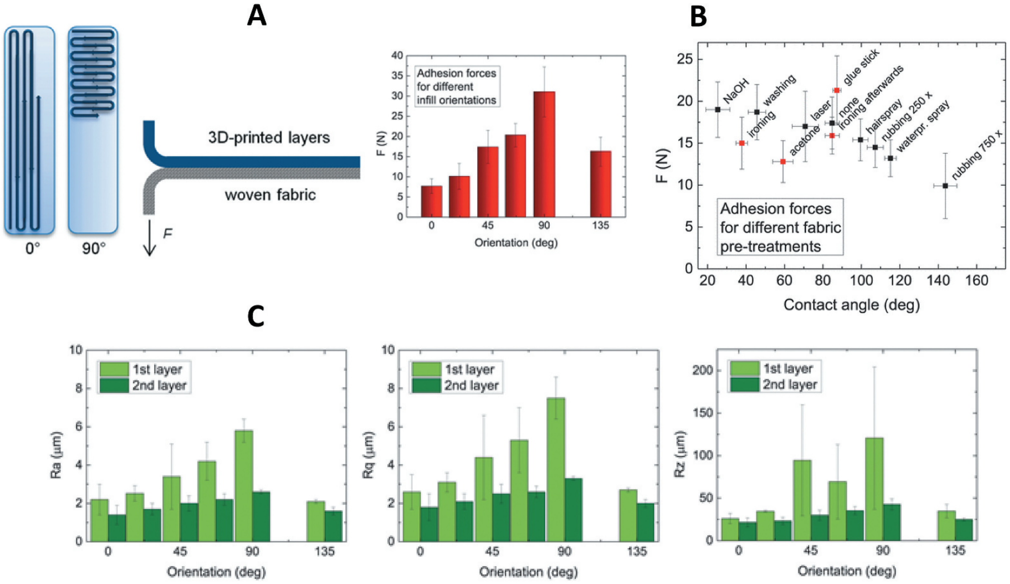

Figure 2. (a): Image of the infill orientations and the adhesion test as well as the adhesion forces measured for different infill orientations of the 3D printed samples. (b): Adhesion forces versus contact angles, measured for different pre-treatments of the textile substrates. (c): Roughness values Ra, Rq, and Rz measured for different infill orientations of the 3D printed samples. Figures reproduced from: **Kozior et al. (2018).**

Another key aspect is washing. In the case of apparel, the nature of aqueous domestic washing, tumble or line drying, ironing and pressing treatments (so-called fabric care treatments) or dry cleaning in perchloroethylene further complicate the durability of the adhesion process, particularly under the stresses applied during wear. The use of washing has been reported to control the wettability and the textile surface energy (Korger et al., 2016). Adhesion forces before and after washing have been shown to positively correlate to extrusion temperature and negatively correlated to print speed and layer height (Sheron Mpofu et al., 2020).

2.1. Additive manufacturing onto textiles: controlling form via post-composite morphologies

An innovative approach is to additive manufacture onto stretched fabrics, Figure 3, which upon release transforms from a flat 2D pattern into a 3D geometry (Agkathidis et al., 2018; Berdos et al., 2020). TPU is additively manufactured onto stretchable fabrics such as Lycra and through careful design via computational simulations, and control of the printed patterns, various geometries can be readily realised (see, Figure 3) where 2 flexible materials, when acting together, allow for

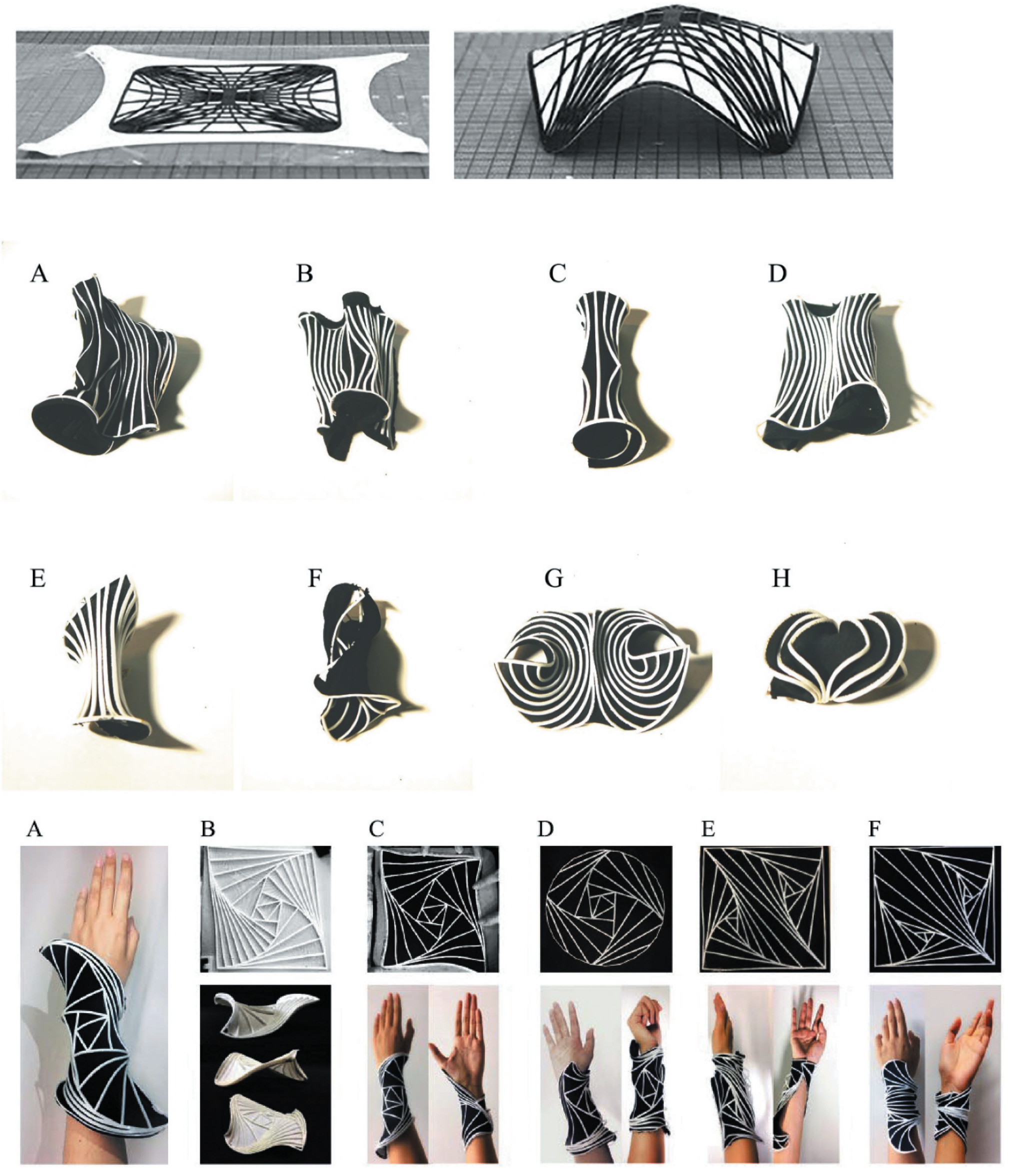

Figure 3. Top image: image illustrates the flat 2D pattern and the resulting 3D geometry after release. Middle image: Set of patterns used in experiment 1; Bottom image: Experiment 1, iterations A-H. Images reproduced from: **Berdos et al. (2020)** Tests (a, b, c, d, e, and f)—two-directional embossed patterns calculated to produce a wearable with prescribed form. Images reproduced from: **Agkathidis et al. (2018).**

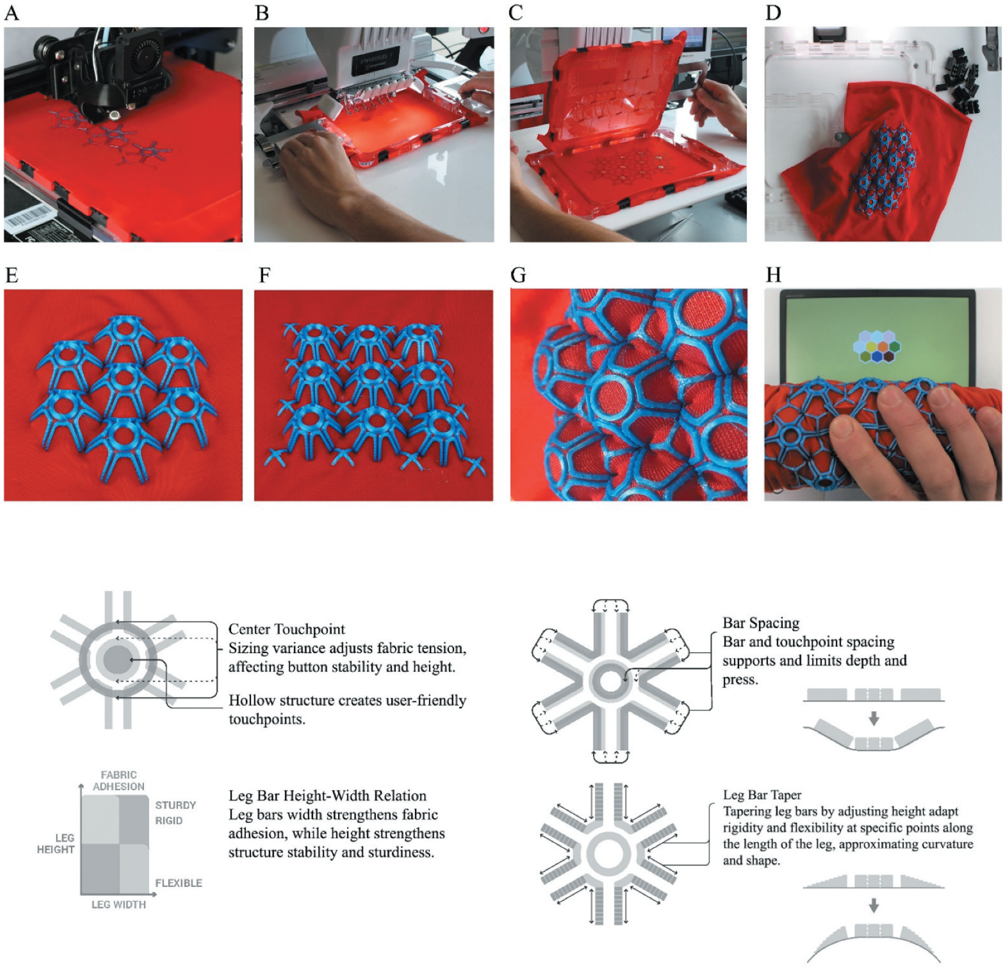

Figure 4. Top panel: Additive manufacturing of pushbuttons. (a): The additive manufacture or embroider of patterns on one pre-stretched Lycra sheet as the button layer; (b): Embroider conductive and insulation traces on another pre-stretched Lycra sheet as the Circuit layer; (c): Alignment of the two layers which are stitched together; (d): Removal to form the 3D push-buttons. Bottom panel: (e): Nine buttons in a hexagonal tile; (f): Nine buttons in a 3 × 3 tile grid; (h): Results as an on-screen visualisation of real-time signal processing where the pushbuttons are electrically wired. The line drawings show the various parameters that will tailor the pushbuttons. Images reproduced from: **Goudswaard et al. (2020).**

variable states of stiffness and structural capacity, and is termed *Active Fabrication*. (Agkathidis et al., 2018; Berdos et al., 2020) Another innovative approach is "*FabriClick*" where the additive manufacturing of push buttons on fabrics has been shown to be possible (Goudswaard et al., 2020). Figure 4(a–d) shows the workflow of the 3D push buttons. The first stage involves the additively manufacturing or embroider of patterns on pre-stretched Lycra sheet. Next conductive and insulation traces on another pre-stretched Lycra sheet as the Circuit layer are embroidered. The two layers are stitched together to form the 3D push buttons. Figure 4(e–g) show nine buttons in a hexagonal and tile formation. The authors also showed that the FabriClick can be connected to a computer (Figure 4h) via connecting the embroidered circuitry to an Arduino using crimps which allows the on-screen visualization of real-time signal processing (Goudswaard et al., 2020). The authors suggest that the FabriClick has a multitude of applications, such as assisting patients to alert medical staff when in need or be used as a life-logging or self-reporting interface that is easy to access or in whole-body or VR gaming approach, while in social contexts, the buttons from the wearer could be either extruding, exaggerated to attract others attention and curiosity, so that could become an icebreaker that facilitating social conversation (Goudswaard et al., 2020).

4D printing is an emerging field in additive manufacturing of time responsive programmable materials and objects (Biswas et al., 2021; Koch et al., 2021; Ryan et al., 2021). Figure 9, shows a schematic of the 4D printing process that combines additive manufacturing and smart materials to create products that react to external stimuli over time. To this end, Leist and co-workers (Leist et al., 2017) utilised FFF with PLA upon Nylon fabric for the creation of smart textiles. PLA possesses thermal shape memory behaviour and maintains these abilities when combined with nylon fabric that can be thermomechanically trained into temporary shapes and return to their permanent shapes when heated. Figure 9 shows PLA additive manufactured (via FFF) onto nylon fabric (Solid Power Mesh Fabric Nylon Spandex made up of 90% nylon and 10% spandex) where upon the application of an external stimuli, in this case heat (in a pool), at 70°C a flat structure is readily transformed into a cylinder. This structure is then removed from the heated pool and allowed to cool to room temperature, remaining stiff and maintaining its cylindrical shape. Upon the application of heat, the cylinder unravels back to its initial permanent flat shape when the cylinder is returned to the heated water (Figure 9). This exciting response is further illustrated with additive manufactured PLA upon Nylon for encapsulating or grabbing objects. As shown in Figure 9, a common laboratory magnetic stirrer bar placed into the centre of the additive manufactured modified fabric is able to be encapsulated when the external stimuli, temperature, is applied above 60 °C. This is then removed and allowed to cool and maintains its folded structure with the stirrer bar encapsulated. This can be reversed when the fabric is returned to a heated water bath (70 °C). *So how does this exciting discovery works that allows smart textiles to be readily transformed into custom shapes when an external stimuli is applied, in this case, heat?* The authors cleverly utilise the benefits of PLA, which is a semi-crystalline thermoplastic and thus by definition, becomes soft when heated and hard when cooled and can undergo this processes several times without any change in their chemical/mechanical properties. This of course works only if the temperature is above its T_g and that the thermoplastic doesn't reach its T_m. In this case, PLA possess a T_g of ~ 58–60°C and a T_m of ~150-220°C, and temporary shapes can be created from the PLA material when the thermal stress (external stimuli) is applied above the T_g and maintain when the PLA is cooled. This shape can be reversed back to its original when the temperature is applied above its T_g. As Leist et al point out, this innovative approach allows for custom shapes and aesthetics for clothing, or the encapsulation and release of materials when activated by their environments. DrainSmith Clearly, this approach has opportunities combining AM and thermoplastic feed stocks to realise the benefits of 4D printing for creating smart textiles and beyond.

2.2. Additive manufacturing of textiles

Rather than additive manufacture onto textiles, as so far highlighted above, another approach is to additively manufacture the textiles themselves. FFF (and to a lesser extent SLA) can produce parts and sheets that exhibit tradition textiles qualities. The main difference being the lack of textile fibres either synthetic or natural. This is a hurdle all additive manufacturing faces when coming to replicating, embellishing or fabricating what could be considered textiles. Melnikova et al. (2014) used SLS to fabricate single-face weft knitted fabrics using nylon as the sintered powdered material used in the additive manufacturing process. However, the authors discredited this approach, stating that it was too hard to be used in typical textile applications such as garments and rather opted for FFF technology. The authors utilised FFF printing with ABS but found it too brittle for the desired fine structures, instead, they opted for PLA—also in combination with less flexible materials such as BendLay (butadiene)—which was proven to be able to reproduce some textile-based structures. (Beecroft, 2016; Beecroft, 2019; Melnikova et al., 2014) challenged this negative report of SLS exploring both single- face and double-face weft knit tubular structures and explored SLS additive manufacturing printing parameters to vary the pipe wall thickness, internal diameter and loop height and width with their compression, extension, stretch and flexibility recorded (see, Figure 5). Beecroft demonstrated that it is possible to additive manufacture tubular knit-based structures via SLS which exhibited the stretch and extensibility of traditional knitted textile structures.

The use of additive manufacturing has made enough of an impact on the fashion world that it has entered the world of performance and mainstream media attention. A drag queen on the 2021 season of Ru Paul's Drag Race UK donned a prehistorical inspired outfit that was almost entirely additive manufactured (see, Figure 6). The model had their face and body scanned and the dress and face mask combination were both sculpted around the scanned form. The mask shape was designed to accompany specific makeup choices and fit perfectly to the models face. The Bodice was not very flexible but functional as a show piece for its purpose on the catwalk.

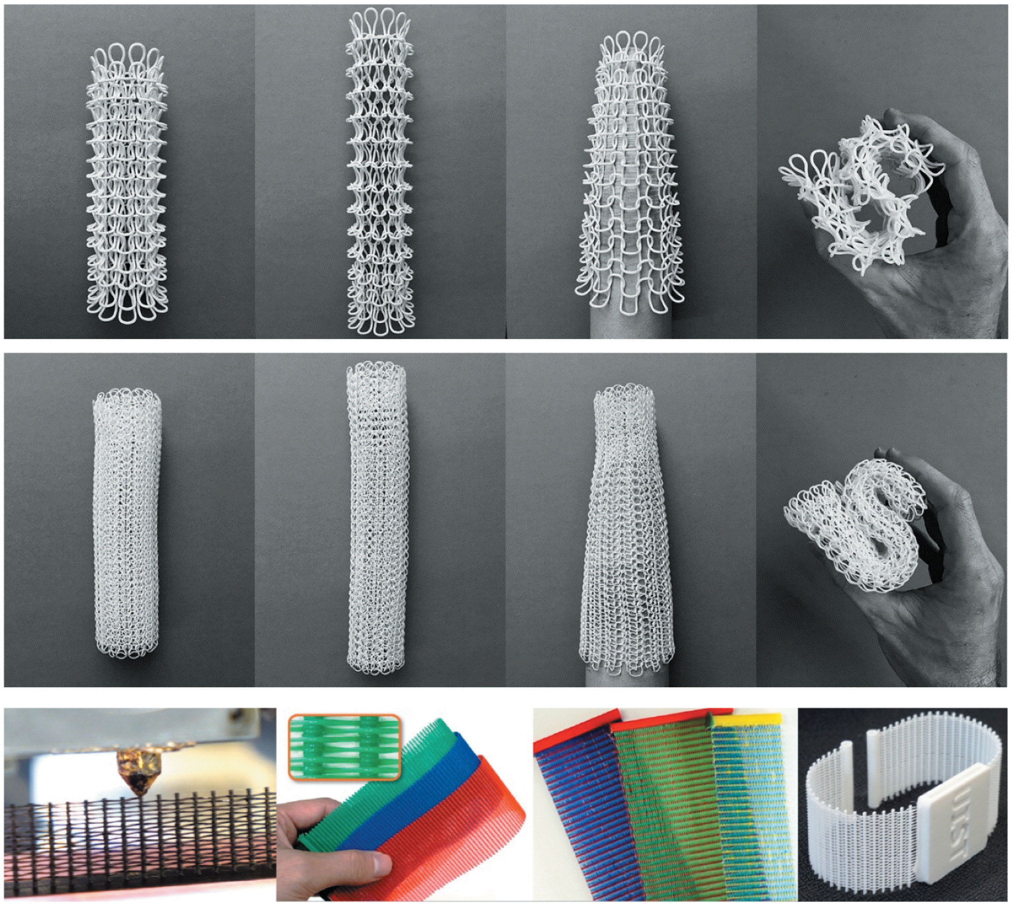

Figure 5. SLS additive manufactured Nylon (PA12) into a single-face (Top image) and double-face (middle image) weft knit tubular structures. In both cases, each image is (left to right) compressed, extended, stretched and folded. Images taken from: (**Beecroft, 2019**) Bottom Image: Using an additive manufacturing (FFF) nozzle to deliver 3D weaving, which leads to a range of useful 3D printed structures. A base is first additive manufactured (which can be removed), followed by pillars (in the z-axis) and then fibres (xy-axis) allowing one to use additive manufacturing to weave a fibre. The additive manufactured woven PLA fabric is free-standing and is bendable and can be integrated with an additive manufactured solid object. Images reproduced from: **Takahashi and Kim (2019).**

Danit Peleg designed and printed her own final fashion collection in 2015 using only desktop printers (See, Figure 6). The collection demonstrated two things of note. First, the increasing viability of additive manufactured garments in the everyday. Second, increasing accessibility of additive manufacturing allows creatives, academics, and engineers to experiment and test the limitations of additive manufacturing. Peleg printed her collection with FilaFlex, a flexible polymer filament. The materials choice and skeletal/planar lattices enabled for garments that swayed and deformed with normal body movements but with had enough elastic potential to reform to its intended shape. Peleg's planar patterned textiles were based on mesostructures designed by Andreas Bastian (Figure 7). The patterns demonstrate how selective deposition of planar geometries can enable bend and flex which can then translate into drape, mimicking traditional textiles. The mesostructured patterns allow for omnidirectional movement along one plane. This non-restrictive hexagonal grid model pairs well with Peleg's garment making techniques and demonstrates viability for wearable technology.

Spahiu et al. (2020) used FFF to explore a range of filament materials to print a fully finished dress finding that the flexible Filaflex was the most suitable (polyurethane-based TPE) material to print an auxetic structure making the additive manufactured dress more comfortable and usable. Additionally the authors conducted a survey to gauge consumer behaviour (100 respondents) which indicated that the majority of respondents believed that additive manufacturing will be beneficial for garment production, which the authors believe is related with the wastage of garments and the possibility to produce personalised garments even at home. (Spahiu et al., 2020; Uysal and Stubbs, 2019) demonstrated a 3D printed glove using FFF with textile-like structure, including the use of drape tests. Takahashi and Kim (2019) have presented a technique to fabricate soft and flexible textiles using PLA via FFF. This novel additive manufacturing approach to producing 3D printed fabrics

Figure 6. Top Image: Additive manufactured dresses as shown on the 2021 season of Ru Paul's Drag Race UK. Image from: **https://boudoirnumerique.com/magazine-en/rupauls-drag-race-uk-season-2-the-drag-queen-awhora-takes-inspiration-from-iris-van-herpen-for-her-3d-printed-outfit-59328** Bottom Image: 5 Additive manufactured fashion pieces by Danit Peleg. Images from: **https://danitpeleg.com/the-process/.**

is based upon controlling the movement of the FFF print head which weaves the stringing PLA fibres across a row of pillars (see, Figure 5)—the method pulls melted PLA material quickly moving the printing head away to achieve a stringing effect. In such a fabrication, a base is first printed (which can be removed later if so desired), upon which pillars are additive manufactured (z-axis) which are equivalent to a *warp* and then fibres (xy-axis) are additive manufactured, which are equivalent to the weft in *traditional looming* (Takahashi & Kim, 2019). The authors also demonstrated that conductive ABS could be used to additive manufacture 3D woven electronic structures. Such a novel approach of using additive manufacturing to weave PLA will surely be extended to other materials. Very recently, (Forman et al., 2020) reported *DefeXtiles*, a new strategy to additively manufactured quasi-woven fabrics which are thinner and more flexible in comparison to other approaches. In this approach, the textile is printed perpendicular to the print bed allowing complex geometries to be produced such as pleated and curved textiles. Figure 8 shows the length scale that can be achieved right up to 70 meter rolls of fabric produced in a single print along with how the printing technology works and images of complex structures. Last, (Grothe et al., 2020) have reported the first use of SLA printing onto textile fabrics.

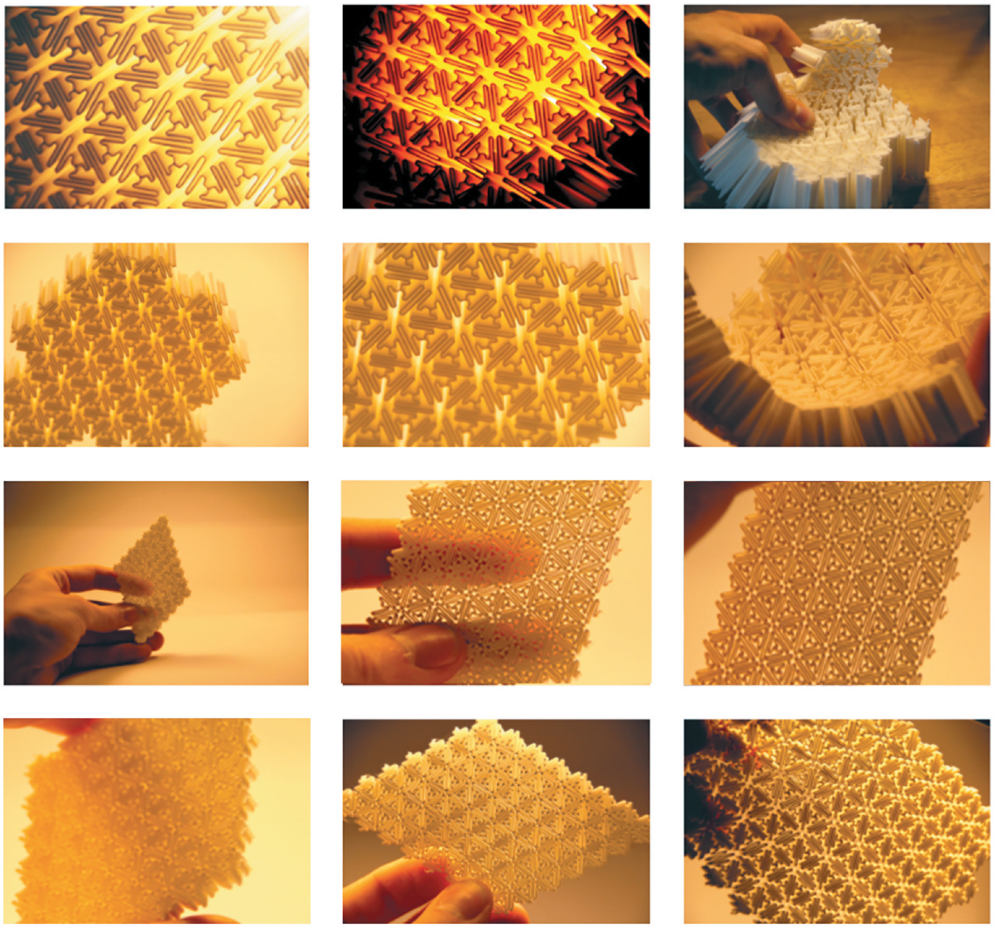

Figure 7. Images of planar patterned textiles based upon Mesostructures showing cellular materials, auxetic properties, and repeating planar (extruded) patterns. Images by Andreas Bastian, from: **https://danitpeleg.com/the-process/**.

3. Additive manufacturing of SMART TEXTILES

As the smart textile industry 4.0 based systems increase, the requirement for wearable antennas is equally growing allowing wireless connectivity, which is part of the Internet of Things (IoT) where physical objects, termed "things" are part of a network of physical objects such as sensors connected to the internet to transfer data. Such example could be clothing for the elderly, allowing them to communicate in emergencies without having to wear noticeable assistive devices, or such as medical/health sensors (*e.g.*, Smart Healthcare) monitoring vital analytes for health with the data continuously sent to healthcare professionals for remote digitalised healthcare monitoring and intervention. To this end, (Akbari et al., 2017) have reported, for the first time, the integration of additive manufacturing of graphene ultrahigh frequency (UHF) radio-frequency-identification (RFID) antennas on textiles and other materials (wood and cardboard). The authors compared the curing of additive manufactured graphene antennas on textiles via conventional oven or photonically via pulsed Xenon flashes. Prior work has utilised additive manufacturing to produce metallic antennas which are relatively expensive, require high curing temperatures, due to them being metallic and generally have been reported to utilised non-biodegradable and toxic chemicals/solvents (Akbari et al., 2017) and generally involve fabrication via screen-printing and/or doctor blading and due to the requirement of a screen/stencil respectively, and can limit design changes and other approaches have utilised ink-jet printing (Roh et al., 2010). The use of the 2D material graphene in the fabrication of antennas has bene reported to allow low curing temperatures and use as lightweight components (Akbari et al., 2016; Palacios et al., 2010) utilising its reported beneficial properties, which include: high charge mobility, zero band gap and high mechanical properties In contrast, (Akbari et al., 2017) utilised the benefits of graphene and additive manufacturing via the use of commercially available

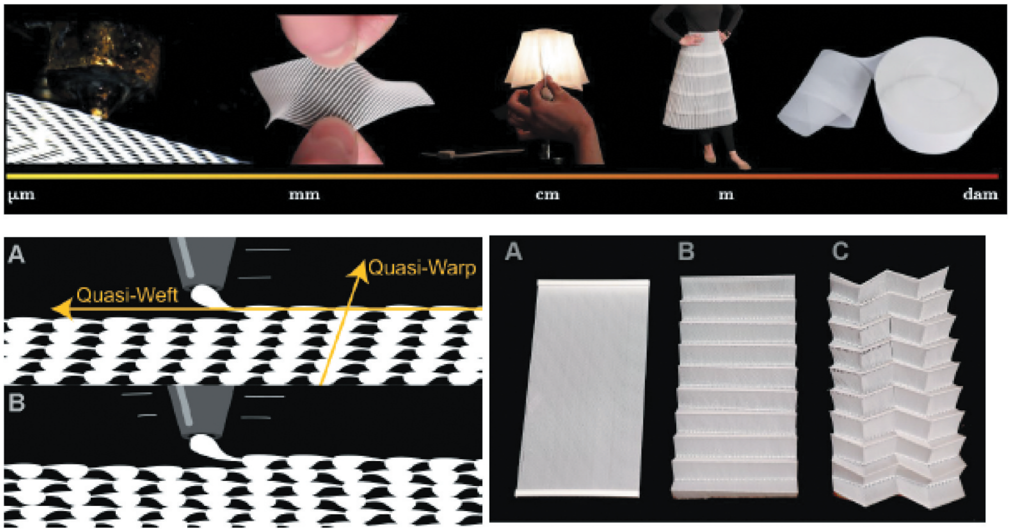

Figure 8. Top image: Length scale overview of DefeXtiles from millimeters to decameters. (1) microscope image of a DefeXtile being printed, (2) A DefeXtile being stretched, (3) an interactive lampshade with capacitive sensing, (4) a full-sized skirt, (5) a 70 m roll of fabric produced in a single print. All samples were printed on a desktop FFF printer. Bottom left image: DefeXtiles' working principle leverages under-extrusion of 3D printing filament to create breathable textile structures. Note that the extrusion rate is constant; the structure is formed as small globs are simply stretched along the print di-rection. A) shows this gap-stretch behaviour which generates a "quasi-warp" and "quasi-weft". For A) the nozzle prints from right to left causing the pillars to lean right. For B) the quasi-warp is straight as the nozzle alternates direction each layer. Bottom right image: DefeXtiles of increasing complexity. (a) A flat sheet printed with support pillars, "(b) a pleated sheet, and (c) a meta-material sheet. Images reproduced from: **Forman et al. (2020).**

few layered graphene nanoplatelet ink utilising Direct-Ink-Writing (DIW) which is an extrusion-based additive manufacturing method utilised in meso- and micro-scales. In this DIW approach, the ink, in a liquid-phase, in this case, graphene ink, is dispensed out of small nozzles defining the size of the resultant print under controlled flow rates and deposited along digitally defined paths to fabricate additive manufactured structures. Using this approach (Akbari et al., 2017) additive manufactured onto 100% cotton fabrics comparing the curing of the ink via a continuous pulsed photonic light or via traditionally employed oven curing, with the former showing superior read range results over the latter. Such an approach (Akbari et al., 2017) offers a rapid and inexpensive manufacturing approach for UHF RFID graphene tags on textiles with micron-resolution without the need for any masks/stencils/screens and clearly has the potential to be extended to other 2D and related materials. Smart clothing with antennas to connect to the IoT is essential to meet the demand for wireless communications and the potential application of wearable textile antennas in this field continues to increase. Recently, this avenue of research has been further explored by He et al. (2019) who fabricated and explored the performance of textile-integrated stretchable UHF RFID tags, and evaluated their reliability in high moisture conditions (*e.g.*, immersing into water), as well as during and after multiple bending and stretching. Stretchable antennas were fabricated by additive manufacturing (via direct write) via printing a silver conductor onto an elastic band. The integrated circuit (microchip attachment) to joint to the additive manufactured antenna was explored in three ways: 1) Glueing the

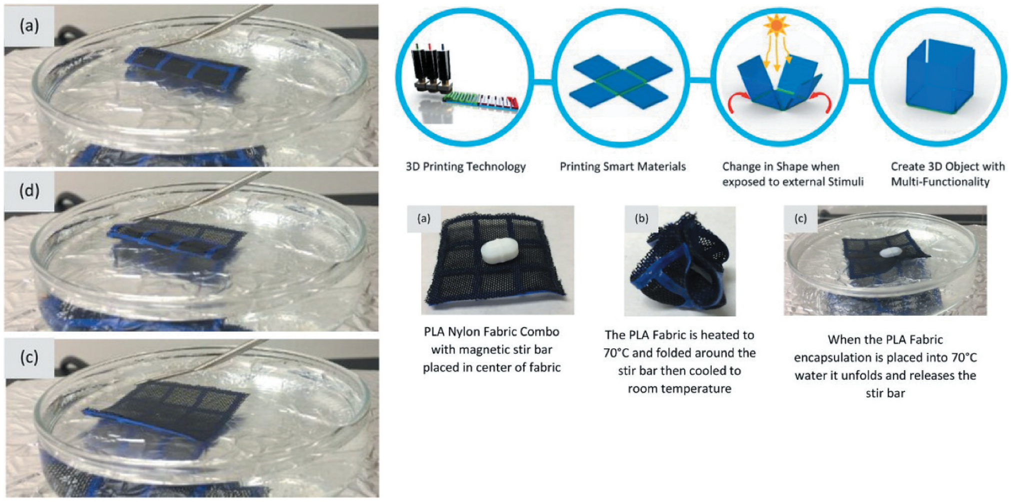

Figure 9. Top right: Schematic of the 4D printing process that combines 3D printing and smart materials to create products that react to external stimuli. Bottom right: An example of using smart textiles for encapsulation applications. (a) A magnetic stir bar is placed in the centre of the PLA nylon fabric. (b) The PLA nylon fabric is heated to 70°C and encapsulates the stir bar, then removed from the heated water to cool to room temperature and able to maintain its shape. (c) The PLA nylon fabric unravels and releases the stir bar when the PLA nylon fabric is returned to the heated bath. (left image). Top left: A PLA and nylon fabric is heated to 70°C and rolled into a cylinder then cooled. (a–c) The PLA nylon cylinder unfolds into its permanent flat shape when reheated in the 70°C pool of water. (bottom right). Images reproduced from: **Leist et al. (**2017**).**

antenna and the integrated circuit with conductive epoxy glue; 2) additive manufacturing the antenna directly on top of the integrated circuit structure; 3) connecting the integrated circuit via embroidering with conductive yarns. All approaches were evaluated as antennas and after wetting and cyclic bending (*e.g.*, stretching and bending). The tags with additive manufactured antenna—integrated circuit joints (approach 2 as described above) achieved the longest read ranges, which were around 0.8 and 1.6 meters better than the tags with epoxy-glued and embroidered joints, respectively. Wetting and cyclic bending did not stop the tags from working in a suitable way, and they did not have any permanent effect on the tags' wireless performance (He et al., 2019). The results of the immersing test demonstrated potential for wearable tags in a high humidity environment., which could be used for example, near a sweating body and even when dipped in water. The authors also reported that bending test results indicate that the tags could be bent repeatedly while maintaining a stable performance, in all three fabrication cases (see above) which is clearly very important when integrating antennas into clothing. However, only the embroidered antenna–Integrated circuit attachment showed the best reliability in continuous strain while the others failed. Clearly, this is an area that needs development for additive manufactured antennas and those manufactured by other means, to be actually useful in textiles. Other initial work in this area has utilised the additive manufacturing of the relatively flexible material NinjaFlex (*Polyurethane*) onto cotton-based textiles with the latter demonstrating proof-of-concept (Khan et al., 2019) with the inherent challenges encountered documented for others to learn from. Other researchers, to note, have utilised NinjaFlex upon polyester fabrics for electroluminescence applications (Tadesse et al., 2018).

Another approach is to consider innovation in the underling textile with that of the advantages of additive manufacturing. In this regard, (K. Kozior et al., 2019) have utilised, for the first time, the electrospinning of polyacrylonitrile (PAN) nanofiber mats with fused deposition modelling (FFF).

Electrospinning is an established technology that allows the creation of nanofiber mats derived from diverse polymers and related materials. Such applications in air/water filters, wound dressings, drug delivery and textiles (Mirjalili & Zohoori, 2016). In a range of application involving electrospinning, is the requirements to be mechanically stable which can involve the adhesion of electrospun nanofiber mats onto rigid objects. K. Kozior et al. (2019) reported the direct additive manufacturing via FFF of PLA onto PAN nanofiber mats. Under optimised conditions the adhesion between both parts of the composite is high enough to prevent the PAN nanofiber mats from being peeled off the additive manufacturing polymer composite. Contact angle measurements revealed no significant differences in hydrophilicity of the additive manufactured PAN nanofiber composite mats compared to bare PAN nanofibers, while abrasion tests emphasize the significantly increased mechanical properties with increased abrasion resistance. K. Kozior et al. (2019) Such work has the potential to be explored further with different electrospun textile materials and different additive manufacturing techniques and feed stocks.

4. Conclusions

This review has overviewed recent advances and developments in textile additive manufacturing which is a truly multidisciplinary research field. The ability to rapidly design and additively manufacture bespoke, cost-effective, individualised (exact fit via scanning) and customised textiles is an exciting field that will continue to grow allowing for new designs and functionalities to be realises that cannot be easily achieved by conventional textile fabrics. The environmental benefits are clear allowing localised manufacturing reducing CO_2 due to reduced distances to ship the final products and also avoiding mass produced apparel, but rather additive manufactured on demand removing the need to be stocked/stored.

The ability to adopt textile additive manufacturing as a new digital manufacturing approach is clear, where scales of economy can be achieved via “print farms” and additionally the use of very large format printers where potential a whole garment could be either AM or modified with AM. The use of textile additive manufacturing will allow for local manufacturing centres, reducing carbon footprints and ability to manufacture on-demand. In our opinion, there are many more avenues to follow and develop and below we summarise some that are apparent from this review:

(1) There are reported to be seven different types of AM technology, yet, from the above, only a few are utilised and clearly using those yet to be reported for the textiles manufacturing have many advantages to offer/explore.

(2) The majority, if not all of textile additive manufacturing utilise oil-based plastics. Recycled plastic and/or bio-based plastic is yet to be explored where eco-design will allow for rapid additive manufactured bespoke textiles to support a products entire lifecycle in a circular economy perspective/approach.

(3) One area overlooked is the wearability, where additively manufactured textiles need to be designed to be worn for longer than a few hrs (*i.e.* a catwalk) which will induce sweating/moisture build-up if not designed properly.

(4) Following on from point (3), the washing of additively manufactured textiles is critical to longevity and sustainability, but from the above overview, is often overlooked/not considered. This will allow additive manufactured textiles to be designed and developed such that we do not end up with single-use textiles/fashion so that they can be worn more than once; this builds upon the point above when they become end-of-life.

(5) Another area of interest in additive manufacturing are antimicrobial feed stocks. Currently this seems to be an unexplored area where additive manufactured medical-based textiles have an interesting potential to produce additive manufactured bespoke bandages that fit to patients, via digital scanning of wounds etc.

In summary, we expect this area of research to be of growing interest in the future.

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