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Adhesion and Stab-resistant Properties of FDM-printed Polymer/Textile Composites

Adhezija in odpornost pri vbodu kompozitov, izdelanih s tehnologijo FDM tiskanja polimera na tekstilijo

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Abstract

Stab-resistant clothing has been used for centuries by soldiers. Today, it is also used by policemen and other people in dangerous jobs or situations. While chain-mail or metal inserts in protective vests are heavy and uncomfortable, lightweight and bendable alternatives are currently the subject of investigation. Special textile fabrics offer a certain level of stab-resistance that can be improved by different coatings. In this study, we investigated composites of different flexible 3D printing materials, used for the fused deposition modelling (FDM) technique, on woven fabrics. Besides the adhesion between both parts of these composites, the quasi-static stab-resistant properties were investigated and compared with those of pure textile fabrics and 3D prints, respectively.

Keywords: 3D printing, fused deposition modelling (FDM), flexible polymer, stab-resistance, VPAM-KDIW

Izvleček

Proti vbodom odporna oblačila že stoletja uporabljajo vojaki, danes pa tudi policisti in ljudje na nevarnih delovnih mestih ali v nevarnih okoliščinah. Žična pletiva ali kovinski vložki v zaščitnih jopičih so težki in neudobni, zato dandanes raziskujejo lahke in upogljive alternativne materiale. Specialnim tkaninam lahko izboljšajo odpornost proti vbodom z različnimi premazi. V tej raziskavi so bili izdelani tekstilni kompoziti s pomočjo različno upogibljivih polimernih materialov za 3D-tiskanje, ki jih uporabljajo pri modeliranju s spajanjem slojev (FDM). Poleg adhezije med komponentama polimer-tekstilija je bila raziskana tudi odpornost tekstilnih kompozitov proti kvazistatičnim vbodom in izvedena primerjava z lastnostmi tkanin oziroma 3D-tiskanin.

Ključne besede: 3D-tisk, modeliranje s spajanjem slojev, FDM, upogibljiv polimer, odpornost proti vbodu, Združenje testnih centrov za materiale in proti napadom odporne konstrukcije (VPAM), smernice za testiranje »zaščite pred vbodi in udarci« (KDIW)

1 Introduction

Stab-resistant garments are gaining importance due to the increasing amount of fatal stabbing injuries [1]. To avoid heavy and uncomfortable body armour, especially in the case of the long-term use of stab-resistant clothes, today's textiles and other polymer-based stab-resistant garments, which enable drapability, air and water vapor permeability combined with low thermal resistance, are the subject of investigation [2–4].

Textile fabrics for stab-resistance are often prepared from *p*-aramids or ultra-high molecular weight polyethylene (UHMWPE), and sometimes from other technical yarns, such as carbon or S-glass, and are typically used as woven or needle-punched fabrics [5-8]. Ceramic coatings can be applied to improve fibre-fibre friction, hardness and wear resistance [9,10], while coatings with shear-thickening fluids stiffen at the moment of an impact and have practically no effect on fabric drapability [11, 12]. Reinforced polymers and composites, on the other hand, can often absorb more energy, but are usually more rigid [13–15].

Recently, 3D printed stab-resistant body armour has received increasing interest [16–18]. Tests of these samples often show fractures along the printing orientation in the case of fused deposition modelling (FDM) printing [16], which suggests that combining them with textile fabrics would improve in-plane strength.

This approach is reported here, combining woven fabrics with different elastic FDM-printed materials, to investigate the textile/3D-printed composite compared with both single materials. One important parameter required for the formation of a proper stab-resistant composite using 3D printing on a textile fabric is the adhesion between both parts, which is largely influenced by the stand-off distance (commonly referred to as the z-distance) between the nozzle and fabric during printing [19–21]. Stab-resistance itself can be investigated, for example, using dynamic tests, such as the German VPAM-KDIW 2004 [22], the British HOSDB (Home Office Scientific Development Branch) [23] or NIJ standard 0115.00 of the National Institute of Justice of the USA [24, 25]. Quasi-static tests are also defined, e.g. by ASTM F1342 [26], and are performed on universal test machines, where the upper clamp holds a standardized knife, and instead of a lower clamp, a sample holder or a backing with plasticine or foams is applied, and the load-displacement curves are recorded [27]. Quasi-static tests using plasticine and a standardized VPAM-KDIW blade were applied in this study.

2 Materials and methods

All samples were 3D-printed on a plain-woven fabric (thickness 0.45 mm) from Dynel/viscose (70%/30%), with a water contact angle of 64°, i.e. hydrophilic, which may be supportive for the adhesion of a 3D-printed polymer [28].

A Creality CR-10S Pro FDM printer with a nozzle size of 0.4 mm was used to prepare the samples, applying a layer height of 0.2 mm. All materials were printed with a nozzle temperature of 245 °C on an unheated printing bed at a speed of 30 mm/s, an infill density of 100%, applying a rectilinear infill (orientation ±45°), and a flow rate of 110%. The z-distance between the sample surface and nozzle was varied (-0.5 mm, -0.7 mm and -0.8 mm, where negative values denote printing “inside” the sample to improve adhesion).

Three elastic filaments from thermoplastic polyurethane (TPU) were used with a shore hardness of 98 A, 85 A and 82 A, respectively, with the latter being the most elastic.

For adhesion tests, strips measuring 150 mm in length and 25 mm in width were printed on the textile fabric (three samples per material and z-distance). Samples for stab-resistance tests measured 100 mm in length and 100 mm in width, respectively. All samples had a height of 0.4 mm, i.e. 2 layers.

Adhesion tests according to DIN 53530 were performed using a Sauter TVM-N (Kern & Sohn GmbH, Balingen-Frommern, Germany) universal test machine and evaluated according to ISO 6133, procedure B (recommended for less than twenty peaks per measurement).

For quasi-static stab-resistance tests, a blade according to VPAM-KDIW [22] was inserted into the upper clamp of the universal test machine, while the lower clamp was replaced by a box with plasticine (from Carl Weible KG, Schorndorf, Germany) on which the samples were placed. The plasticity of the plasticine is defined in VPAM-KDIW as follows: a steel ball (diameter of 63.5 mm and a mass of 1039 g) falling on the plasticine from a height of 2.00 m results in an indentation depth of 20 mm ± 2 mm. The tip of the blade stabbed the sample with a constant velocity of 16 mm/min, while force and displacement were measured.

A Camcolms2 digital microscope was used to take microscopic images of the samples.

3 Results and discussion

As an example, Figure 1 depicts a typical measurement of the force-displacement curve during an adhesion test. Such a structure, with many small peaks, is typical for the adhesion of a 3D-printed layer on a woven fabric, since the distance between nozzle and sample surface alternates, and the pores in the woven fabric will not always be identical, so that the imprinted polymer can penetrate more or less, resulting in a variation of the form-locking adhesion between both parts of such a composite.

The results of all adhesion measurements are compared in Figure 2. Generally, a z-distance of -0.7 mm is advantageous, especially for the softest filament with a shore hardness of 82 A. It is well-known from previous investigations that the optimum z-distance is where the polymer is sufficiently pressed into the textile substrate, before the nozzle is clogged, as occurs for lower z-distances [19]. Clogging starts here at a z-distance of -0.8 mm, as shown by optical inspection during the printing process. For this reason, the corresponding adhesion forces are lower than those measured for z = -0.7 mm.

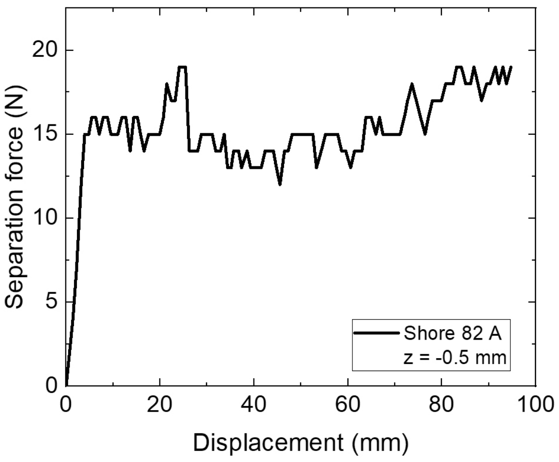

Figure 1: Sample measurement of the adhesion forces of the softest TPU (shore hardness of 82 A) on the woven textile fabric, shown here with the highest z-distance of -0.5 mm

On the other hand, softer materials typically show a higher adhesion than harder materials, which is also visible here, when comparing the results for the optimum distance of -0.7 mm. Generally, a maximum adhesion force of approximately 50 N or, normalized by the sample width of 25 mm, of 20 N/cm, which was found for the softest TPU under ideal printing conditions in this study, corresponds well with a previous study of another group with similar materials [29].

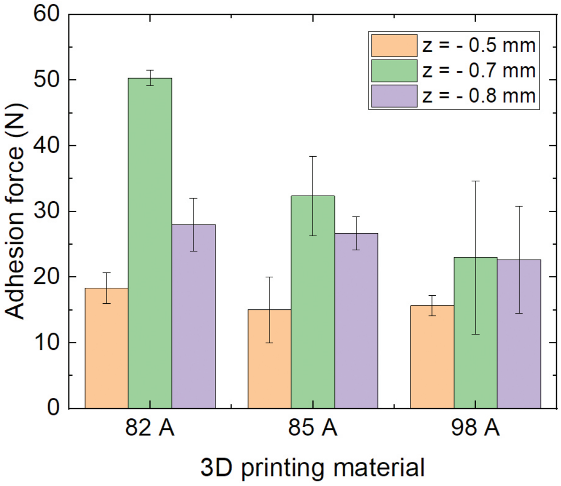

Figure 2: Average adhesion forces of samples under investigation, with error bars showing standard deviations

The adhesion, however, is only one factor that leads to improvement in stab-resistance due to the polymer printed on the textile fabric, compared with textile fabric alone. Figure 3a depicts sample force-displacement curves for a composite (two layers of TPU with a shore hardness of 85 A printed on the woven fabric) and a pure textile fabric. The force necessary to penetrate the composite with the blade is clearly higher than that for the pure textile fabric.

The average cutting forces are depicted in Figure 3b. Here, it is clearly evident that the TPU with a shore hardness of 82 A only leads to a small improvement in the cutting force, while both harder TPUs can better withstand a penetrating blade, leading to the enhancement of the cutting forces by a factor of approximately 3–4. No significant difference between the TPUs with a shore hardness of 85 A and a shore hardness of 98 A is evident (t = 0.74 in the Welsh-test, i.e. smaller than the critical t-value of 3.60 for the 95% double-sided confidence interval). On the contrary, the differences between the pure textile or the 82 A sample, respectively, and both 85 A and 98 A samples are significant for a 99% double-sided confidence interval, which is also valid for the difference between the pure textile and 82 A composite.

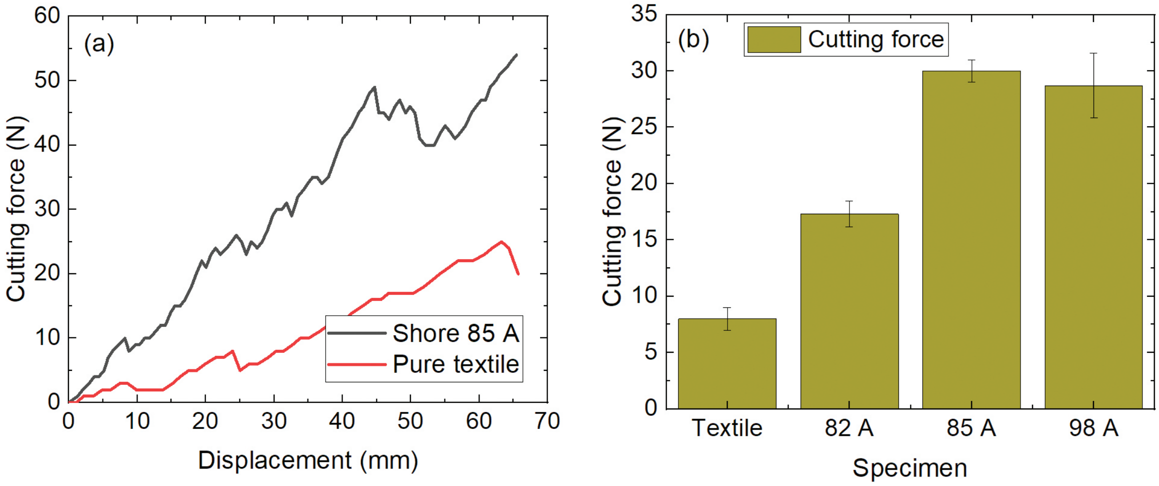

Figure 3: a) Sample measurement of the cutting forces through the TPU with a shore hardness of 85 A on the woven fabric; b) average cutting forces for the pure textile fabric and polymer/textile composites

This behaviour is reflected by the microscopic images of the composites after the stabbing test, as shown in Figure 4. While the softest material (82 A) demonstrates a mixture of bending and cutting, the strands of both harder materials are clearly cut. This suggests combining materials of different elasticity to absorb more energy than possible with only one of these mechanisms.

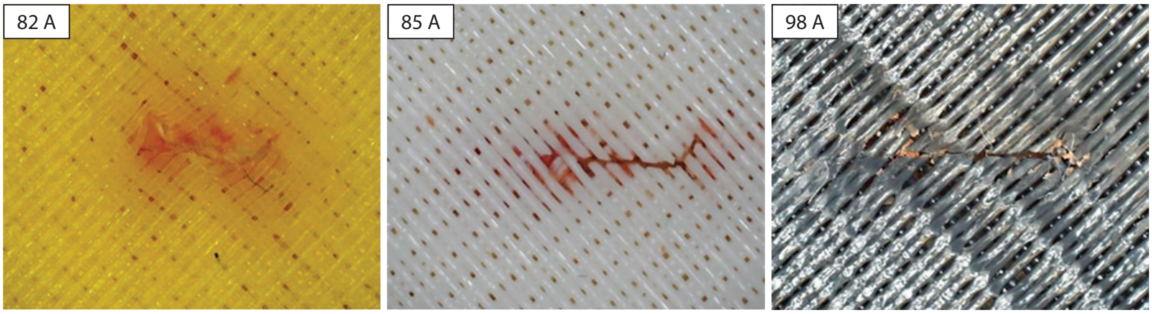

Figure 4: Microscopic images of composite samples after the quasi-static stabbing test

It should be mentioned that, in spite of the increased flow rate, neighbouring strands are still not fully connected, indicating that even higher cutting forces can be achieved with an enhanced 3D printer whose settings enable a continuous connection of neighbouring strands without air voids between them.

4 Conclusion and outlook

Three TPU filaments were FDM-printed on a woven fabric and investigated with respect to the adhesion between both parts and to the quasi-static stab-resistance of these composites. While the softest TPU (shore hardness of 82 A) showed the best adhesion, both composites with harder TPUs necessitated higher stabbing forces. Combinations of different materials, e.g. with the softest TPU printed on the textile fabric and covered by one of the harder TPUs, can be expected to result in better adhesion throughout the composite and to combine different energy absorption modes, thus increasing the stab-resistance of such lightweight, bendable composites for the use as body armour.

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