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IMPACT STRENGTH OF 3D-PRINTED POLYCARBONATE

Hans de Vries, Roy Engelen, Esther Janssen

High Tech Campus 7, Eindhoven, Netherlands

Abstract. *A vertical wall printed by Fused Filament Fabrication consists of a ribbed surface profile, due to the layer wise deposition of molten plastic. The notches between the printed layers act as stress concentrators and decrease its resistance to impact. This article shows the relation between impact strength and layer height by experimental data and finite element simulations of the stress intensity factor and the plastic zone near the tip of the notch. The impact resistance increased from 6 to 32 kJ/m^2, when the layer height was decreased from 1.8 to 0.2 mm. When notches were removed by sanding, the samples did not fail any more during impact testing, resembling the behavior of smooth molded test bars. Tensile strength values up to 61 MPa were measured independent of layer height. Birefringence measurements were done to determine the actual stress levels, which ranged from 2 to 5 MPa.*

Key words: *3D-printing, polycarbonate, layer height, residual stress, impact strength.*

1. INTRODUCTION

Fused Filament Fabrication is an additive manufacturing process in which a product is built up layer-by-layer. Each subsequent layer must adhere to the previous layer. In the case of polymers this is done at temperatures well above the glass transition temperature, such that the polymer chains have enough mobility to interpenetrate and a strong interface layer is formed.

The tensile and flexural strength of 3D-printed polycarbonate parts can be nearly as high as for injection molded material. Values of 88–89% of the bulk- or injection molded strength have been published [1,2]. Slightly lower values of 63–82% have also been reported, which is probably due to different printing toolpaths and process settings [3,4].

An important geometric difference with injection molded material is the notch that is formed between the printed layers. These can act as loci of stress concentration and might impair the impact strength. Moreover, internal stress may add or detract from the strength of the material. This justifies an investigation of the additional stress that builds up in the material during the 3D-printing process.

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Corresponding author: Hans de Vries
High Tech Campus 7, 5656AE Eindhoven, Netherlands
(E-mail: j.w.c.de.vries@signify.com)

Unlike for injection molded material, not many studies on the internal stress of 3D-printed materials have been published. Here, a few that do exist are briefly mentioned. In [5] the deformation and associated stress was experimentally determined from contact measurements and analytically described for ABS (acrylonitrile butadiene styrene)-plates. From correspondence with the authors it became clear that their solution cannot be readily applied to samples with a completely different form factor – single pass, vertical walls as used in our work. Still, their study is interesting because of its potential to determine the stress in opaque materials. In another investigation, the deformation field was determined by a speckle technique [6]. This also concerned plates of ABS. The hole drilling method was used to measure the deformation in printed ABS-plates [7]. What all these studies have in common is that they show that the stress at the surface of 3D-printed material is (slightly) compressive while at the interior it is (slightly) tensile. Finally, in a study on 3D-printed ABS it was also speculated that the notches – or lobes as these authors called it – between the printed layers can act as stress concentrators [8]. In this work the effect of the lobes or notches in 3D-printed structures of polycarbonate on the mechanical strength is investigated. This is done by subjecting as-printed and polished samples to impact tests. In both type of samples, the stress level is estimated from birefringence measurements.

2. EXPERIMENTS

2.1. Test samples

Single wall structures were printed on a desktop printer (Ultimaker 2+), which was modified to allow printing of polycarbonate at a temperature between 250 and 300°C. Maximum bond strength is reached above the glass transition temperature, when the polymer molecules diffuse across the interface of two consecutive layers [9]. Printing was done with layer heights of 0.2 to 1.8 mm.

The thickness of the wall after printing was around 2 mm for all layer heights, except for the 1.8 mm layer which had a 3 mm thick wall (see Table 1). Test bars of 125x13x2 mm^3 were made by machining them out of vertically (sic) printed walls. The stack of printed layers was in the length direction of the sample (see Figure 1). A part of the bars was polished to remove the notches between the layers. This is supposed to reduce the stress concentration at the tip of these notches as was referred to in the introduction.

2.2. Mechanical tests

Charpy impact tests were performed (Impact XJC-25, Chengdu Jingmi Co. Ltd.) on as-printed and polished samples. It must be noted that this test was not executed completely according to any standard, only the anvil was set to the required width of 40 mm [10]. The impact strength was determined with the samples positioned as shown in Figure 1, thus striking on the face of the wall. Machining the test samples from the printed walls means that the narrower cut side is smooth, and thus polishing of that side makes no sense. Still, the impact strength in that direction was tested as well.

For tensile testing, dog bones (ASTM type IV) were cut from the printed walls and mounted in a Zwick1464 test machine. The tests were performed at a speed of 4 mm per minute.

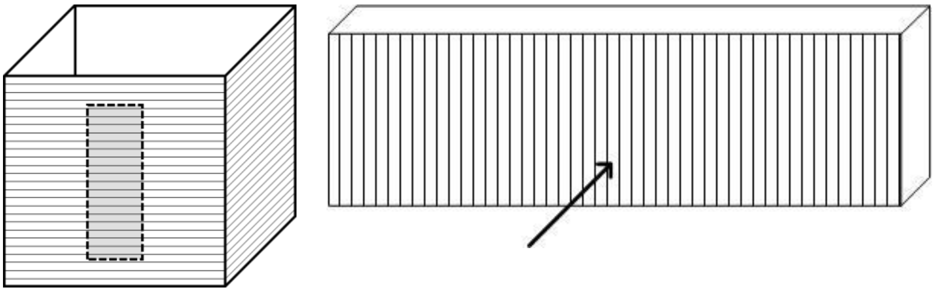

Fig. 1 Structure for impact testing, the hatching representing the printed layers. The dashed grey area (left picture) indicates the position in the vertical wall where the test bar (right picture) is cut from. The arrow shows the direction of the impact

2.3. Birefringence

Internal stress can be determined by retardation caused by birefringence. This was measured by polarization microscopy (Leitz Laborlux 12 Pol) with a 1942K-compensator. For reasons of comparison, the birefringence in injection molded samples was also measured.

Some materials have a refractive index that depends on the polarization of light. Non-cubic crystals and plastics under stress exhibit this phenomenon. An incoming light beam is split in two beams with mutual perpendicular polarization directions. After exiting the material, the two beams have a phase difference since one beam will be retarded compared to the other. By means of a compensating filter the phase difference can be determined and the retardation (R) can be obtained from a table.

The retardation depends on the thickness of the material (t), the stress-optical constant (C), and on the stress level:

$$R = Ct(\sigma_{11} - \sigma_{22}), \tag{1}$$

where the σ_{ii} are the first two principal stress components. For polycarbonate several values for the stress-optical constant are mentioned [11,12]. For this investigation a value of 8.9x10-11 Pa^{-1} was adopted. This implies that the absolute value of the stress values mentioned in this report are subject to a possible correction if the material's constant must be changed.

3. RESULTS

In this section, the nondestructive analyses will be presented first. This includes both the optical microscopy and polarization measurements. The next part concerns the outcome of the destructive tests i.e. tensile and impact strength.

Photographs of a few printed and polished samples are shown in Figure 2. It is a top view of the sample as sketched in Figure 1. Thus, one is looking at the cross section of the printed wall.

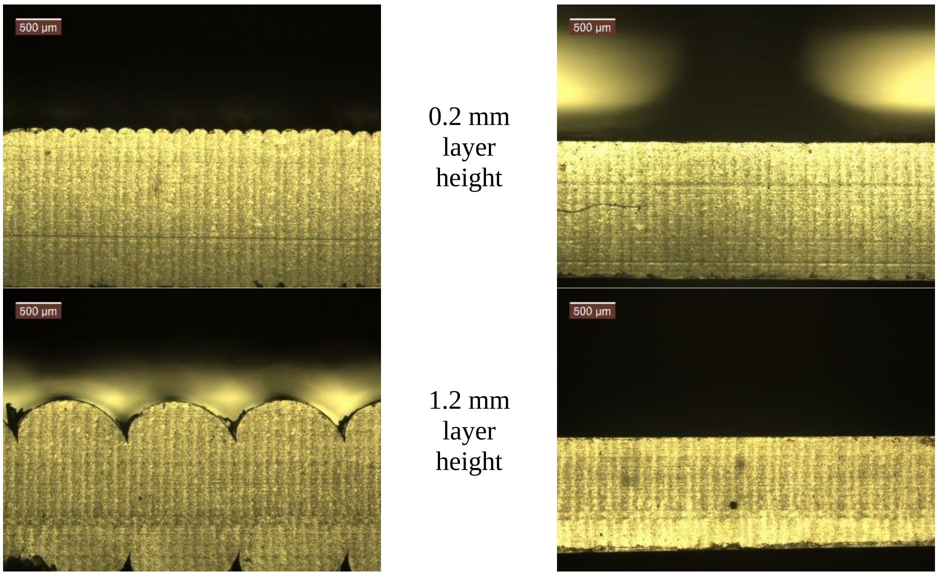

Fig. 2 Top view of printed bars (see Figure 1) as-printed (left) and after polishing (right). The red scale bar is 0.5 mm

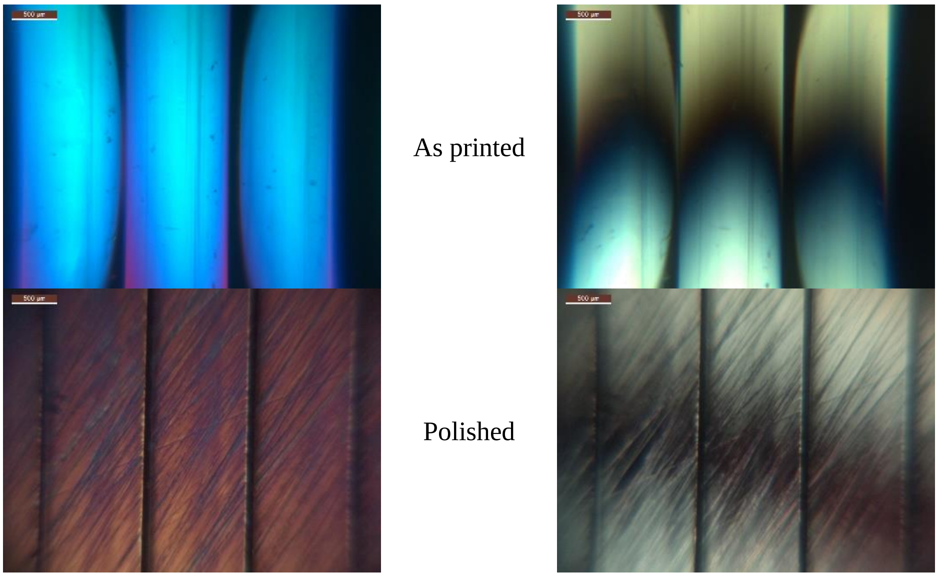

Fig. 3 Side view of samples. Polarized images of sample with layers of 1 mm height. Left: compensator at 0°; right: with compensation (as-printed ~9.5° and polished ~7.5°)

3.1. Birefringence / Stress

The internal or residual stress that was obtained from the retardation measurements is listed in Table 1 for the as-printed and the polished samples. It must be remembered that this is the difference between the two first principal stress components. Each measurement was made right in the center of the layer. An example is shown in Figure 3 for a sample with layers of 1 mm height. This is a front view of the sample as sketched in Figure 1. Thus one is looking at the ridged front wall of the sample. The black band indicates the compensated or stress-free situation. This is approximately 9.5° for the as-printed case and ~7.5° for the polished case.

It should be noted that the same samples were measured both before and after polishing. To calculate the stress from the retardation, the thickness of the material is needed (see eq. (1)). In the as-printed samples this is the printed thickness of the wall (t_{print}), and for the polished samples it is the remaining material, which is the thickness of the interface (t_{int}).

In Figure 4 we show the stress data as a function of the printed layer height. Data is included that was obtained on injection molded pieces of polycarbonate. There is no clear difference between the internal stress in the as-printed and polished samples, which indicates that the residual stress does not depend on the ridged geometry of the printed layers. For the small printed layer height an increased internal stress is observed. As the printed layers are higher, the internal stress approaches the level of the injection molded material.

Table 1 Retardation (R) and stress (S, difference between first two principal stress components). The printed layer height (h), thickness of wall after printing (t_{print}) and of interface (t_{int}) are given.

h mm	t_{print} mm	t_{int} mm	R nm	S MPa	R nm	S MPa
			As-printed		Polished	
0.2	1.93	1.73	853	4.91±0.26	776	5.37±0.17
0.4	1.90	1.72	899	5.26±0.14	669	4.49±0.32
0.8	2.14	1.60	727	3.78±0.23	636	4.36±0.10
1.0	2.09	1.42	627	3.34±0.17	394	2.72±0.26
1.2	2.19	1.39	640	3.26±0.31	373	2.55±0.20
1.8	3.10	1.61	685	2.45±0.11	473	2.35±0.42

3.2. Tensile Strength and Impact Strength

Tensile strength tests were made on dog bone type samples. The available results are listed in Table 2 and graphically shown in Figure 5. Not in all cases a polished sample could be made for testing. The strength was 77–94% of the bulk value for the injection molded polycarbonate, showing that the process is well controlled. It also shows that the tensile strength of the material is a material property that is not significantly affected by both the layer height and the ridged geometry that are the result of the 3D-printing process.

The measurements from the impact tests give the energy that is absorbed during the shock. In order to compare the results of various samples having different geometries, it was decided to use the energy per cross sectional area. In the case of 3D-printed samples this is the internal cross section for which the thickness of the interface between two layers is taken.

The test results are compiled in Table 2. A graphical representation of the test results can be found in Figure 6. In the case of polished 0.8 mm high layers, two out of four samples did not fail. The polished samples with layers of 0.2- and 0.4-mm height did not fail at all. This means that the impact strength was more than 200 kJ/m^2 given the maximum energy of 4J of the heaviest hammer in the test facility (in the figure this has been indicated by the dashed arrows). Evidently, the impact strength depends on both the layer height and the ridged geometry that are the result of the 3D-printing process. Anticipating the discussion of these results, the ISO (179/1eA) test value with a notch radius of 0.25 mm for molded polycarbonate is 65 kJ/m^2. When the notch radius is varied, impact strengths in the range of 10 to over 80 kJ/m^2 were measured [13].

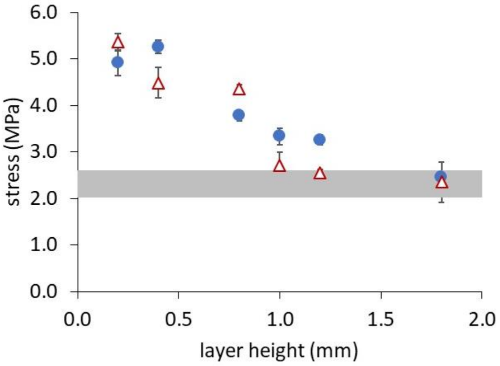

Fig. 4 Stress calculated from retardation measurements by eq. (1). Data from Table 1. As-printed (●), polished (△). The shaded band indicates the stress level in unnotched injection molded material

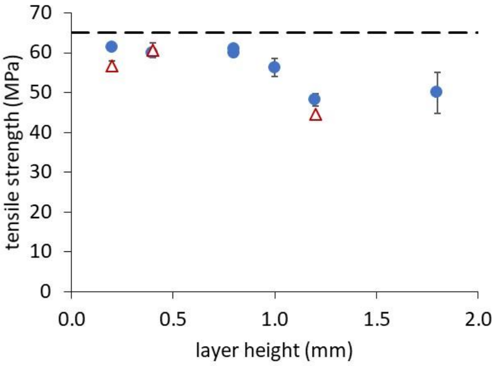

Fig. 5 Tensile strength with data from Table 2. As-printed (●), polished (△). The dashed line shows the injection molded value

Table 1 Impact strength (J) and tensile strength (TS) for as-printed and polished samples. The printed layer height (h) is given, other sample data are in Table 1. In some cases no polished samples could be made.

h (mm)	J (kJ/m^2)		TS (MPa)	
	as-printed	polished	as-printed	polished
0.2	32±2	> 200	61.4±0.3	56.8±1.1
0.4	14±2	> 200	60.0±1.1	60.6±1.9
0.8	10±2	30±10	60.0±0.9	not tested
1.0	9±2	not tested	56.2±2.2	not tested
1.2	7±2	12±7	50.0±1.5	44.6
1.8	6±0.002	not tested	50.0±5.2	not tested

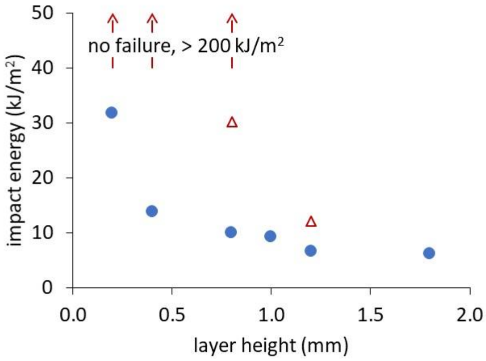

Fig. 6 Absorbed impact energy versus printed layer height (see Table 2). As-printed (●), polished (△). The vertical arrows indicate "no failure" (energy above 200 kJ/m^2) for polished samples

4. DISCUSSION

During the process of 3D-printing material is added layer-by-layer. The process requires that this is done at an elevated temperature to ensure good adhesion between the layers, which is caused by diffusion and reptation [14]. As stacking of the layers proceeds, the already deposited material begins to cool down and shrinks. Thus, thermal stress builds up throughout the entire structure.

The additive manufacturing process also leads to inhomogeneity since the printed walls are not smooth but have rounded edges and sharp notches. At such notches stress concentrations occur and these might reduce the impact strength of the printed material. This was also supposed in an investigation of printed ABS [8].

The experiments that are described in the previous sections, were designed to shed more light on the following questions:

- What is the level of the internal stress in 3D-printed material?
- What is the influence of the inhomogeneous nature (i.e. non-smooth surface finish) of FDM-printed material on its strength?

It lies at hand that these questions are closely related.

The above questions will be discussed first in a general sense based on the experimental results. Afterwards, a detailed treatment of the several topics of this investigation will follow.

4.1. General

Not much has been published to date on the residual stress in samples made by 3D-printing. Relevant to the present investigations is an analytical approach of the deformation and internal stress in 3D-printed beams from ABS [5]. It reports radii of curvature of 1.4–2.0 meter in beams of 5 mm in height made by layers of 200–350 µm thick. These numbers would lead to an internal stress of 2–3 MPa. Tests on 3D-printed ABS-plates of 3 mm thickness from layers of 240 µm thick, showed bending in the order of 10 µm over a span of 80 mm [6]. One can estimate that the stress amounts to about 6 MPa. Also in ABS, by the hole-drilling method, a residual stress of 6 MPa was determined [7]. Although in these cases ABS was used as material, the level of stress is comparable to the value we have found in polycarbonate.

In the current study, the internal stress that could be extracted from birefringence measurements is in the range between 2 to 6 MPa (see Table 1 and Figure 4). This agrees with the abovementioned literature data. Our own results for injection molded polycarbonate are on the lower end with about 2 MPa.

No information was found concerning the distribution of the stress over the dimensions of the tested samples made by additive manufacturing techniques. Of course, as for injection molded material such studies have been published. For instance, by gradually removing thin layers from an injection molded polycarbonate bar and subsequently measuring the stress at the surface, it was found that the stress becomes lower as one reaches the center of the material [15]. At the surface the stress was compressive. Elsewhere, the stress near a weld line was modeled, and near the interface the stress increases rapidly [16]. This subject will be addressed further in the next paragraphs.

4.2. Residual stress distribution

The initial birefringence measurements were done in the center of the layer, i.e. the polarized light travels through the thickest cross-section of the printed ridged structure. No real difference exists between the printed and the polished samples, as one can see in Figure 4. With above indications in mind of stress peaks near a weld line in injection molded material, an attempt was made to additional birefringence measurements over the wall thickness of the printed layers. However, only a very tentative indication was found that indeed the stress increases towards the interface. No quantification of the stress at that location was possible.

4.3. Tensile and Impact Strength

The tensile strength does not depend very markedly on the deposited layer height. There is a trend to higher strength as the printed layers get thinner (Figure 5) and the strength of injection molded material is seen to be approached (60–65 MPa). As for the effect of the notches, these do not seem to have a large effect since the polished samples have the same tensile strength as the polished specimens. Again, in the literature little has been published regarding the influence of layer height on the tensile strength. To date the only thorough piece of information concerns 3D-printed PLA (polylactic acid) [17]. A slight decrease was observed there with thicker layers (0.04 to 0.2 mm).

Quite a different picture arises if we look at the impact strength. Here, the height of the printed layer has a significant effect on the test result. Thinner layers are much more resistant against an impact (Figure 6). Polishing away the edges makes even more of a difference. Striking the polished specimen with layer height of 0.2 mm, 0.4 mm, and 0.8 mm (partly) on the flat surface, did not lead to fracture at all within the limits of the test equipment. With printed layers of 0.8 mm (partly) and 1.2 mm height, the impact strength after polishing has increased by a factor of between two and three.

In combination with the apparent removal of the stress concentration at the layer interfaces, it must be concluded that there is also an increase in the robustness against impact loads. In the next paragraph this will be explored further.

4.4. Stress intensity and Plastic zone

To try to explain the improved resistance of samples fabricated with thin rather than thick layers to impact loads, the concept of the crack-tip plastic zone can be used [18].

From a theoretical point of view, at a crack tip with a vanishing radius the stress would become infinite. Since this does not reflect reality, for numerical calculations it was proposed to assume a rounded crack tip with an enhancement factor for the stress. The stress at the end of the crack is then higher than the applied stress. In addition, a region of plastic deformation was defined around the crack tip that prevents the crack propagating on its own. This so-called plastic zone blunts the sharp end of the crack.

Considering the influence of the printed layer height on the impact strength, it is worthwhile estimating the size of the plastic region. Based on studies of the fracture behavior of ductile materials, an expression for the extension of the plastic region was derived [19]. For the present investigation a slightly different form can be used:

$$r_{pl} = \frac{\pi}{32}\left(\frac{K_I}{\sigma_Y}\right)^2, \tag{2}$$

where K_I is the stress intensity factor and σ_Y is the yield stress.

Estimating the magnitude, for K_I values of 2.8 MPa.m$^{0.5}$ for sharp and 5–10 MPa.m$^{0.5}$ for blunt notches were reported [20]. Elsewhere, 1.25 MPa.m0.5 was used [19]. Concerning the yield stress, this will typically be around 40 MPa [15,19]. As a result, we get r_{pl} values of 0.06 to 0.6 mm. This means that this crack-growth-damping-zone can be of the same dimension as the thinner printed layers of 0.2 and 0.4 mm, and perhaps even close to that found in samples with layers of 0.8 mm height. This will be further commented on at the end of this subsection.

All the data for the stress intensity factor was determined for injection molded material. While the similarity in mechanical properties between this and 3D-printed material has been shown, it is better to separately estimate the stress intensity factor for the 3D-printed material. This was done by finite element simulations. A 20 mm-long sample of layered material was modeled in detail for the range of layer heights conform the dimensions specified in Table 1. Linear elastic material properties were used for standard polycarbonate with a modulus of 2.4 GPa and 0.37 for the Poisson’s ratio. The application of a half penny-shaped crack-tip mesh at the notched interface between two layers allows for the accurate calculation of the stress field around the notched interface between the layers. The stress intensity factor was calculated using the J-integral method determined after imposing 1% tension to the sample. In Figure 7 the result of the stress intensity factor is shown for the fabricated layer heights.

In an actual loading situation, the stress will become higher near the end of a crack or notch, as was explained above. Should the critical stress be reached, cracks will grow, and failure occurs. This is indicated by the critical stress intensity K_{IC}, which is regarded as a material constant. From the data in Figure 7 one can infer that for thinner printed layers the actual stress intensity is further away from the critical level than for thicker printed layers.

Thus, the increased resistance of thin-layered structures against shock impact is understandable.

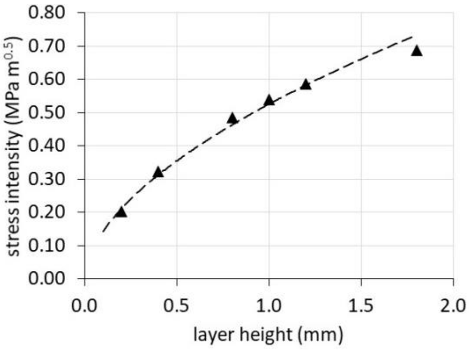

Fig. 7 Stress intensity K_I as function of printed layer height. The dashed line is a guide to the eye

As for the size of the plastic zone around the notch, the layer-height dependence of the stress intensity factor of Figure 7 in combination with equation (2) suggests that the plastic zone grows almost linearly with the height of the printed layer. The validity of this observation is still under investigation.

4.5. Notch radius

The influence of the notch radius has previously been studied for molded samples. This concerned testing of samples with a predefined notch. The impact strength of polycarbonate at room temperature increased by a factor of about six if the radius of the notch was increased from 0.125 to 0.25 mm [13]. Values were reported of 10–80 kJ/m^2. Compared with the values in Table 2 these are in line with the strength of 3D-printed polycarbonate. Experiments on samples with notches of 0.13 to 0.5 mm radius showed roughly a doubling of the impact strength [21].

It is not yet possible to make an estimation of the radius of the notches between the printed layers. Still, qualitatively, a rounding-off as the layers are thinner was found. Again, this makes the samples made with thin layers stronger than those with thick layers.

To summarize, three mechanisms have been identified that all enhance the impact strength of 3D-printed structures. Printing of thin layers leads to a rounding of the notch and thus a lower stress peak at the interface between the layers. The second mechanism stems from the size of the plastic zone around the notch that reduces crack growth. There are indications that this zone is of the same dimension as the height of the thinnest layers. Finally, polishing the printed wall to make it smooth removes the origin of the stress concentration.

5. SUMMARY AND CONCLUSIONS

Various experiments and analyses were carried out on 3D-printed samples with deposited layer heights from 0.2 mm to 1.8 mm. The purpose was to understand the relation between mechanical strength, internal stress and layer height in FDM-printed polycarbonate products. As it was supposed that the shape of the printed layers forms a notch-like indentation, several samples were polished to obtain a smooth wall. The main point of attention of this study was to evaluate the level and the variation of the internal stress and the possible relation with the impact strength of the samples.

3D-printed plastic parts may contain more internal stress than injection molded parts, due to the layered way of fabrication. This leads to deformation and residual stresses, especially for engineering plastics, which are processed at high temperatures. In this study, the measured internal stresses ranged from 2 MPa for molded samples to 2-5 MPa for 3D-printed parts, depending on the deposited layer height.

Polycarbonate is known to be sensitive to notches. Notched molded samples have a lower impact strength than unnotched samples, because the notch acts as stress concentrator. Due to the layered structure of 3D-printed parts, the surface intrinsically contains many notches. Depending on layer height, and thus the radius of the notch, the measured impact strength ranged between 6 and 32 kJ/m^2. Similar values (10-80 kJ/m^2) have been reported for notched molded samples [13].

Tensile strength is dependent on the processing temperature and is not influenced by the notches on the surface. Perpendicular to the layers, single pass, vertical printed walls have a strength of up to 61 MPa, which is 95% of the value measured for injection molded samples.

The following conclusions can be drawn from the results of the investigations and are supported by results from finite element simulations:

5.1 Internal stress

- Stress concentrates at the notches between the printed layers. Removal of the edges to make a smooth wall reduces the stress concentration and makes the stress almost constant over the layer height.
- The notch between thin layers is rounded as compared to the notch in thick layers. This reduces the magnitude of the stress at the interface.
- The internal stress is of equal magnitude in the center of the layers in as-printed and polished samples. This was determined by optical birefringence measurements.
- The internal stress increases as the printed layers get thinner. In the thickest layers of 1.8 mm the internal stress level was the same as that of injection molded material.
- The stress intensity factor is lower for thinner layers which means that in samples with thinner layers more stress-load can be applied before fracture occurs.
- There are indications of the existence of a plastic zone around the notch which is of the same size as the height of the thinner layers. This zone hampers the propagation of cracks.
- It is very likely that the stress is not constant over the wall thickness of the printed layers. An attempt was made to determine such variation, but with an inconclusive result. This is a subject for further research.

Based on this set of conclusions, some trends in the impact strength can be noted.

5.2 Impact Strength and Tensile Strength

- The impact strength is highest in samples with thin layers because of the rounded notches. The role of the plastic zone around the tip of the notch is however not yet completely understood.
- Removing the edges increases the impact strength in thin layered samples further because the stress concentrations are taken away.
- The impact strength depends on the geometry of the printed samples (e.g. notch radius and layer height) it cannot be regarded as a material constant
- The tensile strength is weakly affected by the layer height.
- Provided that the processing conditions during printing are such that a proper adhesion between the printed layers can be achieved, the tensile strength can be regarded as a material property for the 3D-printed samples.

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