CHARACTERIZATION OF WELDING NOTCH DESIGNS AND THE IMPACT ON MECHANICAL PROPERTIES OF 3D-PRINTED PLA PARTS JOINED BY A 3D PEN

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Abstract: 3D-printing has been established as a fast and low-cost technology to produce prototypes in small numbers. However, depending on the geometry of a part the print time still can be reduced by splitting the part in two or more smaller parts and later joining them. The reduction of the print time is caused by the possibility of printing the smaller parts with less or maybe even without any support or the use of two or more 3D printers. The joining can be done by different welding or gluing methods. For this paper 3D printed polymer parts with different welding notch designs were welded by a 3D pen and after characterized based on their mechanical properties. The notches were designed in CAD and the parts were then 3D printed. The material chosen was PLA as it is one of the most common polymer materials for FFF 3D printing. For testing and mechanical characterisation of the strength of the joined samples, four different kinds of notches were designed, manufactured and tested according to the norms for the tensile strength test and the Charpy impact test of thermoplastic polymers. The results were compared to the one of a single part printed sample. Although the mechanical properties of the welded samples were not as good as the ones of a fully printed one, the assembly even of the weakest variant, the triple notch, is still strong enough for most applications in the field of rapid prototyping. The method is easy applicable and can be fast done to ensure a good connection between 3D printed PLA parts.

Keywords: *Joining; 3D printing; Welding; PLA; 3D pen*

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1. INTRODUCTION

Nowadays the 3D printing of polymer parts is a common and widespread method, not only in the industry, but as well as in private households. Whether it is the need of rapid prototyping or the fast and easy construction of models or repair parts, the 3D-printer offers great solutions. However, there are limitations to this method like the size of the build plate on a 3D-printer, which prevents the user from printing bigger parts. Problems can occur also for tall and especially thin models that require extra stability to remain upright during the printing process. For this kind of parts, the occurring problems are for example dimensional inaccuracy, rough surface with imperfection or even failed prints. Solutions for these problems are stabilizer support structure, extra cooling, lower print speed or a bigger footprint (brim or rafts) which can be considered either in the designing stage or during slicing. To avoid the problem of the limitation of the build plate, parts which are too big are split into smaller parts and later joined. This can be done by a lot of different joining methods like fastening, adhesive or solvent bonding, fusion, friction and vibration welding or mechanical interlocking. Nowadays, widely popular joining methods are Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW) techniques, which have proven their feasibility since 1991, when they were patented as a welding technology for Al-based alloys (Iftikhar, 2021). Lately these techniques prove their capabilities in the field of polymer welding and even in the case of hybrid joints (polymer-metal). The process is capable of repeatedly producing continuous weld seams with very high joint efficiencies, (Lambiase, 2020). However, because of the resulting temperatures in the welding area for some polymers appears the risk of self-lubrication or the occurrence of a hard shell. Last effect appears when the outer material cools quicker than the inner one, which will make the material contract and pull away from the surfaces of the parts which are being welded. In this case it is mandatory to obtain a consistent cooling rate on the entire volume of the welding seam. To compare the previously mentioned disadvantages, a new technology is proposed, the welding by using a 3D pen (Jaksic, 2015). This approach is fast and easy to apply to obtain a solid and durable mechanical connection between the parts. Even though the process is based on extrusion welding without an external heat source, it is barely documented in polymer welding literature. It is an affordable and fast process of welding polymer parts together as it just requires a 3D pen, and some filament that will be further melted and extruded directly into the joint. The main purpose of this paper is to characterize this method and test it. Different kind of welding notches were designed and applied on CAD models of samples. The v-notch, the triple-notch, the s-notch and the d-notch. The purpose of using notches for the welding with the 3D pen is to ensure that the nozzle of the 3D pen gets in contact with the parts to plasticize the contact surfaces and create a better weld connection. The samples were welded and then tested on their mechanical properties.

2. METHODOLOGY

The purpose of this study is to present straightforward measurement techniques to characterize the strength and efficiency of a weld formed between two 3D printed parts. The mechanical feasibility of the proposed joint forms is determined in terms of tensile strength, elongation at break and absorption of impact energy. To gain values which describe the quality of the welding of two joined parts compared to a single part, two tests were chosen, the tensile strength test and the Charpy impact test. These tests show the mechanical properties on load which can occur to welded parts. To produce the samples a professional desktop 3D printer the BCN3D SigmaX R19 was used due to the accuracy along the axes and to the IDEX (Independent Double Extrusion System) printheads working system. Mirror printing mode allowed two sets of samples to be printed in half the time which is required on a single printhead printer due to the mirror movements of the second extruder. The material which was used is the 2,85 mm in diameter PolyTerra™ PLA in cotton white for the tensile strength test and in savannah yellow for the impact test. PLA was chosen as it is one of the most common used materials for 3D printing of polymer parts. Due to the risk of delamination of the layers during elongation, (for tensile tests) and bending (for Charpy) of the specimen, the build orientation plays an important role in the evaluation of the welding efficiency (Ai, 2022). Therefore, horizontal orientation was considered for all printed tensile strengts specimens. Since the influence of the printing parameters is not considered, all samples were printed using the following same process parameters,Table 1.

Table 1. Printing parameters used for the samples

Printing conditions					
Layer height [mm]	0.15	Infill density [%]	35	Infill print speed [mm/s]	40
Line width [mm]	0.4	Infill pattern	Grid	Wall print speed [mm/s]	35
Wall line count	3	Infill overlap percentage [%]	15	Cooling [%]	95
No. of top layers	8	Printing temperature [°C]	210	Support structure	No
No. of bottom layers	8	Build plate temperature [°C]	45	Print mode	Mirror

For the selection of the printing parameters, the recommendations of the material manufacturers but also the capability and configuration of the 3D printer was taken into consideration. Wall, top and bottom shell thickness were kept uniformly in order to avoid the influence of printing parameters (such as numbers of top and bottom layers) over the efficiency of the joints. The quality of the weld is also influenced by the flatness of the plate contact surface. In the case of FFF (fused filamenmt fabrication), layer thickness has a significant influence on the surface roughness and printing time. Considering that the nozzle diameter is 0.4 mm, a layer height of 0.15 mm was used. To keep the contact surfaces between the sample flat, the Z seam was kept outside the welding zone. Further the starting point of each layer was set in the clamping/attachment area of the part in the jaws of the tensile strength test machine to avoid a weak spot in the area of testing.

The samples for the tensile strength test were designed according to EN ISO 527 test specimen type 1A (International Organization for Standardization [ISO], 2012). The samples for the Charpy impact test were designed after EN ISO 179 test specimen type (ISO, 2010). Five different variants were chosen to be compared with each other, four of them with notches for welding and one as a fully printed single part. The variants with notches were designed in CAD as two similar parts with no connection but notches (Figure 1) on the front and the back of the sample at the joining surfaces. The 3-notch was designed unsymmetric to prevent two thin areas of the part wich would result in two weakpoints of the material.

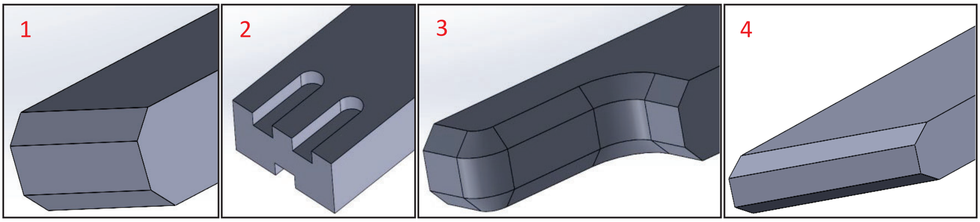

Figure 1. Different notch variants: 1) v-notch, 2) 3-notch, 3) s-notch, 4) d-notch

The used 3D pen is the 3D Simo Multipro (Figure 2) with the settings for PLA and the lowest extrusion speed setting. The material for the weld lines is a PLA filament which was included in the 3D pen kit and has a similar melting temperature as the PLA of the parts, which is important for the welding process.

Figure 2. 3D Simo Multipro with settings and purple PLA filament

For each test five samples of each variant were printed and conditioned at room temperature for at least 24 hours. After they were welded together (Figure 3) by using the 3D pen with a different PLA filament another conditioning of 24 hours was done before the specimen were tested.

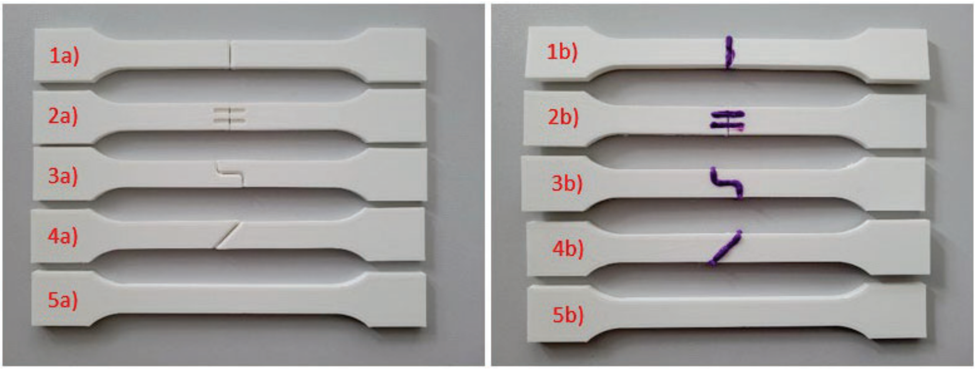

Figure 3. Test specimen for the tensile strength test: 1) v-notch, 2) 3-notch, 3) s-notch, 4) d-notch, 5) fully printed part; a) unwelded, b) welded

For the welding process no pretreatment of the samples was done because additional work steps should be avoided to keep the process simple. The joining parts where fixed by a form during the welding process and hold in place for several seconds to cool down before being turned around and welded on the opposite side. The v-notch and the d-notch samples were more convenient to weld as it is a straight line wich is easier to weld than curved lines or lines with interruptions. The 3-notch samples took the longest to weld as a short break was required between the two lines on the front side to avoid additional material between the notches.Tensile test samples were tested on a universal testing machine (INSTRON, 4411 H4193, max. load 5 kN), at a crosshead speed of 50 mm/min. Charpy test samples were tested on a pendulum impact testing machine (Zwick, 5102.201, max. pendulum length 225 mm and max energy of 5 J). The hammer was chosen according to the norm.

3. RESULTS

The tensile strength test results show (Figure 4) that all variants which were welded had lower maximum tension forces which caused a break of the material, then the sample which was printed as a single part. The average of 18,44 MPa for the single part is much higher than the triple notch variant with 8,31 MPa. However, the d-notch with an average of 13,67 MPa showed the best result of the welded variants. The average elongation at break was for all variants below 5% as PLA is a very stiff material.

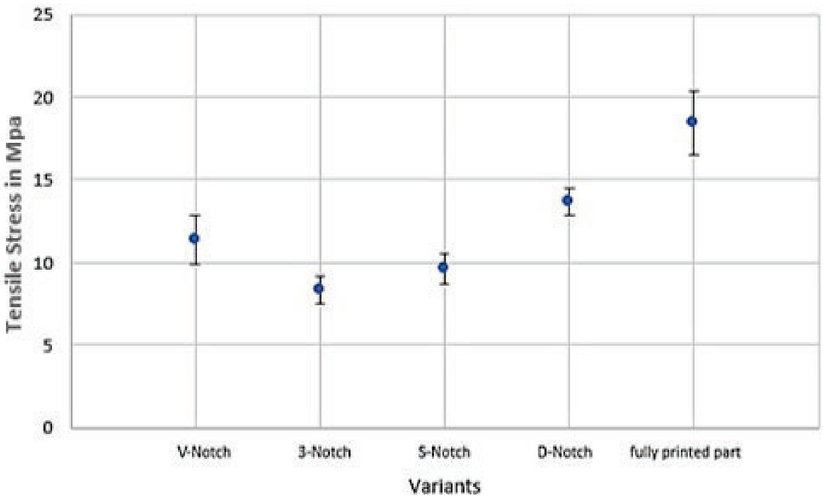

Figure 4. Average tensile stress at break of the different samples

The results of the Charpy impact test (Figure 5) show a far range of the impact resistance from the average of 1,99 KJ/m^2 for the triple notch up to the 9,96 KJ/m^2 for the fully printed variant. The s-notch and the d-notch showed good results with both close to an average of 7 KJ/m^2.

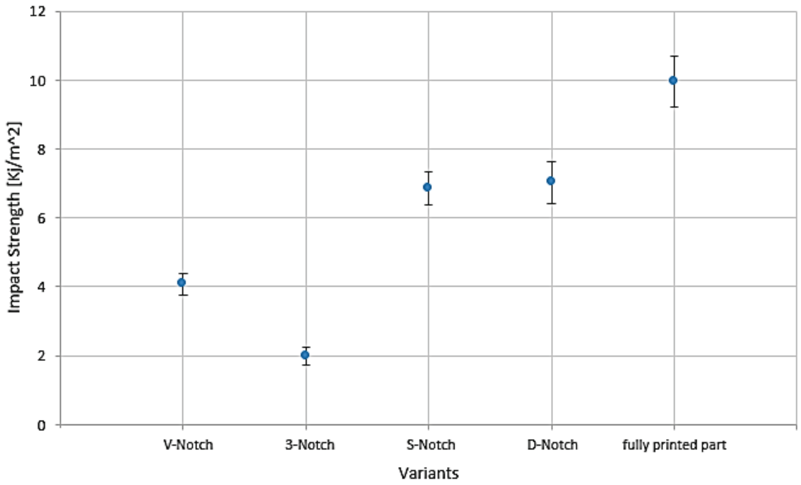

Figure 5. Average impact strength of the variants

Both tests show that of the welded variant the d-notch had the best mechanical properties and was not too far of the results from the fully printed part. The 3-notch however had the lowest mechanical properties which is related to the joining surfaces which are responsible for taking the forces of the two tests. Figure 6 shows the different types of breaking of the 3-notch, the s-notch and the d-notch.

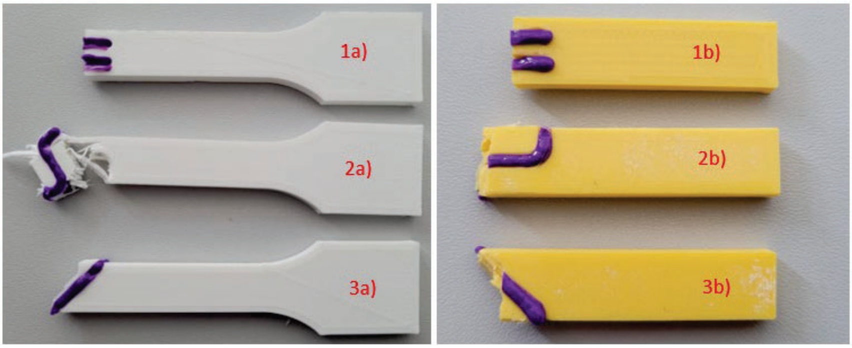

Figure 6. Broken test specimen: 1: 3-notch, 2: s-notch, 3: d-notch, a) tensile strength tested, b) impact tested

It is clearly visible, that some of the material of the s-notch version and the d-notch version is still connected to the weld line and one of the joined parts broke partially. The 3-notch sample broke at the joining surfaces of the two separate printed parts. A cross section picture of a welded part (Figure 7) shows the connection between the part and the filler material. The mixture of the colours in the joining zones show that a welding process has taken part and both materials were plasticized. On the picture a gap is visible between the parts, which indicates, their mechanical properties tested, were the ones of the connection itself.

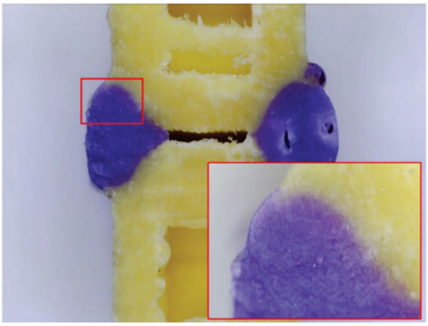

Figure 7: Cross-section of the welded v-notch sample for Charpy

4. CONCLUSION

The method of welding by using a 3D pen has proven to be a fast and easy applicable technique which shown good results for mechanical properties of the joined parts. However, the notch design is important and should be considered while constructing parts which later must be joined. The d-notch shows good results in both tests and offers a strong joint for 3D printed parts. Depending on the application of a 3D printed part which must be joined, other notches can be considered as well. If a part just has the purpose of being a prototyping design model and has no mechanical loads affecting it other weld lines like the 3-notch can be used as well.

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