# Fast and flexible production of mechatronic integrated devices by means of additive manufacturing

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***Abstract* - Due to continuous improvements in process technology additively generated components are increasingly used for prototypes and small series devices. In comparison to conventional manufacturing process chain, additive manufacturing enables in principle embedding of conductive circuits and electronic components during the part building process. However, technologies like Selective Laser Sintering (SLS) or stereolithography (SLA) imply disadvantages concerning high process temperatures or time consuming cleaning steps. In contrast, Fused Deposition Modeling (FDM) seems to be well suited for production of mechatronic integrated devices due to the use of thermoplastic materials for electronic productions (e.g. ABS, PC/ABS), a low thermal load of electronic parts and a simple process management. In this paper, additive manufacturing of mechatronic devices by means of FDM in combination with direct printing of silver ink for generating conductive circuits is investigated. The silver ink is deposited in the matrix or applied on the surface of the part by a dispensing system during the building process. The in situ sintering process of the ink is carried out by a subsequently infrared laser (IR) irradiation. In order to generate components with a high mechanical stability the adhesion of the extruded material strings is optimized considering processing temperature and flow properties of the extruded thermoplastics (ABS, PC/ABS). Furthermore, depending on the flow behavior important FDM process parameters (e.g. volume flow, hatch distance) are adjusted to minimize cavities and generate media-tight components. The conductive circuits are characterized with respect to their electrical conductivity and mechanical stability.**

***Keywords—Additive manufacturing; electrical conductive circuits; embedding; silver particle ink; sintering by laser radiation***

## I. INTRODUCTION

3D-MID components offer high potential regarding function integration, miniaturization and design flexibility [1]. MID originally means molded interconnect devices. Nowadays the acronym MID is also extended to mechatronic integrated devices, because more and more functions are combined in one component and the manufacturing process is no more limited to injection molding of thermoplastics [2]. Increasing geometrical and functional requirements on 3D-MID demand an economic manufacturing of functional MID prototypes for pre-series tests. At the moment only partly adequate manufacturing techniques exist on the market for this kind of application and for manufacturing of small series. Furthermore, current MID manufacturing technologies only consider functionalization of the finalized part. The LDS technology e.g. enables direct activation of parts by laser irradiation of laser additives, which are doped into the plastic matrix. An additional metallization process allows a selective deposition of metal particles on the laser activated zones. However, generation of embedded structures and components which ensure protection against e.g. fluids and mechanical loads, is limited by the currently existing manufacturing techniques. To enable a cost-efficient manufacturing of customized electronics by an additional high functionality, one approach is to completely redesign established process chains and to combine additive processes like e.g. direct printing with additive manufacturing (AM) technologies [3]. Due to major improvements in the last years AM technologies made a great step from prototyping to manufacturing. For the integration of electronic functionalities some AM technologies can be complemented by enhanced assembly processes and direct printing technologies used within the field of organic and printed electronics [4]. In recent years, many investigations concentrate on combining the AM-processes stereolithography (SLA) and selective laser sintering (SLS) technology with direct printing technologies [3]. Here, the generation of conductive structures is mostly based on using silver inks or pastes and sintering by oven or photonic technologies. Additive building processes enable embedding of conductive structures, electrical components or small subsystems within the matrix by using photonic technologies for sintering. Thus, multi-layer structures can be generated. In this context, additional space allows manufacturing of conductive circuits with a higher cross-sectional area for e.g. enhanced ampacity [3].

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The electrical functionalization of AM-parts during the building process is influenced by process-specific conditions. Stereolithography parts e.g. consist of photopolymers which are hardened by laser radiation. The layer wise building of parts is realized by applying a thin layer of photopolymer by a coating blade and an additional laser irradiation. Therefore, integration and joining of electronics within parts depend on cleaning steps like removing of resin in cavities, which is a complex and time consuming process [5]. Besides, the SLS process has also disadvantages because of high pre-heating temperatures (e.g. 170°C for PA12). High process temperatures during SLS process initiate unintended sintering of ink and could lead to thermal damage of electrical parts caused by long-term building processes.

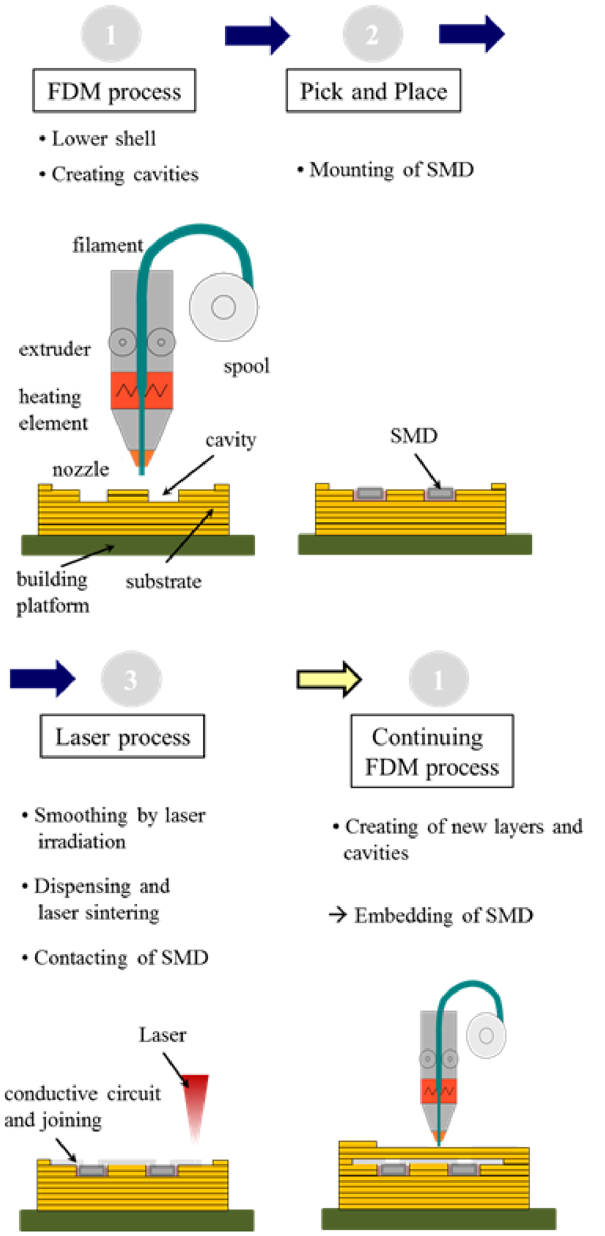


Fig. 1. Process chain of MID using FDM process and laser sintering of silver ink.

So, Fused Deposition Modeling (FDM) is an attractive AM process in contrast to the described process technologies due to the low thermal stress during part building and avoidance of powder or resin [6]. In addition, a fast building process along with possibility of generating functional components are characteristic attributes for FDM [6]. However, FDM parts have a textured surface due to the extrusion of filament material. So, the use of e.g. inks on FDM substrates can lead to infiltration into gaps between extruded stings, which contain risk of shorting. Zhou et al. [7] have investigated the generation of conductive circuits on FDM parts by inkjet. The used conductive materials were nanoparticle silver inks, which are thermally sintered by oven process. The results showed a conductivity between $2.5 \cdot 10^6$ S/m and $5 \cdot 10^6$ S/m and a slowed drying of printed lines, which is mostly caused by different sintering effects. It was found that these effects are caused by nanoparticle motion driven by evaporation flow, which leads to nanoparticle segregation (the “coffee ring” effect) and a crust formation on the top surface of the printed structures that prevents further drying [7].

One solution for reducing the evaporation flow is using inks with higher viscosities and bigger particle sizes. This approach leads to a simultaneous sintering behavior along the cross section of the printed lines and to a higher conductivity. In this context, the paper presents a new method for additive manufacturing of mechatronic integrated devices using FDM in combination with laser sintering of silver ink. The diameter of silver particles is < 10 µm, whereby viscosity is high enough to decelerate effects like particle motion or segregation [7]. After the generation of a lower shell, an integrated laser smoothing process of the FDM part surface enables dispensing of silver ink on the part without spreading. The sintering process of the silver ink is carried out by laser irradiation of ink directly after application. Fig. 1 shows the single process steps sequentially.

## II. Materials and Setup

### A. FDM machine

The FDM machine consists of an extruder, which heats the thermoplastic filament und extrudes the semi-molten material by a nozzle on the building platform. The extrusion temperature is up to 300 °C. The platform has a size of 200 x 200 mm and is heated to reduce shrinkage and distortion of parts. The nozzle diameter is 0.75 mm and the used filament diameter is 3.0 mm. The extrusion head moves in X-Y plane and deposits material according to the part geometry. To build a new layer on top of the previous one, the extrusion head can be moved in Z plane. The minimal layer thickness is 0.2 mm.

### B. Dispensing system

The dispensing process enables deposition of silver ink for generation of conductive circuits and contacting functional components. The used dispensing unit in this work is a Performus IV (Fa. Nordson EFD) and operates with compressed air. The dispensing unit is mounted on a 3-axis system and has a nozzle with a diameter of 0.20 mm (1/4”). The dispensed volume of the medium is varied by dosing time and dosing pressure. The used ink (Elecolit 3043, Co.

Panacol) is a silver ink based on micro particles with a diameter of < 10 µm. Further ingredients are organic additives and epoxy resin.

### C. Laser

The used setup is a scanner based IR-laser system with a wavelength of 1070 nm and a nominal power of 1000 watts. The used laser power is at 10 watts. The focus diameter is 40 µm and the operation mode is continuous wave (cw). Concerning different investigations in this paper, the focus diameter is varied to d = 3 mm and d = 5 mm to realize smoothing and sintering processes of the materials. Hereby, laser intensities are used from 0.5 W/mm² to 1.4 W/mm².

## III. Design of Experiments

FDM uses a temperature controlled extruder to force out thermoplastic filament materials and deposit the semi-molten polymer onto a platform in a layer by layer process. The processing parameters depend on the input of the slicing software. These include extrusion speed, axes speed, process temperature, fill gap and raster orientation. The first aim in the experiments is to determine the mechanical properties of the FDM specimens consisting of the materials acrylonitrile-butadiene-styrene (ABS) and polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS) depending on the building parameter. The determination of a suitable process window for processing the materials in this work is based on the parameters process temperature, volume flow and fill gap (fig. 2), which has the strongest influence on part properties [6].

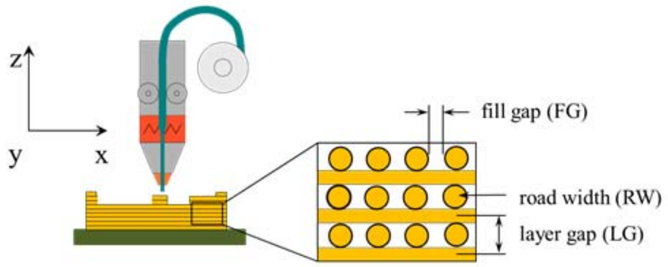


Fig. 2. Lay down pattern of FDM part with raster orientation of 0°/90°

The Volume flow (VF) is defined by extruded material flow per time (cm³/s) during process. Extrusion of the filament material as well as connection between single layers is affected by viscosity of material, which can be represented as a function of process temperature. By increasing process temperature, viscosity gets lower and extrusion of material is been facilitated. An increase in process temperature also effects positively the connection between single part layers because of greater mobility of molecules and improving ability of forming interconnections between molecules. This results in an increased forming of interdiffusion zones [6], which improve mechanical stability. Too high process temperatures lead to a decrease of mechanical stability of FDM parts due to decomposition.

First, test specimens for tensile tests are generated determining suitable FDM process parameters for ABS and PC/ABS by using different process temperatures and different volume flows. An evaluation of the results is intended to show the connection between process temperature, amount of extruded material (VF) and mechanical stability. Afterwards, the fill gap and the raster orientation will be adapted generating parts with high mechanical stability and low amount of pores. In addition, functionalization of FDM parts will be investigated by creating conductive circuits using microparticle silver ink and photonic sintering. Before dispensing ink, surface of FDM parts is pretreated by laser irradiation for local smoothing effect. This procedure is intended to avoid infiltrating of ink into FDM matrix. The laser irradiation process of the ink is carried out quasi-simultaneously by a scanning system using high deflection speeds. The generated conductive circuits are characterized with respect to adhesion on substrate by means of pull-off test according to EN ISO 4624:2003. The electrical conductivity is detected by four point measurement.

## IV. Results

FDM specimens of the materials ABS and PC/ABS were generated and compared with samples generated by injection molding. For each type of specimen, three specimens per parameter were fabricated and tested. The test geometry is a tensile bar according to DIN EN ISO 3167 with a size of 170 mm x 20.00 mm x 4.00 mm. The loading rate of the test is 5 mm/min. In the first step, influence of process temperature and volume flow will be evaluated with regard to forming of interdiffusion zones between single layers, see fig. 3. The parameter VF is varied from 100 % to 200 % in steps of 10 %. The measured tensile strength is the basis for evaluation. The fill gap is kept constant at 1.0 mm, because the parameter has no influence on the viscosity of the material. The following specimens are built with a raster orientation of 0°/90° because of achieving best results in preliminary studies.

Both materials ABS and PC/ABS show different processing areas in dependance of process temperatures. By increasing process temperature, the viscosities of the materials decrease, whereby semi-molten strings can spread in X-Y direction. This results in a denser structure of the matrix because of closing pores by higher flowing motion of materials. By using volume flow of 100% gaps between the extruded strings are visible, which indicates a too low material flow. In contrast to that, using volume flow of e.g. 200 % leads to overfilling and inaccurate part dimensions. Here, the volume flow is adjusted to 140 % ($3.94 \cdot 10^{-3}$ cm³/s) for ABS and to 160 % ($4.21 \cdot 10^{-3}$ cm³/s) for PC/ASB achieving dense matrix structure without deviation of part dimensions. The reason for the difference of VF values between ABS and PC/ABS is the lower viscosity of PC/ABS at 300 °C, which influences extrusion properties and plastic deforming immediately after extrusion. At the same time process temperature has direct influence on adhesion of single layers of FDM parts.

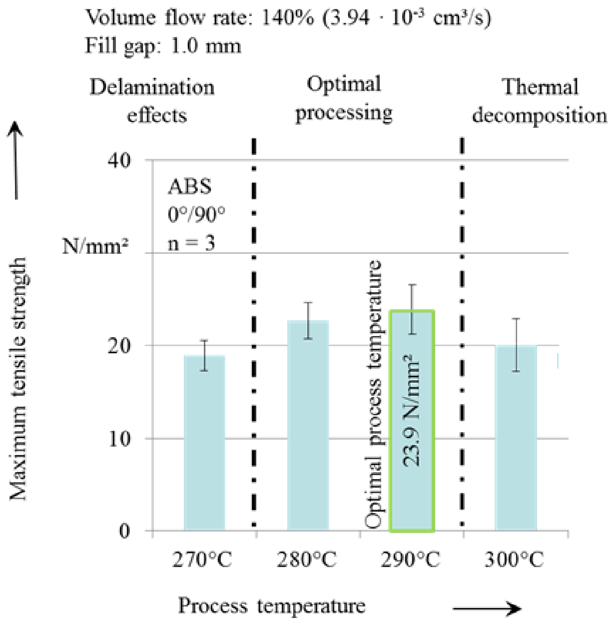


Fig. 3. a) Influence of process temperature on tensile strength of FDM parts (ABS) at constant volume flow of 140%

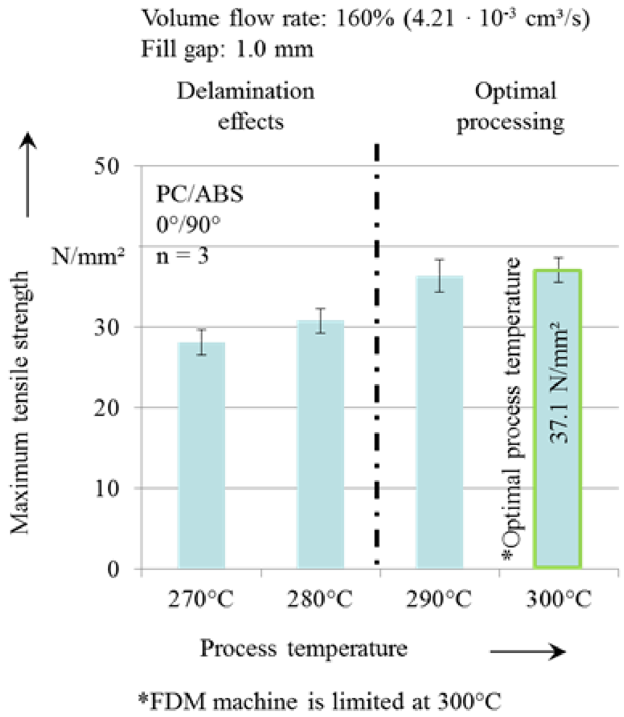


Fig. 3. b) Influence of process temperature on tensile strength of FDM parts (PC/ABS) at constant volume flow of 160%

High process temperatures promote molecular motion and forming of interdiffusion zones, until thermal decomposition is been reached. Figure 3 shows that the maximum tensile strength for material ABS is achieved at 290°C, which leads to a tensile strength of 23.9 MPa. At this process temperature forming of interdiffusion zones is completely defined. By increasing process temperature, thermal decomposition of ABS leads to decreasing of mechanical stability of the material. In contrast to that, a blend PC/ABS material has a higher thermal stability compared to ABS because of the higher melting temperature of PC. Optimal process temperatures therefore start at 290°C. The highest tensile strength is achieved at 300°C with 37.1 MPa. However, extrusion temperature of the used FDM machine in the test is limited at 300°C. So, effect of rather increasing of process temperature can not be investigated at this time exactly, but will be done in future experiments.

The parameter fill gap influences filling of FDM parts the most beside the parameter volume flow. In this context, following investigation evaluates optimization of mechanical properties of generated FDM parts by changing the parameter fill gap. The aim is rather closing of pores in FDM parts and thereby realization of further improving of mechanical part properties. The determined values for the parameter process temperature and volume flow are adopted from tests before, see figure 3. Beside, effect of raster orientation (0°/90° and -45°/+45°) on tensile strength is also investigated.

The diagrams in figures 4.a) and 4.b) show maximum tensile strengths in dependance on extension. By decreasing the parameter fill gap, extruded strings are deposited more densely next to each other. Hereby, existing gaps can be reduced and forming of pores minimized. So, higher mechanical stability can be achieved. However, a very low fill gap is reflected in overfilling parts, which results in inaccurate part dimensions and formation of streaks. Tests show a dense part matrix without these negative effects for a fill gap of 0.3 mm at a VF of 140% for ABS respectively a fill gap of 0.3 mm at a VF of 160% for PC/ABS. In addition, by using this parameter setting a signifcant increasing of maximum tensile strength for both materials ABS and PC/ABS of around 10 N/mm² can be measured compared to values in figure 3. This is equivalent to an increase of 30 percent of tensile strength for ABS and 20 percent for PC/ABS, compare figure 3 and 4.Due to low forming of pores during FDM process, which cannot be prevented completely, mechanical properties of generated test specimens are still lower compared to injection molding parts, see fig. 4.

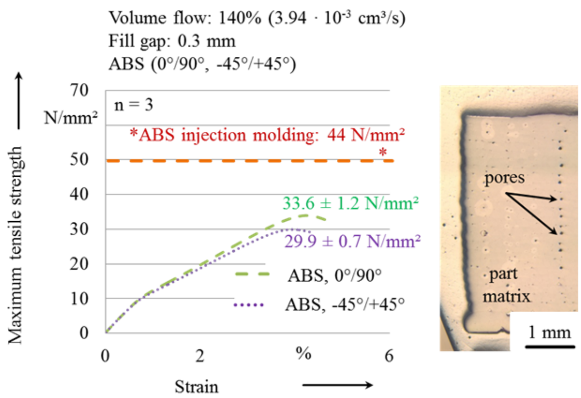


Fig. 4. a) Influence of fill gap and raster orientation on mechanical properties of FDM parts (ABS)

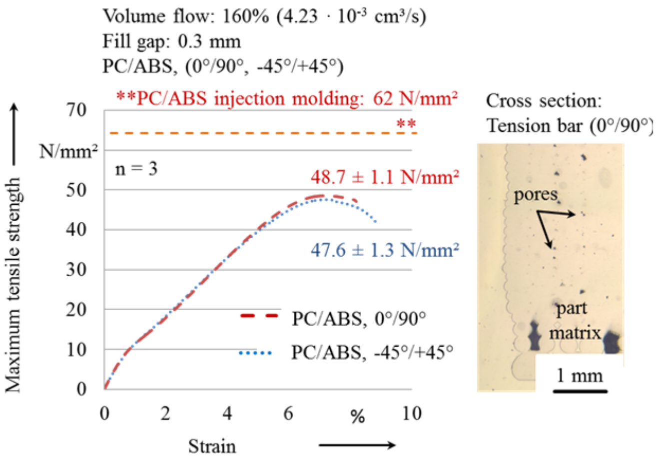


Fig. 4. b) Influence of fill gap and raster orientation on mechanical properties of FDM parts (PC/ABS)

The influence of raster orientation of 0°/90° and -45°/+45 is recognizable on the progression of the curves but does not significantly differ from each other.

The surface quality of FDM parts is among the worst compared to other additive manufacturing processes. One reason is that the thermoplastic filament has to be extruded by a nozzle and the nozzle diameter determines primarily the fineness and accuracy of the geometric structure [6]. However, the generation of electrical structures on FDM parts by direct printing technologies enables new possibilities concerning the layout structure and the flexibility of MID parts but also leads to new issues. Beside the different material pairings of plastic and ink based on metal particles, there are many different challenges of printing ink on FDM substrates [7]. One is the challenge of discontinuity of the printed lines caused by the topography and the low surface energy of the FDM substrate surfaces. Next to existing mechanical surface modifications, a local smoothing of part surface is carried out based on IR-laser irradiation in this paper. Hereby, a laser selectively irradiates surface and creates a media-tight trace on the upper layer of the part. During smoothing process, the heated material is melted, then levelled in the trace and solidified in an approximately smooth and sealed condition [10]. The media-tight trace avoids dispersing of ink into matrix or adjacent surface areas after application. Following, silver ink is dispensed by dispensing system on generated traces and sintered by a subsequent quasi-simultaneous laser irradiation process, see figure 5. The traces are in a length of 25 mm. The specific conductivity for structures is approximately $\sigma = 3.7 \cdot 10^6$ S/m. The value is equivalent to six percent of the bulk material silver. In contrast to sintered nanoparticles, there is no indication of forming sintering necks between the single microparticles. The reason is the lower surface energy of microparticles in contrast to e.g. nanoparticles [11]. Despite lower specific conductivity compared to nanoparticle inks, microparticle inks are significantly less expensive and due to higher viscosity more suitable for an additive structure generation by multiple dispensing and laser sintering processes. Hereby, the conductivity of structures can be increased.

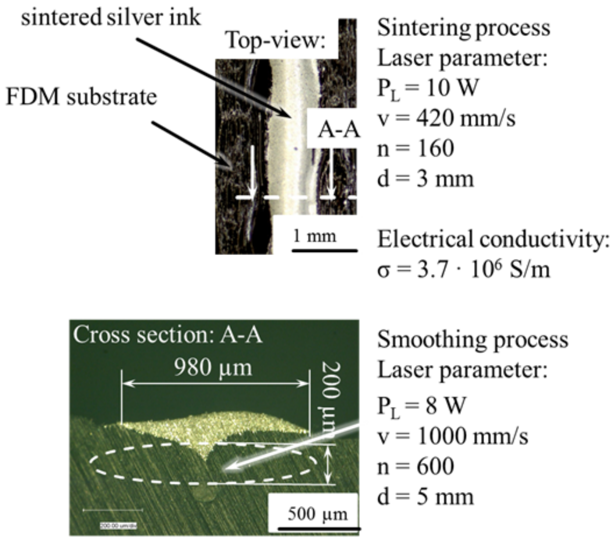


Fig. 5. Generation of conductive circuit on FDM part by direct printing and laser sintering

Sufficient adhesion of conductive circuits on electronic parts has to be ensured guaranteeing reliability against mechanical loads during operating phase. In the following, determination of adhesion of generated pads on FDM parts is done by pull-off test. The test is carried out by stamps, which are bonded on the laser sintered silver ink. Than, an increasing pull-off force divides the sintered silver ink from the FDM substrate. Thus, adhesion is calculated by maximal pulling force and size of area, which is separated from substrate. The test pads are in size of 10 x 25 mm, which are generated by dispensed lines of silver ink with a distance of 0.75 mm next to each other. By using this setting parameter, a coherent coating area in x-y direction with an average thickness of 50 µm in z direction can be created. The laser smoothing and sintering parameters are adopted of the data in fig. 5.

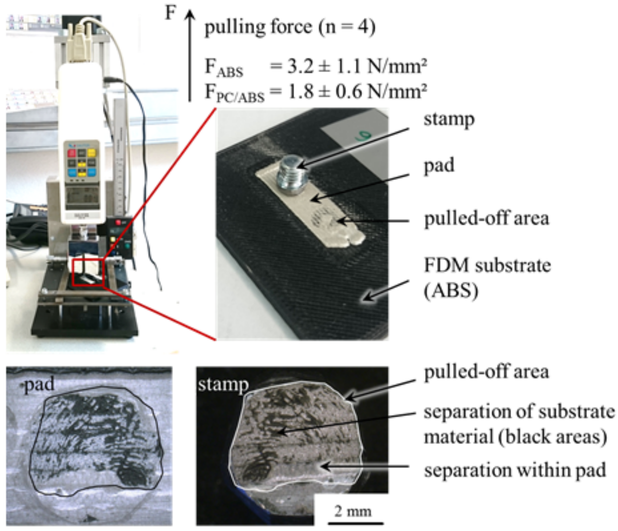


Fig. 6. Adhesion measurement by means of pull-off testing

In test, failures are mostly detected within pad or within substrate material, see fig. 6. Especially, a partly separation of substrate material by pull-off test demonstrates high adhesion of generated pads on FDM substrates. The average pulling force for ABS is 3.2 ± 1.1 N/mm² and for PC/ABS 1.8 ± 0.6 N/mm². The large difference between both measurement values is resulted in properties of PC. After laser irradiation process of PC/ABS, molten areas solidify in an irregular relief with partly forming of bubbles on the surface, which impedes adhesion of silver ink. This is caused by uncontrollable depolymerize of PC into volatile components like cyclical oligomers, phenyl and fluorenone due to resulting temperature [13], [14]. A further adjustment of laser parameters and pretreatment of FDM material will be investigated at the moment to achieve smoother surface profiles and avoid formation of bubbles. Turning to a comparison between test results and adhesion for copper on LCP (4.3 ± 1.1 N/mm²) generating by means of LDS technology shows similar data [15]. Here, the LCP substrate is generated by injection molding. Therefore, first comparison between the established LDS technique for series processes and the technology, presented here in the paper, is seen as realistic.

## V. Conclusion and Outlook

This paper describes an approach for optimization of process parameters for generation of functional FDM parts. The used filament materials in the tests are ABS and PC/ABS. With regard to extrusion process of thermoplastic filament material, the most influencing building parameters process temperature, volume flow and fill gap are evaluated by mechanical characterization of test specimens. Test shows, that process temperature in combination with volume flow has high influence on mechanical stability of FDM parts. The connection of single part layers is based on the forming of interdiffusion zones by molecular motion, which can be enhanced at higher process temperatures. A limitation of mechanical stability by increasing process temperature is given by decomposition temperature of the material. At this point decreasing of mechanical stability occurs. Significant reduction of gaps within part matrix can be carried out by variation of parameter fill gap. The results show an almost coherent matrix with only occasionally forming of pores. At the same time mechanical stability can be additionally increased without loss of part dimension accuracy. In comparison with established manufacturing techniques like injection molding (IM), generated FDM parts in this test have a tensile strength of 33 N/mm² for ABS (IM: 44 N/mm²) and 48 N/mm² for PC/ABS (IM: 62 N/mm²). This is equal to 75% of tensile strength of injection molding parts. Beside, generation of electrical structures on FDM parts is investigated. The conductive structures are generated by laser sintering of silver ink. The electrical conductivity of these structures is equal to six percent of bulk material silver. Moreover, adhesion of these electrical structures on FDM parts is 3.2 ± 1.1 N/mm² for ABS and 1.8 ± 0.6 N/mm² for PC/ABS and approximately in the range of adhesion values achieved with LDS technology for series generation.

Future work will deal with evaluation of long term stability of mechatronic FDM parts. Hereby, climate change test will be carried out to determine influences of the interaction between plastic and silver ink caused by different thermal expansion coefficients.

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