New printing technology for fully graduated material properties

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Abstract:

Generative technologies permit today the processing of a wide variety of materials. In the manufacture of functional prototypes, the limits of these technologies are however soon exhausted with the result that compromises need to be accepted. In order to meet the increasing demand of the industry, a new material, technology and machine concept was developed based on printing technology. Compared to standard generative systems where only one material per build process is usable this new technology allows generating parts of different mechanical properties in a wide range. This development enables the production of fully graduated material properties in one step.

1 Introduction

The use of functional prototypes is hardly restricted due to a small variety of materials which can be used for the generative processes. This is one of the reasons why the goal of generating parts with the same physical and chemical properties as the later in mass production produced parts can not be reached. One more reason is that the molecular structure of polymer parts is different depending on the used technology. Therefore the mechanical properties are also different. In selective laser sintering for example different powders can be used like polymers, casting sand or metals. But if a high surface quality is needed, a post-treatment of the parts is necessary. With the use of post-processing steps like vacuum casting the useable material spectrum can be enlarged [Geb00, Chu03].
The demand of industry especially in polymer applications is progressively increasing about fully functional prototypes. Therefore it is necessary to open the generative technologies for the use of a vast material variety. The decreasing life cycle time of products makes the development of new and more flexible technologies necessary. In most of the presented developments the materials were adapted to the specific properties of the technology where they are used. From beginning on, the potential of the generative technologies is mostly not fully used. Therefore a flexible generative technology was developed to enable the production of parts where the material properties can easily be changed during processing and where parts with fully graduated properties can be produced [Uhl04].

2 Printing Technology

The controlled deposition of very small volumes of material can be easily realised by two different groups of technologies: the continuous jet and the so called drop-on-demand technologies. The continuous systems are mainly used when big quantities of fluids or inks are needed in a continuous way at a high rate of drop repetition. With the drop-on-demand (dod) technology the deposition of every single drop can be controlled and every drop is produced on demand [Ede99]. Now a day this technique is used in colour ink-jet-printers for office and home applications. Some generative technologies, like the 3D-printing and the ballistic particle manufacturing, are using these systems for printing three dimensional geometries. Generally two different dod-systems can be differed: the bubble-jet and the piezo-jet technology [Ede99]. The bubble-jet is only useable if some components of the liquid can be evaporated suddenly without thermal degradation. Therefore if polymer based fluids have to be printed the piezo-jet technology is more preferable. Figure 1 shows how generally such a piezo print-head works.

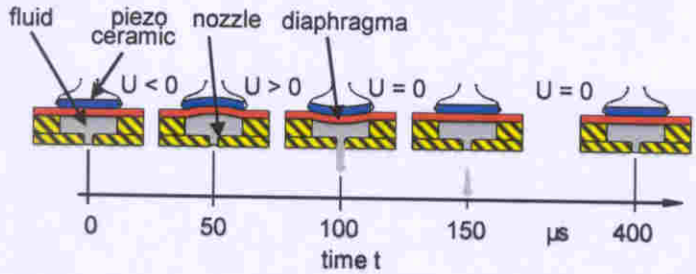

Figure 1: General function of a piezo print-head for drop on demand ejection

The conventional 3D-printing technology is using different techniques in building up the part geometry. In a first step powder material is deposited in defined layer thicknesses and the layer geometry is solidified by a binder which is printed into the powder. The part quality is then depending on the used powder and binder. A local variation of materials or of the later part properties is possible by using particle filled binders. The newest generation of 3D-printers is able to print parts in colour by using coloured binders which are deposited by different nozzles [Chu03, Geb00, Mot01, Sac97, Who03].

In order to be able to change the materials and to influence the mechanical properties in one part, it is necessary to deposit inside of every layer different materials. This is only possible if all the material for building up the part is completely deposited by the printing process. Therefore the 3D-printing strategy was not useable for the new developed technology. At the ballistic particle manufacturing technology all required material is printed. But none of the available machine systems are able to realize different material properties in one manufacturing process or inside of one part. The printing technology and the selection of print-heads, as well as the printing strategy are depending on the material which has to be printed. Therefore the selection of the materials was representing one essential part of development.

3 Selection of the material

In the classical production of polymer parts there are two possible routes. One is to use pre-polymerised materials in form of granules like the thermoplastic industry uses for injection moulding or extrusion. The alternative is to use low-molecular polymer in combination with a shaping process and to let react the materials to a macromolecular polymer like in reactive injection moulding. With the generative technologies both routes can be used. Thermoplastic material is used for selective laser sintering (SLS), fused deposition modelling (FDM), ballistic particle manufacturing (BPM) and the technology of solidifying by chemical reaction is used at stereolithography and at the ink-jet printing system from Objet Geometries Ltd.
The use of thermoplastic material for dod-technology is restricted by the physical properties in the liquified status. All available standard thermoplastic materials have a too high viscosity for being used in an ink-jet printing system. Therefore a reactive system of at least 2 components was chosen which fulfils all physical requirements to be printable.
In a first step, tests were made to check the printability of the selected materials. Not only viscosity is one of the important parameters, but also the surface tension as well as the density in dependency of the temperature. A typical formation of a single drop is shown in figure 2. The pictures were made in steps of 20 µs each so that every phase of the out-coming and the

forming processes of the drops could be observed. This observation allows the exact adjustment of the process parameters to obtain single drops for every selected component. Finally the materials could be printed in a very large parameter range, but mainly the results of drop ejection are so called drops with satellites or sprayed drops (figure 2) which are useless for the build-up process.

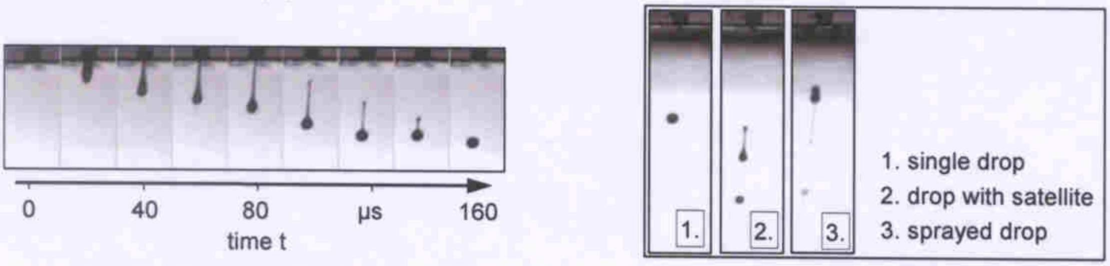

Figure 2: Drop formation at the nozzle / different kind of drops

The usage of a reactive material systems offers very significant advantages compared to thermoplastic materials. Over the combination of different components the resulting material properties can be varied in a very wide spectrum. Figure 3 shows the elasticity modulus of different mixtures of the components by using one common reactive basic material. The showed properties for the reactive materials are only from some selected mixtures. Depending on the mixture proportions all properties between mixture M1 and M2 can be realised. These results show that the mixtures M1, M5 and M4 have elasticity moduli which are comparable to those from standard thermoplastic materials.

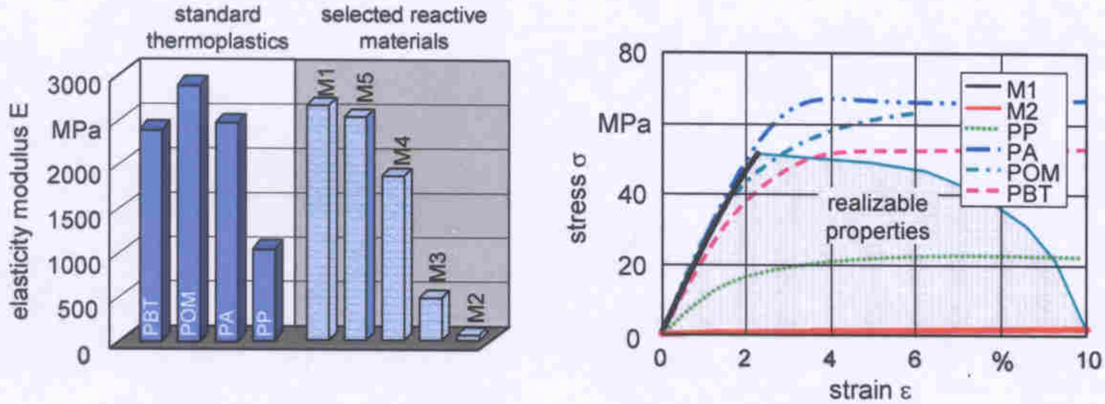

Figure 3: Comparison of material properties of standard and the selected materials

Figure 3 shows also the elastic and extension behaviour again in comparison to other thermoplastics. It can be observed that the mixture M1 has approximately the same performance as the other thermoplastics. Contrarily mixture M2 has an extremely elastic characteristic. Finally the result of these investigations is that all material properties between M1 and M2 inside the grey coloured area are realizable only by changing the mixing proportions of the components.

4 Developed printing technology

In order to realise all those material properties, the control of the material out-put during the printing process is essential. Several investigations were done to analyse the drop formation at the nozzle and to find out at which parameters one single drop could be ejected in a reproducible way and which mass every single drop has depending on the printing parameters. To ensure that the different materials are printed in the correct mixing proportions the masses of the drops were measured by varying the process parameters. From the information about the drop masses the process parameters were selected, so that the defined part properties could be reached after the build-up process is completed. In figure 5 the influence of impulse frequency f_i and nozzle voltage U_N on the mass of single drops is shown for the selected reactive components.

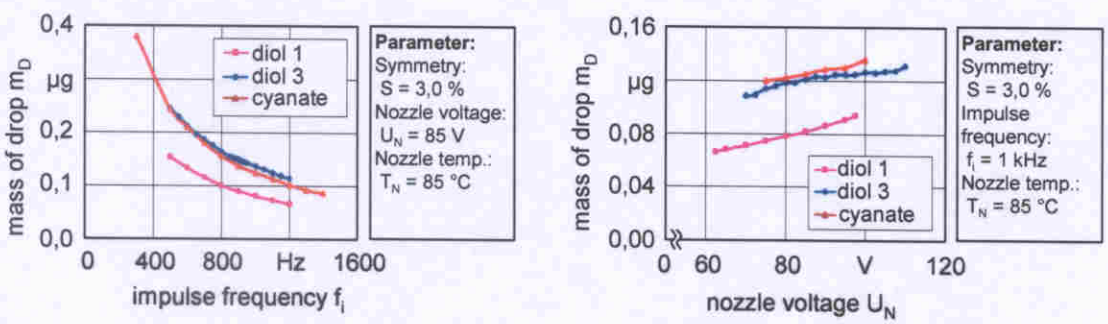

Figure 5: Mass of drops depending on impulse frequency and nozzle voltage

The analyse of impulse frequency shows that the mass of the drops is varying in a very large spectrum; from less than $m_D = 0{,}1$ µg at an impulse frequency over $f_i = 1200$ Hz up to over $m_D = 0{,}3$ µg at less than $f_i = 400$ Hz for the cyanate component. This represents a difference in mass of over 300 %. The behaviour of the two diol components is very similar. But at an impulse frequency less than 500 Hz and higher than 1200 Hz, a drop formation couldn't be observed.

The influence of the nozzle voltage on the mass of drops is similar for all three components. The drop mass is constantly increasing with higher nozzle voltage. The difference of mass between the single materials is due to the different density of the components. The curves are showing only the range of voltage where single drops are ejected from the nozzle. At lower voltage, a drop detachment from the nozzle does not take place. At higher voltage, more than one drop (satellite drops) is ejected per impulse so that it will be impossible to deposit the material in a defined area.

The nozzle voltage has additionally a very high influence on the output velocity of the drops. As shown in Figure 6, the velocity of the drops is growing by increasing the nozzle voltage. This parameter is significant for the final drop diameter after the impact on the solid surface of the build base. The impact diameter of the drops is finally responsible for the geometry of the deposited line. A splashing of the drops by hitting the surface or previous deposited material was not observed.

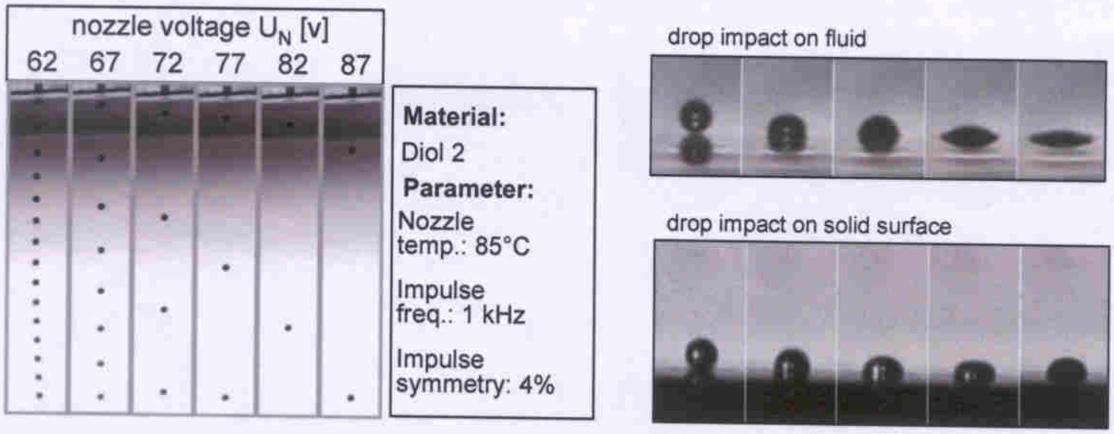

Figure 6: Velocity of drops depending on nozzle voltage / drop impact

The measured drop velocity ranges from $v_D = 0{,}3$ m/s at $U_N = 62$ V up to $v_D = 2{,}78$ m/s at $U_N = 87$ V. The changing of velocity is corresponding to 0,1 m/s/V.
One parameter which was finally chosen for adapting the needed masses of the drops during the printing process is the symmetry of the impulse. The symmetry defines the length of the impulse depending on the impulse frequency. The drop mass is increasing with the symmetry. In the spectrum where a symmetry variation is possible and single drops can be ejected the masses can be varied approximately about ± 0,03 µg which represents ± 25 %. This variation is enough for realising the needed mixing ratio.

The process was finally adjusted in a way that printing of the three reactive components in different mixing proportions could be obtained only by varying the mass of the drops. This opens the possibility of changing the material properties from one volume increment to the next, so that inside of one layer and also over the complete part geometry the mechanical properties could be entirely varied.

First printing experiments showed that the reactive components were completely hardened only a few seconds after the conjunction in the build area. The reacting time could also be adjusted by temperature of the materials and additionally by chemical additives. Figure 7 shows single reacted lines where the contour of every single drop is still to see after the reaction. This shows that the solidification takes place immediately after the contact of the reactive components. Lines as well as thin closed layers were successfully realised with this printing technology as well as areas with local different material properties.

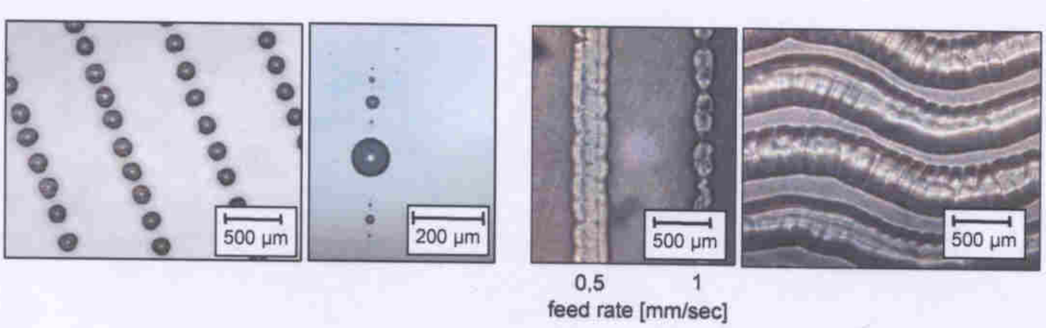

Figure 7: Deposited single drops / printed and solidified lines

The generation of data inside a 3D-CAD program where locally different material properties could be assigned is not available in today software tools. Therefore an own voxel-based design software is still in development. Additionally, a data format according to the standard STL format was developed to enable the transfer of geometrical and material information to the machining system.

5 Conclusions

The developed printing technology enables the manufacturing of full graduated material properties inside of one part. The technology is based on the local deposition of different reactive polymer components using special adapted printheads. Depending on the mixing proportions of the reactive materials the desired mechanical properties can be realised without any material changing or refill processes of the machining systems. This novel technology enables for the first time to generate parts with fully graduated properties out of one material. In order to realise the different material properties it was additionally necessary to develop a CAD-system which enables the assignment of material properties to every single voxel inside of the CAD-model.

This technology represents a step forward in realising not only prototypes but fully functional parts with a very large spectrum of material characteristics. Additionally, this system allows the manufacturing of graduated properties which are today not realizable by conventional machining or rapid prototyping technologies.

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