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3D Multi-Material Metal Printing of Delicate Structures

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A new 3D screen printing manufacturing method is used to perform printing experiments with a two material layout. For this purpose the screen and the material are changed during the printing process and the materials are printed in an alternating rhythm. We studied the hindering effect of the already printed structures on the printing process. The printing into deepenings constitutes a challenge for the screen printing process and can cause a decrease in quality compared to a one material design. If the aspect ratio of the deepening is high the structure can't be printed and failures occur. With regard to the layout this effect can be compensated by varying the printing rhythm. A frequent change and thus low difference of height between the printed structures is beneficial for the two material print. We like to present first results of the research and give an insight into multi-material 3D screen printing.

Introduction

With regard to the shortage of resources, the need for energy efficient production lines and the miniaturization and increasing complexity of components new challenges arise for consisting manufacturing methods. In the past several production methods have been developed to comply with these requirements. Powder based methods became the focus of interest since they offer a great variety of (bad machinable) materials and the producibility of manifold free-form shapes. Additive manufacturing methods like laser sintering, electron beam melting, stereolithography and many others are specialized to produce complex free-form structures. Characteristic for these production methods is the absence of tooling costs, the freedom of design and the relatively slow build time. Hence they are ideally suitable for custom made components or small batch series. Metal injection molding in contrast is accompanied by relatively high tooling costs. It represents an established mass production method with a high reliability and good surface quality. The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Branch Lab Dresden is working on combinating these two advantages using a new 3D screen printing technology to fabricate delicate 3-dimensional parts. Based on the widely used two dimensional screen printing method the process is suitable especially for filigree structures and small components. Fine walls down to 70 µm and aspect ratios greater than 100 are possible. Since this method uses no supporting powder bed, there is no need to remove unused powder. Thus manufacturing of parts with complex inner structure, undercuts and even complete hollow structures are producible. It's feasibility for mass production processes [1] and the free choice of powder makes it a promising manufacturing method for metal components. The newest object of research focuses on extending the variety of printable components by developing a process in which two or more materials are printed in parallel.

3D-Screen printing technology

The 3D screen printing technology is based on a 4-step process illustrated in figure 1. In a first step the desired layout has to be defined by a CAD model. It is transferred to the printing screen using a photolithographic process and a chemical resistant photosensitive coating. In doing so the areas on the screen that are not part of the desired structure are filled with synthetic. The areas that are part of the layout structure remain free and thus permeable for the printing suspension. Once the suspension is prepared in a second step the printing process can be performed. The paste is spread on the screen and pressed through the open areas with a printing squeegee generating one layer of green structure on the substrate. This step will be explained in more detail later on. The idea of the 3D screen printing method is now to repeat this printing step and build up a three dimensional structure layer on layer. A precise alignment of the screen and the printed structure is substantial for a reliable process and a high quality output. After each layer the structure has to be dried to develop enough

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hardness for the next printing step. Subsequent to the generation of the desired 3D green body it has to undergo a thermal treatment for debinding and sintering.

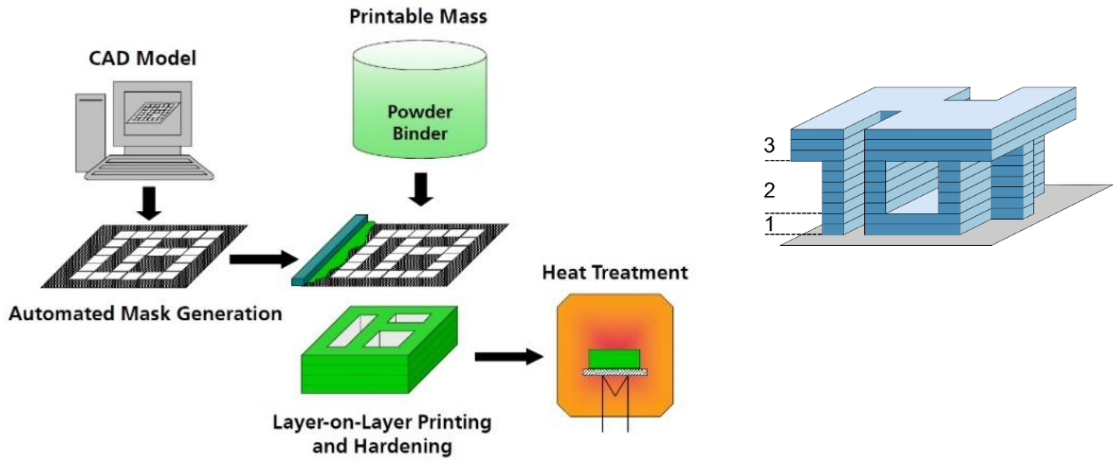

Figure 1: The 3D screen printing process scheme. First the CAD model of the desired layout is transferred to the screen using a photolithographic mask. During the printing process the printable mass is pressed through the open areas of the screen and dried on a substrate. Repeating this printing step a three dimensional structure is generated layer-on-layer that can be sintered to full density. The right sketch shows a potential 3D-structure with undercuts and hollow areas. Three different screens are necessary to produce this shape.

By using different screens for a specific set of layers it is possible to generate three dimensional structures with an alternating cross section. In figure 1 a potential structure based on a three screen layout is shown. Undercuts and hollow structures are possible without the need for a supporting bed. In comparison to the two dimensional screen printing process the requirements concerning paste rheology and machine precision change [2]. The printing pastes are developed individually at the Fraunhofer IFAM with regard to the desired geometric structure and material. Nearly every material that is available in powder form can be processed to a printable paste.

3D-screen printing process with two material layout

While the material change in z-direction is easily realized by (gradually) changing the printing suspensions components with respect to the desired grading, further technological challenges have to be adressed at the multi material layout. Figure 2 illustrates the screen printing process with two materials. The sketch shows a cross section of the printing screen and substrate. In the first step the printing suspension has to be spread homogenously over the screen by a flood squeegee (flooding). During the flooding step the meshes of the screen that are part of the layout are filled with suspension. After the meshes are filled a printing squeegee is pushed against the screen. Due to its elasticity the screen deforms and gets into contact with the substrate while the frame remains in its position. The printing squeegee now is moved over the layout bringing every filled mesh in contact with the substrate. Due to its cohesion with the substrate the paste is released out of the screen. Repeating these steps the structure of the first material is built up several layers. Now to print the second material B the screen has to be changed and aligned to the already printed structures of material A with high precision. After material B is flooded it has to be printed leading to the situation detailed in the lower right corner of the sketch. The printed structure of material A touches the screen counteracting its downward movement. The screen has to be deformed under the pressure of the printing squeegee to get in contact with the substrate in the cavity. Depending on the paste rheology and screen there is a maximum aspect ratio R = h/w for which the second layout can be printed between a three dimensional structure. For a better understanding the 3D screen printing process for two materials is discussed on the first set of layers respectively. The first printed material is labeled A and the second printed material is labeled B. Depending on the printing rhythm this situation can switch during the process but this case will not be dressed here.

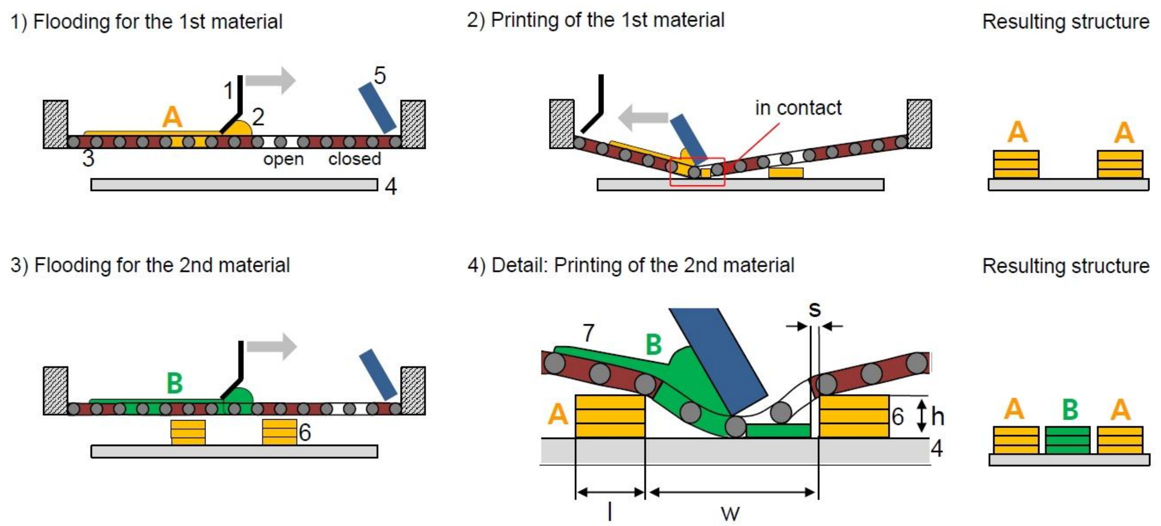

Figure 2: The screen printing process with a two material layout. The first material A is flooded (1) and printed (2) as known. Notice the screen bending which brings the screen into contact with the substrate. When the second material B is printed (3, 4) the green structure of material A will disturb the printing process by preventing the screen from getting in contact with the substrate. 1 flooding squeegee, 2 printing paste A, 3 screen, 4 substrate, 5 printing squeegee, 6 printed structure, 7 printing paste B, l line width, w cavity width, s spacing between the two materials, h height of material A

We designed a special test layout that includes a great variety of geometric structures to study the influences of the geometric parameters. Several line-space-configurations for two materials with a line width starting from 75 µm up to 400 µm and a cavity width of 325 µm up to 1050 µm are positioned in an angle of 0°, 52° and 90° to the direction of the squeegees movement. Further the spacing between the two materials is varied to consider the influence of an insatisfactory alignement of the different screens. Concentric quadratic and circular structures have been used to study the supporting effect of the already printed material as a function of line width. The line width of material A ranges from 75 µm to 400 µm and the inner structures are in the dimension of 60 µm up to 3500 µm. In addition several more complex structures are placed on the screen to analyse geometric printing situations which can be relevant in praxis applications like tapered lines or lines of different curvature.

To rate the producibility of the two material test design we carried out printing experiments with 5 or 10 layers each set of one material. Thus the layer difference between the already printed structure of material A and material B is 5 or 10 after each set. Depending on the printing rhythm the layer difference switches or changes during the process. Since only the first set of layers is considered here the layer difference is referred to the height of the printed structure of material A. The experiments are carried out on the first generation 3D-screen printing machine from Bauer Technologies GmbH. A high precision synthetic screen with a mesh size of 330 and an emulsion over mesh of 18 – 20 µm from MP+L - Produktions GmbH as well as a printing squeegee with a Shore hardness of 55° type 32 from RK Siebdrucktechnik GmbH were used for the experiments. We used a commercial Zeiss Stemi 2000-c stereo microscope to analyse and measure the printed structures. For our studies we chose two model materials: an alumina powder T60/64 from Almatis GmbH with a median size of 2,7 µm and a 316L stainless steel powder PF-3F from Epson Atmix Coorporation with a size of 2,9 µm. These materials are not appropriate for the sintering step and are chosen solely with regard to the printing process.

As a reference one material line structures with variable line width were added on the layout. The minimum line width that could be achieved was 70 µm for the alumina paste and 80 µm for the steel paste. Both pastes could be printed with line spaces down to 50 µm. Since 50 µm corresponds to the thinnest layout design it is not clear if any thinner spacings are possible. Looking at the line-space-configurations for two materials there a several parameters which can be varied: The line width of the first material, the line width of the second material and the spacing between the first material lines. In total we used eight different line-space-structures orientated in three different angels respectively. Since the different orientations on the screen showed no significant effect on the printing quality they are not differentiated here. We estimate the combination of a 55° shore squeegee with a supporting board (type32) and a screen tension of 26 N/cm to be too inflexible to adapt to the structures during the printing process and expect a significant influence using a softer component combination. In Figure 3a a microscope picture of a two material line-space-structure with the steel paste as material A is shown. The structure resulted from a printing experiment with a layer difference of 5 which correlates to a differential structure height of approximately 75 µm at each screen change. Since the ceramic background and the alumina printing paste is in white color, the alumina structure is colored red for better differentiation. The spacing between the steel and the alumina lines remains constant at 50 µm and the darker lines printed of steel paste have a constant width of 150 µm (5). The red marked alumina lines have a decreasing line width starting from 300 µm with a stepsize of 25 µm. According to the picture the thinnest printed line has a width of 150 µm and has been printed into a spacing with an aspect ratio of R = 0.3. Although more fragile lines are visible they become thinner with each printed layer. That effect is shown in Figure 3b on a solo line structure of steel paste where one can clearly see the degrading constancy in height for thinner lines. The thinnest printable line is marked by an arrow.

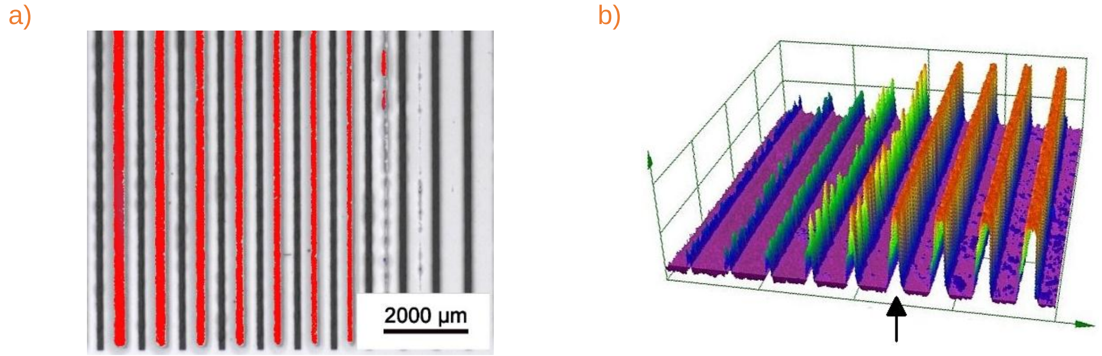

Figure 3: Printed line-space-structures. a) Microscope picture of a two material line-space-structure with constant line width and spacing of material A (steel, dark) and decreasing line width of material B (alumina, colored red). The layer difference is 5 (75 µm) and the thinnest printed alumina line has a width of 150 µm. b) Confocal laser scanning microscopy of a line structure of one material (steel). The thinnest reliably printed line is marked. Thinner lines are still visible but loose contact to the screen after a few layers.

Comparing printing experiments with a layer difference of 5 to printing experiments with a layer width of 10 the influence of the first materials height is visible. The minimum line width of material B ranges from 150 µm to 200 µm for a printed height of 75 µm of material A and from 250 µm to 350 µm for a printed height of 150 µm of material A. The spacing between the two printed materials has been varied between 50 µm and 250 µm. As seen at the summarized results in **Error! Reference source not found.** no significant tendency between the spacing and the minimum line width is found.

Experiment	Spacing between the two printed materials [µm]	Average minimum line width of material B [µm]
Experiment type 1 - Layer difference 5 (75 µm), - line width material A (150 µm)	38	167
	50	158
	150	200
	250	183
Experiment type 2 - Layer difference 10 (150 µm) - line width material A (150 µm)	38	308
	50	258
	150	342
	250	283

Table 1: Summarized printing results of the line-space-structures for two materials. The average minimum line width shows a clear dependency of the experiment type. The spacing has no significant tendency.

Looking at the results received from the concentric quadratic and circular structures we can see that the supporting effect of the printed structure is more prominent if the cavity is surrounded by all sides. For the circular structures as well as for the quadratic structures we found a minimum dimension (6) of

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[5] Due to shadowing the steel lines appear to be thicker in the picture. The identification of the correct line thickness has been done by comparing to the defined layout structures and high resolution pictures.
[6] Diameter of circles or side length of quadrates respectively.

the inner design that can be printed. It was 500 µm for both layer differences of 5 (type1) or 10 (type2) respectively. The line width of the outer structure was 150 µm and 200 µm and the spacing between the two materials was set to 50 µm. Although the minimum dimension is 500 µm for both experiment types we found experiment type 1 with 5 layers in difference to be more reliable. The 500 µm structure could be printed with a chance of 67 % with 5 layers difference and with a chance of 16 % with 10 layers difference. The majority of the structures built by experiments of type 2 had a minimum dimension of >3500 µm. To examine the supporting effect of material A we varied the line width of the concentric test structures. According to our experiments there is no dependency for a range from 100 µm to 4000 µm. The inner structures of material B could be printed in all cases. Further the already printed structures of material A were not affected by the printing process of material B. No bending or compressing could be found at all printed structures up to a height of 600 µm and a line width down to 100 µm. The strain caused by the screen during the printing process is compensated by the background pattern in the layout.

The cross section of the printed structures of material B shows a considerable characteristic. The width of these structures is not constant in height - it is getting thinner towards the substrate. We expect this effect to happen due to the hindering supporting effect of the printed material A. It leads to a lack of contact between screen and substrate during the printing process. Figure 4 shows a close up sketch of the geometric constitution during the printing process. The desired situation where screen and printing squeegee are flexible enough to build up contact between the screen and the substrate is sketched on the left side leading to the target structure defined in the layout. According to our experimental results we expect the screen to be less flexible leading to a situation sketched on the right side where the screen has no contact to the substrate. The printing paste is pressed through the mesh and forms a drop on the bottom side of the screen. Repeating the printing step will enlarge the drop until it is big enough to get in contact with the substrate. As the contact area of the drop and the substrate is smaller than the target layout the printed structure is thin at the bottom. When the structure starts to build up in height the effective layer difference gets smaller. Thus the structure's cross section is converging to the target layout. A structure shown in the lower right of figure 4 can be the result. This explanation correlates well with the observation that several printing steps are necessary until a first layer of material B is applied on the substrate. Continuing the alternating printing process the structure’s width varies with each layer. Consequently it can be favourable to alter the rhythm of the screen change. Depending on the geometric properties the set of layers should be chosen separately for each material. Instead of having an alternating difference of layers (as in 5xA, 10xB, 10xA, etc.) it can be beneficial to leave material A on the first position for each set (as in 5xA, 5xB, 5xA, etc.). That way more filigree structures can be printed first, whereas easy printable coarse structures can be printed second. From our printing experiments we infer that it is not possible to generalize the results in terms of minimal printable structure dimensions. One has to consider the layout geometry to make a statement about the achievable precision of the print.

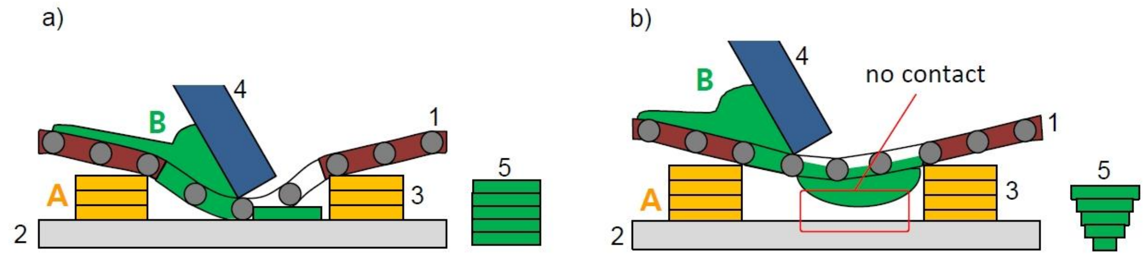

Figure 4: Close up sketch of the printing situation of a two material printing process. In the left sketch a) the desirable geometric constitution during the printing process is shown. Screen and printing squeegee are flexible enough to build up contact between screen and substrate. According to our experimental results the screen is not in contact to the substrate as shown in b). Thus a drop of suspension will form during the iterative printing process. Once the drop is big enough it will get in contact with a contact area thinner than the layout structure. A structure with a cross section shown in the lower right is the result. 1 Printing screen, 2 Substrate, 3 Printed structures of material A, 4 Printing squeegee, 5 Cross section of the printed material B

Besides the mentioned results there are several considerable aspects coming along with the printing process of a 3D multi material design. A precise positioning of the screen is necessary to achieve structures that are constant in height. Each time the printing of filigree structures is continued after a screen change the accuracy of the alignment has to be remarkably higher than the dimension of the structures. Otherwise the surface of the printed structure has an offset compared to the layout on the screen. That way it is not possible to release the paste during the printing process and the width of the structure may get thinner with each screen change. Thus the rhythm of the screen change plays an important role at the multi material 3D screen printing process. While the quality of the second material B is higher for a small layer difference the chance of failure due to imprecise alignment of the screen is higher and the productivity is lower. On the basis of the printing experiments done in this study we identified the screen printing machines precision to be the limiting factor for a reliable print over several sets of layers. A new developed commercial 3D screen printing machine with higher precision will enable to continue the studies of a multi material printing design in more detail. Further we found the paste rheology to have a leading influence on the quality of the print on one material structures. As there are different requirements coming along with the individual printing layouts we expect an individual optimum paste rheology for each multi material print. Additional printing experiments are planned on this issue. Variations of the printing squeegee’s angle and material as well as the printing speed are to be analysed and related to the printing quality of material B. Due to better adaptation to the printed structures we expect a more flexible squeegee without supporting backboard to give better results especially at higher aspect ratios. Additionally the layout of a 3D printing screen contains a background pattern. It is necessary to generate supporting structures that minimize the pressure on the filigree printed target structures. Having a two or more material design the background pattern becomes more complex leading to a shortage of space. Hence the multi material design of the particular screens have to be developed with great attention on this subject.

Conclusion

3D screen printing experiments have been performed using a two material layout design. On the basis of several test structures the minimum printable shape dimension of the second printed material could be identified with respect to the test geometry and the printing process parameters. It is found to be dependent on the height and width of the cavity that is formed by the first printed materials green structure. Line structures could be printed with a minimum line width of 158 µm and 258 µm at a cavity height of 75 µm and 150 µm respectively and a spacing of 50 µm between the two materials. The hindering supporting effect of the printed structure of material A is found to be significantly bigger for concentric circle and quadratic designs where the cavity is surrounded by all sides. The supporting structure inhibits the contact between screen and substrate during the printing process of the second material. This imperfect process also leads to a failure in the printed structure and can be improved by an adjusted printing rhythm of the two materials. However the 3D screen printing method is a promising process for the industrial manufacturing of filigree structures. The two material printing experiments produced satisfactory results and gave information about the feasibility of the process and about potential problems that may arise. Process parameters like the printing rhythm, the printing squeegees hardness, angle and printing speed as well as the paste rheology in respect of the special geometric situation need to be addressed. A currently developed 3D screen printing machine with improved precision will enable further more detailed experiments dealing with these issues.

References

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