Selective Mask Sintering for Rapid Production of Parts, Implemented by Digital Printing of Optical Toner Masks

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Abstract

Selective Mask Sintering (SMS) is a digital, additive fabrication technique with great potential within Rapid Manufacturing. Three-dimensional parts are produced by selectively sintering or melting a thin layer of plastic powder, one layer on top of the other one, by exposure with IR-light through a digitally printed optical mask – i.e., a photomask – in the form of a toner image. The process thus transfers 2D images into 3D parts by melting each layer in a single exposure. This makes the SMS process significantly faster and more cost-effective than traditional laser sintering, which sinters each layer in a point-by-point fashion. The speed of the SMS process makes it suitable for use throughout the entire product life cycle for plastic parts; from the first prototypes, through production of parts, and finally to "Spare parts on demand". Sintermask Technologies AB has developed the SMS-process, and has made the first SMS-machines commercially available during last year. The Selective Mask Sintering process and machine will be described in the following.

Introduction

The Rapid Prototyping / Rapid Manufacturing industry is about 20 years old and is based on various methods of fabricating three-dimensional objects directly from 3D CAD computer models. Common to all such methods is that the objects or parts are built up in a layer-wise fashion, by depositing a thin layer of material in powder or liquid form on top of previously solidified layers, followed by a selective solidification of the current layer. Therefore, these methods are also denominated *additive fabrication*. The methods used are mainly laser-based systems for selective sintering or melting of powders (*Selective Laser Sintering – SLS*) or for selective photocuring of photopolymers – or, inkjet-based systems which selectively deposit the material as a viscous liquid and then by means of lamps photocure the material. These technologies are mainly being used in prototyping applications (*Rapid Prototyping – RP*), with a growing trend towards manufacturing of small-volume series of parts (*Rapid Manufacturing – RM*).

Sintermask takes a somewhat different approach to additive fabrication. Instead of using a laser beam of infrared light to selectively sinter or melt a powder material, Sintermask uses a photomask through which the powder bed is selectively exposed to infrared light generated by a set of IR-lamps. This makes the creation of each layer significantly faster than with a laser-based technology. Sintermask's method is denominated *Selective Mask Sintering (SMS)* and is the fastest and most cost-effective additive technology available on the market for a warm process. The SMS-process was patented in 1998 [1-2] and the company *Speed Part RP AB* was formed in 2000 to commercialize the process. In 2007, in connection with market entry, the name of the company was changed to *Sintermask Technologies AB*. Because of the speed of the process, it is ideally suited for applications within *Rapid Manufacturing* and its extension into something more similar to production at an industrial scale and which we choose to denominate *Rapid Mass Fabrication (RMF)*.

At the heart of the SMS process lies the ability to generate a new photomask for each layer to be built, such that the time required for the steps of Mask-Generation and Exposure becomes significantly shorter than the cycle time (=the total time for creating one complete layer). Sintermask has implemented the generation of individual photomasks by digital printing of optical toner masks, in which each single photomask is created by printing a toner image onto a glass plate. After the exposure of the layer, the photomask must be erased such that a new mask for the next layer can be written onto the glass plate. This puts two unconventional requirements on the toner being used: 1) it must withstand heat so that it does *not* melt and therefore can be removed from the glass plate; 2) after removal, the toner is brought back into the system, such that the cost of toner consumption is minimized. Thus, the toner must have the ability to be *recirculated*. Sintermask has developed such a printer, toner and recirculation system.

The Selective Mask Sintering Process: An Emerging Additive Technology

In Rapid Prototyping and Manufacturing, there are several established and well-known additive fabrication methods for materials as diverse as plastic, metal and sand, and suitable for a variety of applications ranging from casting and tooling to part-making and medical applications [3]. Examples of additive methods are: Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Layered Object Manufacturing (LOM), Digital Light Processing (DLP), PolyJet, Electron Beam Melting (EBM), 3D Printing (3DP), Selective Laser Melting (SLM), Fused Metal Deposition (FMD), Laser Metal Deposition (LMD), Direct Metal Deposition (DMD), Laser Engineered Net Shaping (LENS), Maskless Mesoscale Material Deposition (M3D), High-Speed Sintering (HSS), and others. All these methods have been classified into three general types [4]: 0-dimensional, 1-dimensional and 2-dimensional methods.

0D-methods typically include laser-based methods such as SLS and SLM, in which the build area is selectively solidified in a point-by-point fashion. In this context, the spot of the laser beam, being of finite but small (compared to the build area) size needs to be scanned in both the *x*- and the *y*-directions to cover the the whole build surface. Thus, it is regarded as a mathematical point, which is a 0-dimensional entity.

1D-methods typically include inkjet-based methods such as 3DP and PolyJet, in which the build area is selectively solidified in a line-by-line fashion. In this context, the array of individual inkjet nozzles are arranged along, for instance, the x-direction, such that this array only needs to be scanned in the y-direction in order to cover the whole build surface. Thus, the linear array of inkjet nozzles is regarded as a mathematical line, which is a 1-dimensional entity.

A 2D-method generates a whole image, at once, of the entire cross section of the build job, such that the whole build area is selectively solidified as one whole layer at once. In this context, the solidifying radiation simultaneously addresses all relevant points on the surface of the layer which, being of finite but small (compared to its area) thickness, becomes fully solidified without the need for any scanning in the x- and y-directions. DLP and SMS are 2D-methods for additive fabrication, where DLP works by photocuring a resin while SMS is a warm process that sinters plastic powders.

In this context, Selective Mask Sintering (SMS) is an emerging technology for warm processing of plastic powders which, in the general industry trend of moving from prototyping towards production, probably is the one best suited for the purposes of production of parts based on the sintering or melting of plastic powders, due to the inherent speed and scalability of a 2D-method.

The Steps of the SMS Process

The SMS process can be divided into 5 different process steps, apart from the slicing process of 3D-CAD data common to all additive technologies:

1. Deposition of a thin powder layer;
2. Generation of a photomask;
3. Exposure through mask with IR-radiation;
4. Removal of photomask;
5. Repetition of cycle from Step 1 for the next slice.

In Step 1, the powder surface is lowered by a small amount, defining the layer thickness of the powder layer that is about to be deposited. A recoating device moves powder from a supply container to the build surface. The thickness of the powder layer can be set to be between 50 and 120 μm.

In Step 2, the photomask is generated. This takes place simultaneously with Step 1, such that the new photomask is ready just before the new powder surface is ready. The photomask is a toner image printed onto a moving glass plate, and it constitutes the negative of the cross section of the parts being built. This step is an enabling technology for the SMS-process.

In Step 3 the glass plate is positioned over the prepared powder surface, in close proximity to it. Now, a set of IR-lamps are lit during 1-2 seconds, irradiating the mask as well as the powder surface underneath it. The powder surface is selectively concealed by the toner-covered areas of the glass plate and selectively exposed through the transparent (toner-free) areas of the glass plate. The exposed parts of the powder surface absorb IR-radiation and are thus heated such that the powder, depending on the exposure energy, either sinters or melts into a thin solid layer which bonds to the underlying surface of the part. The toner-covered areas of the photomask preserve the build material in powder form, by absorbing and reflecting IR-radiation. In this sense, the SMS-process is like a negative photolithographic procedure, albeit on a macroscopic scale and using IR instead of UV radiation.

In Step 4 the glass plate is moved away from the powder surface and returns to the mask printer. During the return movement a wiper is engaged, thus mechanically removing the toner image from the glass plate by virtue of the glass plate movement. The toner thus removed is collected for reuse.

In Step 5 the cycle starts over with image data for the next slice of the build job.

The time that elapses from Step 1 to Step 5 is called the *cycle time* of the process. Since SMS is a 2D-method for additive fabrication, the cycle time is independent of the number of parts being built as well as of their orientation. Thus, the more parts that are placed within the build envelope, the shorter is the build time per part. The cycle time is currently in the range of 10-20 seconds, depending on build material and required exposure energy which, for a layer thickness of 100 μm, corresponds to a build speed of 18-36 mm/hr. Due to the fact that Steps 1 and 2 can be performed simultaneously, and if thermal management of the process is further optimized, the cycle time of the SMS-process can potentially be reduced down to 5 seconds.

Digital Printing of Optical Toner Masks: An Enabling Technology for SMS

The ability to digitally create an individual photomask for each layer to be built is what makes SMS possible, and as such an enabling technology we have chosen to digitally print optical toner masks. In order to work in the SMS-process, there are a number of unusual requirements on the toner [5] and on the print engine:

1. The toner must be heat-resistant;
2. Very thick toner layers must be developed over large areas at a high speed;
3. The toner must be reusable.

The requirement that the toner be heat-resistant means that two conditions must be fulfilled: firstly, the toner must be *non-fusing* over the temperature range of the environment in which it is to be used (currently up to about 250°C), as it would otherwise not be possible to remove the toner from the glass plate after the exposure step of the SMS-process; secondly, all relevant physico-chemical properties of the toner should be temperature independent, such as charge, particle size and shape, optical absorption, molecular structure, etc. We have developed a toner which largely fulfills these criteria, based on a high-temperature polymer.

From an optical point of view, there are two fundamental differences between a toner image printed on glass for masking purposes, compared to a toner image printed on paper for the purposes of information transmittal via human eyesight.

The first difference is that a mask operates in a transmissive geometry while an image on paper operates in a reflective geometry – in the former case light must be sufficiently attenuated by the toner layer on only one passage, such that it does not solidify the build material, while in the latter case the light must be sufficiently attenuated by the toner layer on two passages, such that it does not reach the eyes of the observer. For otherwise equivalent properties, a transmissively operating toner layer would thus need to be twice as thick as a reflectively operating toner layer.

Figure 1: *The Pollux 32 machine exhibited at the annual Euromold 2007 fair in December, 2007, in Frankfurt am Main, Germany.*

The second difference is that since the toner of the mask must be non-fusing it remains in powder form, while a toner image on paper consists of a fused toner layer. In the former case, light can still pass through the spaces between powder particles while in the latter case the layer is continuously solid. Therefore, for otherwise equivalent properties, a thicker toner layer is needed for mask operation than for printing on paper.

The development system must consequently be able to operate with a low charge-to-mass ratio of the toner, in order to maximize developed mass per unit area (DMA) and thus the toner layer thickness. In addition, since the negative of the slice is printed, the development system must be able to maintain a high DMA over the entire area of the mask and, furthermore, this has to be accomplished within 2-3 seconds in order not to be the limiting factor for the cycle time of the SMS-process. We have developed such a print engine and development system, based on a combination of proprietary components and commercially available sub-systems.

We have also developed a system for recirculation of the toner removed from the glass plate, based on a two-component developer mixture to which the toner is returned through an admix process. This system is integrated with the print engine, such that the entire system can operate continuously throughout the SMS-process.

The requirement that the toner be reusable means that it should have "good" aging properties, in terms of its charge distribution and average charge-to-mass ratio as it is being recirculated in the system. We have achieved an interplay between toner and system such that the average charge-to-mass ratio of the toner in the developer mixture increases by less than 10% over 5,000 layers (corresponding to one full build tank in the machine).

Figure 2: *A fairy made in PA12-material by the SMS-process.*

Figure 3: *Two pump-houses made of PA12-material by the SMS-process. One of them shows the fit of the SMS-part to the two threaded metal tubings.*

The *Pollux 32* Machine

The *Pollux 32* machine is based on the SMS-process and is the result of the development that has taken place at *Sintermask Technologies AB*. The machine was launched on the market in 2007, and was presented in full operation at the annual *Euromold* fair in Frankfurt, Germany, in December 2007 (see Figure 1).

The *Pollux 32* machine consists of two principal parts: The Build Chamber and the Printer Chamber. The Build Chamber constitutes the front part of the machine and contains two powder tanks – one for the supply of powder material ("Refill Tank") and the other for receiving the parts being built ("Build Tank") – infrared heaters, infrared lamps and a powder-spreading unit which moves powder from the Refill Tank to the Build Tank. The Printer Chamber constitutes the rear part of the machine and contains the Printer Unit itself as well as the Recirculation System for the developer mixture. The glass plate, onto which the photomask is printed with toner, moves along the long direction of the machine, back and forth between the Build and Printer chambers.

The build envelope of the machine is 210 mm x 300 mm x 500 mm (about 8 in x 12 in x 20 in), or 32 liters. The CAD data file input is standard STL format. The machine can produce parts directly out of a plastic powder, as well as tools out of glass-filled plastic powders. Today, parts with good mechanical strength can be made out of the material PA12, but also other materials can be used in the machine. The IR-radiation source of the machine is powerful enough to sinter materials ranging from PET to PEEK. In Figures 2-3 are shown a few examples of PA12-parts made in the *Pollux 32* machine.

Cost Analysis of SMS Parts vs SLS Parts

In 2007, a cost analysis of the SMS-technology compared to other technologies was performed by an industry expert [6]. Among other things, SMS-produced parts were compared to SLS-produced parts, the two warm processes yielding plastic parts of adequate mechanical strength for end-use products. The *Pollux* machine was compared to a commercially available SLS-machine with a build envelope about twice that of the *Pollux* machine – 381 mm x 330 mm x 457 mm (about 15 in x 13 in x 18 in), or 57 liters. The analysis was performed for four different types of parts of increasing size and complexity according to a fully comprehensive cost model, including direct and indirect machine costs, direct costs for materials and labor, as well as production overheads. Under the assumption of a machine utilization of 63%, the number of parts of each kind which is possible to produce per week, as well as the cost for producing those parts, were calculated, thus yielding the price per part. This is summarized in Table 1 below.

Table 1. Cost per part, SMS vs SLS, for four different part types

		Cost per part [EUR]	
Part	Part volume [cm^3]	SLS	SMS
1	0.34	0.52	0.13
2	38	97.50	30.80
3	192	197	114
4	192	228	137

As can be seen, the cost per part of SMS parts, resulting from the study, is in the range 25%-60% of the cost per part of the corresponding SLS-parts – and this in spite of the disadvantage in build volume for the SMS-machine as compared to the SLS-machine.

Future Development: Rapid Mass Fabrication

Already at its present stage, the SMS-process has cost and speed advantages over the nearest-competitor-technology, SLS. Therefore, it is natural to look not only towards *Rapid Manufacturing*, but beyond that, towards what we have chosen to call *Rapid Mass Fabrication*.

Description of RMF

The concept of *Rapid Mass Fabrication* is based on the fact that in the SMS-process, the build time is nearly independent of the build area, which leads to a high degree of scalability inherent in the process. Consequently, the volume of the build chamber will become the most important parameter for a cost-efficient process, such that if build volume increases, production time per part as well as part cost decreases. In a study performed at the University of Erlangen-Nürnberg, Germany [7], the SMS-process shows the potential to reach production times of 1 second per part for a build volume of 1 x 1 x 1 m^3, a part volume of 25 x 25 x 25 mm^3 and a cycle time (*i.e.,* time per layer) of 5 seconds.

The differences between Rapid Prototyping, Rapid Manufacturing and Rapid Mass Fabrication, are outlined below.

Rapid Prototyping is characterized by the fabrication of a small number of parts which are used for verifying a design. The parts often have a short life time, and the focus is on a short product development time rather than part cost.

Rapid Manufacturing is characterized by the production of a few parts, up to a few hundreds, which are directly produced for customers' end-use. Part quality is controlled by manual procedures.

Rapid Mass Fabrication is characterized by mid-size production of parts directly for customers' end-use. Automatic quality assurance procedures are implemented. *RMF* will thus have the potential to directly compete with other, existing production technologies, such as injection molding.

Demands of RMF

The goals are set high for *RMF*, and thus its demands on additive fabrication are severe. *RMF* must reach and exceed the levels of Quality Assurance of today's traditional production industry; *RMF* needs to produce parts of at least the same mechanical properties as those of today's traditionally produced parts; *RMF* needs to reach the same level of cost per part as that of today's traditional production technologies. In order to meet these demands, *RMF* will have to be fully automated, such that no manual labor must be used in the process. Such a totally automated production line will have to include: Continuous feeding of build material into the production line; Preheating the build material before entering into the machine; Automated output from the machine; Automated cooling process; Automated cleaning process; Automatic surface finishing for parts to be utilized in visible positions; Automated final packaging of parts.

In view of results so far, as well as independent studies made, the SMS-process stands out as the only available process that has the potential to fulfill the demands of *RMF*. We are working to develop the SMS-process in the direction where one and the same process can be used for the entire product life-cycle: from the first prototypes, through the production of parts, and finally to "Spare parts on demand".

Summary

We have described how *Selective Mask Sintering* (*SMS*) is an emerging technology among a host of additive technologies of the *Rapid Prototyping and Manufacturing* industry, with a high speed and low cost of production of plastic parts in a warm process, by which parts are mechanically well-suited as end-user parts.

We have also described how the SMS-technology is currently implemented by digital printing of optical toner masks, which is an enabling technology for the SMS-process. This digital printing technology has been developed at Sintermask, and employs a toner-carrier development system with a low charge-to-mass ratio of toner in order to maximize the amount of developed toner on the photomask, as well as a unique toner recirculation system in order to minimize toner costs.

Finally, we have described how the SMS-process has inherent properties that make it well-suited for developing it beyond *Rapid Manufacturing*, into the basis for a future, fully-automated production method based on additive fabrication and which we call *Rapid Mass Fabrication*.

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Author Biography

David Hermann received his PhD in Physics (topic: liquid crystals) in 1997 from Göteborg University. He spent part of 1998 as a postdoc at Tokyo Institute of Technology, Japan, and 1998-2000 as EU TMR postdoc fellow at the University of Naples, Italy. In 2000-2005 he was Assistant and Associate Professor at Chalmers University of Technology, Sweden. In 2005, he joined Speed Part (today Sintermask) to work on toner- and printer-related aspects of Selective Mask Sintering.