Numerical modeling of the strand deposition flow in extrusion-based additive manufacturing

Abstract We propose a numerical model to simulate the extrusion of a strand of semi-molten material on a moving substrate, within the computation fluid dynamics paradigm. According to the literature, the deposition flow of the strands has an impact on the inter-layer bond formation in extrusion-based additive manufacturing, as well as the surface roughness of the fabricated part. Under the assumptions of an isothermal Newtonian fluid and a creeping laminar flow, the deposition flow is controlled by two parameters: the gap distance between the extrusion nozzle and the substrate, and the velocity ratio of the substrate to the average velocity of the flow inside the nozzle. The numerical simulation fully resolves the deposition flow and provides the cross-section of the printed strand. For the first time, we have quantified the effect of the gap distance and the velocity ratio on the size and the shape of the strand. The cross-section of the strand ranges from being almost cylindrical (for a fast printing and with a large gap) to a flat cuboid with rounded edges (for a slow printing and with a small gap), which substantially differs from the idealized cross-section typically assumed in the literature. Finally, we found that the printing force applied by the extruded material on the substrate has a negative linear relationship with the velocity ratio, for a constant gap.

General information
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A performance assessment of a 2 axis scanning mirror galvanometer for powder bed fusion
Additive Manufacturing by powder bed fusion allows production of high strength parts with complex features, not possible through conventional manufacturing. To experiment and test current theory within laser processing of metal powder, an open and customizable laser scanner platform is developed and constructed. The platform seeks to fully support and enable the laser driven process of selective consolidation metal powder, as most industrially available powder bed fusion
machine tools are closed and proprietary systems. This allows the machine tool manufacturer to strictly control how the system is used and therefore maintain stability through limiting the operator to use proprietary software hardware and process materials but unfortunately limits to an equally wide extent how such machine tools can be applied for research purposes as it renders the scientist to become a mere operator of the machine tool. A galvanometer based laser scanning system is here presented. The system was designed to meet a theoretical resolution of 0.009 mm. From inspiration of the use of optomechanical hole plates as reference artefacts for coordinate metrology a test was conducted to verify the accuracy of the laser scanning system. The system was found to perform excellent for relative positioning. Absolute positioning of the laser beam did not conform with design specifications, as the test deviated by 0.12 mm with respect to the nominal test value, yet this is expected in the future to be met from the implementation of a better galvanometer control system.
A Soft Tooling process chain employing Additive Manufacturing for injection molding of a 3D component with micro pillars

The purpose of the research presented in this paper is to investigate the capability of a soft tooling process chain employing Additive Manufacturing (AM) for preproduction of an insert with micro features by injection molding. The Soft Tooling insert was manufactured in a high temperature photopolymer by Digital Light Processing (vat photopolymerization). The mold cavity was formed by two insert halves, by design; both inserts have four angled tines, with micro holes (Ø200 μm, 200 μm deep) on the surface. Injection molding with polyethylene was used with the soft tool inserts to manufacture the final production components. The diameter and height of the pillars that were replicated on the molded components were characterized by means of a 3D profilometer. The influence of the injection molding parameters on the replication was evaluated using a 2-levels DOE of three factors. The uniformity of the pillars are also evaluated regarding the diameter and height.

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Organisations: Department of Mechanical Engineering, Manufacturing Engineering, Technical University of Denmark
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**Augmented Reality Interfaces for Additive Manufacturing**

This paper explores potential use cases for using augmented reality (AR) as a tool to operate industrial machines. As a baseline we use an additive manufacturing system, more commonly known as a 3D printer. We implement novel augmented interfaces and controls using readily available open source frameworks and low cost hardware. Our results show that the technology enables richer and more intuitive printer control and performance monitoring than currently available on the market. Therefore, there is a great deal of potential for these types of technologies in future digital factories.

**General information**

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3D Printing, Additive manufacturing, Augmented reality

**Biological features produced by additive manufacturing processes using vat photopolymerization method**

Bio inspired surfaces have attracted great interest due to their potential applications in different industries by using a variety of structures. The fabrication of microstructures having complex shapes have been developed within the recent decades. This work realizes the direct fabrication of micro biological features by Additive Manufacturing (AM) processes. The study characterizes the additive manufacturing processes for polymeric micro part productions using the vat photopolymerization method. A specifically designed vat photopolymerization AM machine suitable for precision printing at the micro dimensional scale has been developed, built and validated. In order to evaluate the AM machine capability a Tokay gecko test part that contains microscale pillars with widened tips was used as benchmark sample. Two main printing parameters were selected for the study: exposure time and layer thickness. In order to select the optimal range of printing parameters, a sensitivity analysis was carried out prior to the final experiment. The print quality was assessed in terms of features heights, tip heights and tip diameters.

**General information**

State: Published
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Additive manufacturing, Bioinspired surfaces, Biological Features, Micro manufacturing, Polymer components
Publication: Research - peer-review › Article in proceedings – Annual report year: 2017

**Challenges and opportunities of fibre-reinforced polymers in additive manufacturing with focus on industrial applications**

Functional parts made by additive manufacturing of polymers have entered the area of industrial applications in recent years providing a wide range of materials with various mechanical, thermal, and electrical properties. These additive
manufacturing processes can be combined with known fibre-reinforcements applying modified material parameters with the use of fibre-reinforced polymers. An increase of tensile strength and Young’s modulus result from the application of short fibres in a polymer matrix opening up perspectives for a variety of industrial applications such as injection moulding, biomedical engineering, aerospace, racing, and train technology. A literature survey was conducted in order to identify challenges and opportunities in these fields.

General information
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Additive Manufacturing Technology, Review, Fibre-reinforced Polymers, Industrial Applications
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Characterization of additive manufacturing processes for polymer micro parts productions using direct light processing (DLP) method
The process capability of additive manufacturing (AM) for direct production of miniaturized polymer components with micro features is analyzed in this work. The consideration of the minimum printable feature size and obtainable tolerances of AM process is a critical step to establish a process chains for the production of parts with micro scale features. A specifically designed direct light processing (DLP) AM machine suitable for precision printing has been used. A test part is designed having features with different sizes and aspect ratios in order to evaluate the DLP AM machine capability to fabricate polymer micro scale features geometries. Four different factors are evaluated for the AM process analysis: printing layer thickness, exposure time, film thickness and geometry. The process optimization of the workpiece quality features is carried out to highlight potential and challenges of the micro AM process.

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Computer Vision for Additive Manufacturing.
Ever since the commercialization of additive manufacturing in the late 80’s, it has been clear what enormous potential the technology could have, potentially disrupting several industries. However, we have yet to see the technology fully adopted by the manufacturing industry. One of the issues that has prevented widespread adoption of 3D printing for use within manufacturing is the apparent lack of quality control during and after the printing process. This thesis demonstrates how computer vision may be applied in beneficial ways within additive manufacturing. The main contributions aim at solving part of the challenges required for the technology to reach its full envisioned potential, and to reach widespread industry adoption as a de-facto manufacturing modality. Quality control has been a major milestone to overcome in this regard. As a result, a core part of the contributions revolves around this central topic. The work is separated into three main categories: The first two concerning process and quality control of appearance and geometry. The third category concerns machine interaction paradigms within additive manufacturing. Here, challenges are addressed within the 3D ecosystem, aiming towards facilitating a fluid integration of additive manufacturing within the factory of tomorrow.

General information
State: Submitted
Organisations: Department of Applied Mathematics and Computer Science, Image Analysis & Computer Graphics, Department of Mechanical Engineering, Manufacturing Engineering
Considerations on the Construction of a Powder Bed Fusion Platform for Additive Manufacturing

As the demand for moulds and other tools becomes increasingly specific and complex, an additive manufacturing approach to production is making its way to the industry through laser based consolidation of metal powder particles by a method known as powder bed fusion. This paper concerns a variety of design choices facilitating the development of an experimental powder bed fusion machine tool, capable of manufacturing metal parts with strength matching that of conventional manufactured parts and a complexity surpassing that of subtractive processes. To understand the different mechanisms acting within such an experimental machine tool, a fully open and customizable rig is constructed. Emphasizing modularity in the rig, allows alternation of lasers, scanner systems, optical elements, powder deposition, layer height, temperature, atmosphere, and powder type. Through a custom-made software platform, control of the process is achieved, which extends into a graphical user interface, easing adjustment of process parameters and the job file generation.
Cost estimation of a specifically designed direct light processing (DLP) additive manufacturing machine for precision printing

Additive Manufacturing (AM) refers to a portfolio of novel manufacturing technologies based on a layer-by-layer fabrication method. The market and industrial application of additive manufacturing technologies as an established manufacturing process have increased exponentially in the last years creating new opportunities for manufacturers in a variety of industrial sectors. AM is an essential prototyping technique for product design and development that is used in many different fields. However, the suitability of AM applications in actual production in an industrial context needs to be determined. This study presents a cost estimation model for precision printing with a specifically designed Digital Light Processing (DLP) AM machine built and validated at the Technical University of Denmark. The model presented in this study can be easily adapted and applied to estimate within a high level of confidence the cost of any part manufactured with the mentioned 3D printing technology.

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State: Published
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Dimensional accuracy of Acrylonitrile Butadiene Styrene injection molded parts produced in a pilot production

Injection molding inserts manufactured additively by vat photopolymerization have become a serious option for significantly faster and more economical prototyping and pilot production due to technological progress and advancements in photopolymer materials in the recent years. 10 000 parts of a geometry including micro-features have been injection-molded in Acrylonitrile Butadiene Styrene (ABS) with a single 20x20x2.5 mm³ injection molding insert manufactured in a photopolymer composite material. This research investigates the dimensional accuracy of the injection molded parts as a function of inserts wearing and deformation with increasing shot number.

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Economic Analysis of Additive Manufacturing Integration in Injection Molding Process Chain

The purpose of this research is to analyze how additive manufacturing can create value when it is utilized as a supportive technology to injection molding by quantifying the cost advantages that can be obtained. Tooling for the product development phase is investigated as pilot integration area of additive manufacturing with injection molding. Cost considerations are discussed through the development of a cost estimation model. The study shows that integration of
additive manufacturing in the product development phase for fabrication of soft tooling is economically convenient with a cost reduction of 79.8% and 89.9%. The cost models on additive manufacturing have been built so far on the idea of substituting injection molding with additive manufacturing. In response to this literature gap, this research addresses the advantages of additive manufacturing utilized in a synergistic rather than disruptive way to create value in the injection molding process chain

**General information**

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Main Research Area: Technical/natural sciences
Publication: Research - peer-review › Paper – Annual report year: 2017

**Economic trade-offs of additive manufacturing integration in injection moulding process chain**

Additive Manufacturing has emerged as an innovative set of novel technologies capable of replacing established manufacturing processes due to fabrication of highly complex parts and its continuous improvements of efficiency and cost effectiveness. This study is based on the idea that through the creation of synergies between additive and conventional manufacturing technologies it is possible to achieve greater cost advantages and operational benefits than by substituting injection moulding with additive manufacturing. The analysis presented explores the cost advantages that can be secured when additive manufacturing is used to support the fabrication of mould inserts for the product development phase of the injection moulding process chain. This study shows that fabrication of soft tooling by mean of AM is economically convenient with a cost reduction between 80% and 90%. Break-even points analysis based on the lot size of the product development phase is also investigated and it shows that the use of AM is cost effective up to 3400 units for the smaller geometry and up to 500 units for the larger insert geometry.

**General information**

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Organisations: Department of Mechanical Engineering, Manufacturing Engineering, HEC Paris
Authors: Charalambis, A. (Intern), Kerbache, L. (Ekstern), Tosello, G. (Intern), Pedersen, D. B. (Intern), Mischkot, M. (Intern), Hansen, H. N. (Intern)
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2017

**Effects of carbon fibres on the life cycle assessment of additively manufactured injection moulding inserts for rapid prototyping**

A life cycle assessment was conducted to evaluate the global warming potential and human toxicity of injection moulding processes applying newly developed tool inserts produced with vat polymerisation. The inserts were subject to increasing content of carbon fibres to improve their mechanical properties and lifetime. The additively manufactured inserts are compared to the standard materials steel, aluminium and brass. The investigated part of the production and prototyping phase considers the insert itself, the moulded part, and resulting waste material of the injection moulding process.

**General information**

State: Published
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Evaluation of polymer micro parts produced by additive manufacturing processes using vat photopolymerization method

Micro manufacturing scale feature production by Additive Manufacturing (AM) processes for the direct production of miniaturized polymer components is analysed in this work. The study characterizes the AM processes for polymer micro parts productions using the vat photopolymerization method. A specifically designed vat photopolymerization AM machine suitable for precision printing has been developed, built and validated. In order to evaluate the AM machine capability a test part is designed having features with different sizes and aspect ratios. The printing parameters selected for the evaluation are considered as exposure time, light intensity and layer thickness. In order to have an initial optimal range of parameters values, a sensitivity analysis carried out prior to the final experimental plan. The print quality was assessed in terms of separation between the rows and columns of printed cubes, the number of printed features with square cross section and the surface roughness. The results declare the importance of different factors in micro AM processes.

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Evaluation of surface roughness and geometrical characteristic of additive manufacturing inserts for precision injection moulding

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The objective of this research is to investigate the influence of injection molding parameters on the dimensional replication of microstructure surfaces in injection molding with additively manufactured soft tooling inserts in a photopolymer material. The replication degree of micropillars on injection-molded tine rings was assessed and a Design of Experiments (DOE) approach was used to investigate which factors influence the replication. A full factorial analysis with three factors at two levels lead to the conclusion that a high mold temperature increases the replication degree of the pillar diameter and decreases the replication degree of the pillar height. A high melt temperature increases the pillar diameter independently from the pillar height. A higher injection speed affects both pillar diameter and height negatively. In addition, the study showed a significant difference in the replication degree between inserts on the injection side and the ejector side of the
mold respectively. Also, a position closer to the injection gate supports a higher replication degree. Insert wear was found insignificant within the experimental range of up to 100 injection cycles.

**General information**
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Micro Injection Molding, Micro overmolding, Optical micro metrology
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**Injection Moulding Pilot Production: Performance Assessment of Tooling Process Chains Based on Tool Inserts Made from Brass and A 3d Printed Photopolymer**
Additive Manufacturing is becoming a viable option for the production of injection molding inserts in pilot production settings. This work compares an insert made from brass using conventional machining with an insert made from a proprietary photopolymer using Digital Light Processing (DLP) through the application of precision injection molding. The performance of the inserts is analyzed focusing on design, metrological aspects, tool lifetime, and thermal performance. In the experiment, a disk-shape geometry (diameter 41.5 mm, thickness 3.5 mm) was injection molded in Low-Density Polyethylene in a two-cavity mold. The inserts as well as selected injection molded parts were analyzed with an optical 3D micro-coordinate measuring machine. It was found that additive manufacturing technology can lead to a significantly more cost effective pilot production, both in terms of development time and investment. DLP technology enables fast production of micro-features, however insert production with DLP is less reliable than milling e.g. when considering process repeatability. Photopolymer and brass inserts lead to differences in optical surface appearance on the injection molded parts. The lifetime of the photopolymer inserts is challenging to predict reliably. Depending on how many parts need to be produced, the use of several photopolymer inserts instead of one brass insert is a means to overcome the shorter lifetime and can represent a cost-effective alternative to machined inserts. In order to exploit the advantages of using additive manufactured injection mold inserts, specific tool design rules have to be applied.

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**In-line 3D print failure detection using computer vision**
Here we present our findings on a novel real-time vision system that allows for automatic detection of failure conditions that are considered outside of nominal operation. These failure modes include warping, build plate delamination and extrusion failure. Our system consists of a calibrated camera whose position and orientation is known in the machine coordinate system. We simulate what the object under print should look like for any given moment in time. This is compared to a segmentation of the current print, and statistical detection of significant deviation. We demonstrate that this methodology precisely and unambiguously detects the time point of print failure.

**General information**
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Organisations: Department of Applied Mathematics and Computer Science, Image Analysis & Computer Graphics, Department of Mechanical Engineering, Manufacturing Engineering
Number of pages: 4
Integration of Fiber-Reinforced Polymers in a Life Cycle Assessment of Injection Molding Process Chains with Additive Manufacturing

Additive manufacturing technologies applied to injection molding process chain have acquired an increasingly important role in the context of tool inserts production, especially by vat polymerization. Despite the decreased lifetime during their use in the injection molding process, the inserts come with improvements in terms of production time, costs, exibility, as well as potentially improved environmental performance as compared to conventional materials in a life cycle perspective. This contribution supports the development of additively manufactured injection molding inserts with the use of fiber-reinforced vat polymerization technology. The life cycle assessment of the prototyping process chain for rapid prototyping with high exibility provides a base for industrial applications in injection molding.

Life Cycle Assessment of Fiber-Reinforced Additive Manufacturing for Injection Molding Insert Production

Additively manufactured (AM) injection molding (IM) inserts have proved to be capable to substitute conventionally manufactured metal inserts with polymer-based insert enforced with short, virgin, unseized carbon fibers (CFs). It has been shown that the implementation of AM technology resulted in significant improvements when investigating costs and cycle time for smaller part series. However, being a novel technology, AM inserts yield undesired characteristics, e.g. in terms of potential environmental impact because of the lower lifetime compared to metal inserts. Based on physical performance tests, this contribution provides a comparison of environmental performance of conventionally vs. additively manufactured inserts in a full life cycle perspective indicated in Figure 1, including materials, production, use and end-of-life (EoL) stages.
Performance Simulation and Verification of Vat Photopolymerization Based, Additively Manufactured Injection Molding Inserts with Micro-Features

Injection molding soft tooling inserts manufactured additively with vat photopolymerization represent a valid technology for prototyping and pilot production of polymer parts. However, a significant drawback is the low heat conductivity of photopolymers influencing cycle time and part quality. In this research, the thermal performance of a 20x20x2.7 mm³ injection molding insert was simulated. A thermal camera was used to assess the quality and accuracy of the simulation. Both, simulation and measurements showed that the temperature cycle during injection molding becomes stationary within 3 to 5 cycles. After 2800 injection molding cycles, the experiment was stopped and the insert was still intact.

Photogrammetry for Repositioning in Additive Manufacturing

In this preliminary work, we present our current status on how to use single camera photogrammetry to determine the orientation of an additively manufactured partly finished object that has been repositioned in the printing chamber, from a single image taken with a calibrated camera, and comparing this to the CAD model of the object. We describe how this knowledge can be used to update the machine code of the printer so that printing of the object can be resumed at the new location. This opens possibilities for embedding and assembling foreign parts into the additive manufacturing pipeline, adding another layer of flexibility to the process. However, due to various error sources in estimating the orientation of the object, more work is needed before this update can be applied.
PicPrint: Embedding pictures in additive manufacturing

Here we present PicPrint, a method and tool for producing an additively manufactured lithophane, enabling transferring and embedding 2D information into additively manufactured 3D objects. The method takes an input image and converts it to a corresponding height-map, indicating the material density required to achieve a brightness specified at any given location. Non-linear scattering properties are compensated for using predefined falloff profiles. Using the produced height-map, a watertight mesh is distorted to match the specified material densities, after which the mesh is ready for either direct print on an additive manufacturing system, or transfer to other geometries via Boolean mesh operations.

Rheology of high melt strength polypropylene for additive manufacturing

Rheological measurements of high melt strength polypropylene (HMS-PP) were used in order to generate master curves describing the shear-dependent viscosity in comparison to acrylonitrile butadiene styrene copolymer (ABS). The latter material showed specific disadvantages in terms of thermal stability, whereas HMS-PP showed a more stable behavior at the investigated temperatures. Hereafter, the material was used in a fused deposition modeling additive manufacturing process, focusing on the investigation of possible improvements of HMS-PP over ABS. Based on the extrusion parameters for ABS, adapted parameters for HMS-PP were determined using a fused deposition modeling test bench. The rheological survey clearly showed changes in the melt viscosity of both ABS and HMS-PP due to thermal degradation. However, the comparison of rheological data of the virgin materials with those of printed material showed negligible changes. This leads to the conclusion that the thermal degradation of HMS-PP and ABS during the fused deposition modeling process is negligible, due to the short exposure time to elevated temperatures. Copyright © 2017 VBRI Press.
State-of-the-art of fiber-reinforced polymers in additive manufacturing technologies

Additive manufacturing technologies have received a lot of attention in recent years for their use in multiple materials such as metals, ceramics, and polymers. The aim of this review article is to analyze the technology of fiber-reinforced polymers and its implementation with additive manufacturing. This article reviews recent developments, ideas, and state-of-the-art technologies in this field. Moreover, it gives an overview of the materials currently available for fiber-reinforced material technology.

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State: Published
Organisations: Department of Mechanical Engineering, Manufacturing Engineering
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Adaptive Layer Height During DLP Materials Processing

This research aims to show how manufacturing speeds during vat polymerisation can be vastly increased through an adaptive layer height strategy that takes the geometry into account through analysis of the relationship between layer height, cross-section variability and surface structure. This allows for considerable process speedup during the Additive Manufacture of components that contain areas of low cross-section variability, at no loss of surface quality. The adaptive slicing strategy was tested with a purpose-built vat polymerisation system and numerical engine designed and constructed to serve as a Next-Gen technology platform. By means of assessing hemispherical manufactured test specimens and through 3D surface mapping with variable-focus microscopy and confocal microscopy, a balance between minimal loss of surface quality with a maximal increase of manufacturing rate has been identified as a simple angle-dependent rule. The achievable increase in manufacturing rate was above 38% compared to conventional part slicing.

A Model of Parallel Kinematics for Machine Calibration

Parallel kinematics have been adopted by more than 25 manufacturers of high-end desktop 3D printers [Wohlers Report (2015), p.118] as well as by research projects such as the WASP project [WASP (2015)], a 12 meter tall linear delta robot for Additive Manufacture of large-scale components for construction engineering applications. The parallel kinematics of a linear delta robot has the potential to out-complete Cartesian point-based deposition systems with respect to acceleration-and thus repositioning speeds since the primary movable mass in these types of systems can be kept to a minimum. This research identifies that the rapid lift and repositioning capabilities of delta robots can reduce defects on extruded 3D printed parts when compared to traditional Cartesian motion systems. This is largely due to the fact that repositioning is so rapid that the extruded strand is instantly broken, and that repositioning can be completed before material oozing from the extruder can occur. The aim will be to address one of the primary disadvantages to parallel kinematics systems. Calibration and geometrical validation. Calibration of a delta robot can be a source of frustration. This research aims to provide the operator with a strong tool for easing this task. The kinematics and calibration of delta robots, in particular, are less researched than that of traditional Cartesian robots, for which tried-and-true methods for calibrating are well known. A forwards and reverse virtual model of a delta robot has been developed in order to decompose the different types of geometrical errors into 6 elementary cases. Deliberate introduction of errors to the virtual machine has subsequently allowed for the generation of deviation plots that can be used as a strong tool for the identification and correction of geometrical errors on a physical machine tool.
A self-calibrating robot based upon a virtual machine model of parallel kinematics

A delta-type parallel kinematics system for Additive Manufacturing has been created, which through a probing system can recognise its geometrical deviations from nominal and compensate for these in the driving inverse kinematic model of the machine. Novelty is that this model is derived from a virtual machine of the kinematics system, built on principles from geometrical metrology. Relevant mathematically non-trivial deviations to the ideal machine are identified and decomposed into elemental deviations. From these deviations, a routine is added to a physical machine tool, which allows it to recognise its own geometry by probing the vertical offset from tool point to the machine table, at positions in the horizontal plane. After automatic calibration the positioning error of the machine tool was reduced from an initial error after its assembly of ±170 µm to a calibrated error of ±3 µm. Excelling by speed, the calibration was executed in less than 3 min.
A Self-Peeling Vat for Improved Release Capabilities During DLP Materials Processing

This paper describes research to increase the competitiveness of vat polymerisation by increasing the manufacturing rate while lowering the normal forces that induce part stress during the lift procedure of vat based systems. This is achieved through introducing a polymerisation vat that allows for an eased release of the manufactured part from the vat by means of a flexible membrane system. A membrane of fluorinated ethylene polymer will through elastic deformation automatically peel off the part as the part is lifted during layer changes. Peeling has been qualified by means of a truncated inverted cone as test geometry. As the cross-sectional diameter of the cone increase throughout the build-job, the geometry will release from the glass based build platform at the point where the peeling force exceed the adhesion force between platform and part. At failure point the lateral surface area of the top and bottom of the truncated cone is used as a measure of the performance of the vat with respect to release-capability. This has been tested at increasing manufacturing rates. The new self-peeling vat outperformed industrial state-of-the-art vats by 814% percent.

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Calibration of a Numerical Model for Heat Transfer and Fluid Flow in an Extruder

This paper discusses experiments performed in order to validate simulations on a fused deposition modelling (FDM) extruder. The nozzle has been simulated in terms of heat transfer and fluid flow. In order to calibrate and validate these simulations, experiments were performed giving a significant look into the physical behaviour of the nozzle, heating and cooling systems. Experiments on the model were performed at different sub-mm diameters of the extruder. Physical parameters of the model – especially temperature dependent parameters – were set into analytical relationships in order to receive dynamical parameters. This research sets the foundation for further research within melted extrusion based additive manufacturing. The heating process of the extruder will be described and a note on the material feeding will be given.

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Comparison of conventional Injection Mould Inserts to Additively Manufactured Inserts using Life Cycle Assessment

Polymer Additive Manufacturing can be used to produce soft tooling inserts for injection moulding. Compared to conventional tooling, the energy and time consumption during production are significantly lower. As the life time of such inserts is significantly shorter than the life time of traditional brass, aluminium, or steel inserts, multiple inserts might be
needed to produce a large number of parts.
In an ongoing study, a simplified Life Cycle Assessment has been carried out in order to provide information on how the four alternative insert materials perform in comparison in terms of their potential environmental impact and yield throughout the development and pilot phase. Insert geometry is particularly advantageous for pilot production and small production sizes.
In this research, Life Cycle Assessment is used to compare the environmental impact of soft tooling by Additive Manufacturing (using Digital Light Processing) and three traditional methods for the manufacture of inserts (milling of brass, steel, and aluminium) for injection moulds during the pre-production phase.

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Designing for Color in Additive Manufacturing
In this paper we present a color design pipeline for 3D printed or additively manufactured parts. We demonstrate how to characterize and calibrate a commercial printer and how to obtain its forward and backward color transformation models. We present results from our assistive color design tool, allowing for colorimetric accurate prints and visualization of the printed outcome, prior to print. Lastly, we demonstrate our pipeline by accurately reproducing a real physical object.

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Distribution and Orientation of Carbon Fibers in Polylactic Acid Parts Produced by Fused Deposition Modeling
The aim of this paper is the understanding of the fiber orientation by investigations in respect to the inner configuration of a polylactic acid matrix reinforced with short carbon fibers after a fused deposition modeling extrusion process. The final parts were analyzed by X-ray, tomography, and magnetic resonance imaging allowing a resolved orientation of the fibers and distribution within the part. The research contributes to the understanding of the fiber orientation and fiber reinforcement of fused deposition modeling parts in additive manufacturing.

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Evolution of Surface Texture and Cracks During Injection Molding of Fiber-Reinforced, Additively-Manufactured, Injection Molding Inserts

This paper investigates the lifetime and surfacedeterioration of additively-manufactured, injection-moulding inserts. The inserts were produced using digital light processing and were reinforced with oriented short carbon fibers. The inserts were used during injection molding of low-density polyethylene until their failure. The molded products were used to analyse the development of the surface roughness and wear. By enhancing the lifetime of injection-molding inserts, this work contributes to the establishment of additively manufactured inserts in pilot production.

In-Situ Monitoring in Additive Manufacturing Using Contact Image Sensors

This paper investigates the lifetime and surfacedeterioration of additively-manufactured, injection-moulding inserts. The inserts were produced using digital light processing and were reinforced with oriented short carbon fibers. The inserts were used during injection molding of low-density polyethylene until their failure. The molded products were used to analyse the development of the surface roughness and wear. By enhancing the lifetime of injection-molding inserts, this work contributes to the establishment of additively manufactured inserts in pilot production.
Investigation of digital light processing using fibre-reinforced polymers

Literature research shows multiple applications of fibre-reinforced polymers (FRP) respectively in fused deposition modelling and gypsum printing influencing the quality of the products in terms of stress and strain resistance as well as flexibility. So far, applications of fibre-reinforced polymers in digital light processing (DLP) are limited. Fibre-reinforced polymer composites were manufactured into test objects using digital light processing. Short fibres were used in an unordered manner. An anisotropic property due to fibre orientation within the material was observed. The importance of fibre length and shape compared to layer thickness has been investigated including concepts to circumvent clustering of the fibres. This research contributes to the implementation of fibre-reinforced polymers in additive manufacturing technologies. Digital light processing allows generation of miniaturized objects with relatively high surface quality compared to other additive manufacturing technologies. This paper aims to move fibre reinforced resin parts one step closer towards mechanically strong production-quality components.

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Additive Manufacturing Technologies, Digital Light Processing, Fibre-reinforced Polymers, Surface Quality
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Precision and Accuracy Parameters in Structured Light 3-D Scanning

Structured light systems are popular in part because they can be constructed from off-the-shelf low cost components. In this paper we quantitatively show how common design parameters affect precision and accuracy in such systems, supplying a much needed guide for practitioners. Our quantitative measure is the established VDI/VDE 2634 (Part 2) guideline using precision made calibration artifacts. Experiments are performed on our own structured light setup, consisting of two cameras and a projector. We place our focus on the influence of calibration design parameters, the calibration procedure and encoding strategy and present our findings. Finally, we compare our setup to a state of the art metrology grade commercial scanner. Our results show that comparable, and in some cases better, results can be obtained using the parameter settings determined in this study.

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Rheology of High-Melt-Strength Polypropylene for Additive Manufacturing

Acrylonitrile butadiene styrene (ABS) is a widely used material for additive manufacturing (AM) fused deposition modeling (FDM). The rheological properties of high-melt-strength polypropylene (HMS-PP) were compared to commercially available ABS 250 filament to study the possibility of using this material for FDM. The aim of this research contribution was to generate a full description of the viscosity in a plate-to-plate rheometer. Moreover, the materials were used in an FDM process focusing on the investigation of possible improvements of HMS-PP over ABS. The latter material showed specific disadvantages in terms of thermal stability. In particular, the storage modulus $G'$, loss modulus $G''$, and complex viscosity were measured at temperatures between 170 °C and 250 °C and brought to superimpose using the time-temperature superposition method to create master curves of the two materials. The comparison of the time sweep allowed the conclusion that HMS-PP is more stable by showing less variation during the studied period of two hours. The master curves of ABS concluded that data measured at 250 °C deviates significantly from the curves derived from measurements at lower temperatures. In particular, the storage modulus and complex viscosity data of ABS 250 could not be used to enlarge the master curve values. HMS-PP showed a more stable behavior at the studied temperatures, and all data points were suitable to create the master curves. Practical studies to determine adapted extrusion parameters for HMS-PP were carried out using an FDM machine. ABS was extruded through a J-Head extruder with 0.4 mm nozzle-diameter and 243 °C extrusion temperature. The extrusion was performed in a vertical direction with gravitational forces pointing in the extrusion direction. The fused filament depended on the extrusion speed and diameter, resulting in an optimal printing speed of 60 to 80 mm/min. The HMS-PP granule was extruded into a filament of 1.75 mm diameter and then extruded through a J-Head and E3D with 0.4 mm nozzle-diameter and 200 to 240 °C. A comparison of the primary material with the printed material showed negligible changes in the measurement curves which might lead to the conclusion that the degradation of HMS-PP during the FDM process is as low as the degradation of ABS.

Two process chains for creating functional surfaces on mold for 3D geometry

Polymer products with functional surfaces are applied in many fields such as medical and bio technology [1][2]. It is believed that certain types of micro- or nano- structured surfaces can enhance tissue anchoring [3]. However, most technologies for the fabrication of micro-structured functional surfaces are still limited to flat geometries or geometries with constant curvature [4]. Typically products that need micro structuring on the surface have a three dimensional and complex geometry. There are huge demand for investigation in establishing the micro structures on the surface of a 3D mold. This paper describes and compares 2 approaches for fabricating micro- structured surfaces suitable for patterning of 3D shape cavity for injection moulding. The application investigated for the research is a part of a fixture for electrodes to be implanted inside human body. It is a ring with four wings as illustrated by Figure 1.
Additive manufacturing for the production of inserts for micro injection moulding

The production of inserts for micro injection moulding using additive manufacturing technology has the potential to greatly improve the efficiency of pilot production and reduce overall time to market. In this work, Digital Light Processing (DLP) was used to produce micro injection moulding inserts with different types of geometric features. The dimensional accuracy of the mould inserts and workpieces as well as insert durability and mould wearing were investigated and statistically analysed. The mould developed clearly visible cracks but remained in one piece until the experiment ended after 50 shots.

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Injection moulding, Additive manufacturing, Digital Light Processing

Predicting Color Output of Additive Manufactured Parts

In this paper we address the colorimetric performance of a multicolor additive manufacturing process. A method on how to measure and characterize color performance of said process is presented. Furthermore, a method on predicting the color output is demonstrated, allowing for previsualization of parts prior to print. Results show that color prediction can be achieved with an average color difference error of ΔE*00 = 1.5 and std.dev σ= 0.75, with similar order of magnitude as the literature defined threshold for „Just NoticeableDifference” (JND).

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Simulation of a Downsized FDM Nozzle

This document discusses the simulation of a downsized nozzle for fused deposition modelling (FDM), namely the E3D HotEnd Extruder with manufactured diameters of 200-400 μm in the nozzle tip. The nozzle has been simulated in terms of heat transfer and fluid flow giving an insight into the physical behavior of the polymer inside the nozzle. The extruder
contains a nozzle, a heater block, a heatbreak and a heatsink additionally cooled by a fan. The diameter is located in the sub-mm region allowing to reduce the size and surface roughness of the product. The simulation results were experimentally validated. This kind of simulations is facing multiple problems connected to the description of the material properties with temperature and pressure dependency.

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Spatial Accuracy of Embedded Surface Coloring in Color 3D Printing
Recent years, the industrial market for full-color AM is growing rapidly. In the AM industry, most of the major technology providers are developing new systems with improved color capabilities and with improved materials. In the last 12 months alone, 5 new technology platforms have been revealed capable of full-color printing in polymers[1]. Industrial service providers increasingly expand their product-range of full color print services, and as of today, the industry for full-color parts has grown rapidly, into a million-dollar industry [2]. Industrial service providers increasingly expand their product-range of full color print services, and as of today, the industry for full-color parts has grown rapidly, into a million-dollar industry [2]. With a new market emerging at such pace, it is believed a necessity to consider a new surface-metrological issue. To what accuracy are colors embedded to the surface of geometries, with relation to where specified from input data? This paper investigate the accuracy of surface coloring, by adopting a well-known metrological approach from calibrating Coordinate Measurement Machines (CMM’s) and Machine Tools, that already has been transferred to be applicable for AM machine tools, [3] in order to determine the spatial accuracy of embedded color features to artifacts printed on a zCorp 650 color 3D Printer. The spatial color verification artifact is a flat plate with a series of checkered fields on the surface.

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A Comparative Performance Analysis of FDM Machines Based on a Calibration Artefact
During the past ten years Additive Manufacturing (AM) technologies have been constantly developing in terms of materials and processes. This allows the use of the AM not only during the preproduction but also for the manufacturing of final components for commercial use [1], [2]. However one of the still existing challenges for AM concerns the quality of the final components. Every manufacturing process has a strict set of requirements that every component has to meet in order to meet production tolerances, yet AM still shows a lack of industrial standards [3]. The advantage of AM to be able to manufacture components of very complex geometries with intricate internal features becomes in this case a drawback. In fact, the control of the quality and the verification of tolerances become difficult task to accomplish with traditional measuring equipment. Some features can be difficult to reach and there are no standards to compare them with. To
overcome this problem, a method to evaluate the performance of AM machine tools based on the printing of an artefact and the subsequent measuring of its features is proposed and shown. This paper shows a validation of the method by means of a laser interferometer. Furthermore, different AM machines are tested using the printed artefact.

**Applicability of chemical vapour polishing of additive manufactured parts to meet production-quality**
The Fused Deposition Modelling (FDM) method is the most rapidly growing Additive Manufacturing (AM) method[1]. FDM employs a 2.5D deposition scheme which induce a step-ladder shaped surface definition [2], with seams of the individual layers clearly visible[3]. This paper investigate to which extend chemical vapour polishing can be applied to eliminate the layered surfaces from FDM, so that a polished surface quality is obtained. It is quantified to what extend parts can be vapour polished and how geometrical and mechanical properties alter. The fundamental question is whether the surfaces of FDM manufactured parts can be taken from their current quality into the precision engineering domain.

**Comparability of the performance of in-line computer vision for geometrical verification of parts, produced by Additive Manufacturing**
The field of Additive Manufacturing is growing at an accelerated rate, as prototyping is left in favor of direct manufacturing of components for the industry and consumer. A consequence of masscustomization and component complexity is an adverse geometrical verification challenge. Mass-customized parts with narrow geometrical tolerances require individual verification whereas many hyper-complex parts simply cannot be measured by traditional means such as by optical or mechanical measurement tools. This paper address the challenge by detailing how in-line computer vision has been employed in order to verify geometrical tolerances, The paper addresses to which precision, tolerance verification has been achieved, by assessing the reconstruction capability against reference 3D scanning by a selected number of AM processes. Geometrical verification was achieved down to a precision of 20μm for ideal AM processes, whereas the thermally driven SLM due to thermal warpage, resulting in a reconstruction accuracy of 400 μm.
Development of a Paraffin Wax deposition Unit for Fused Deposition Modelling (FDM)

During the last decade Additive Manufacturing (AM) witnessed a big development in terms of technologies, processes and possibilities. However of materials and their use still represents a big challenge. In fact availability of materials is rather limited if compared to conventional manufacturing. This project illustrates the redesign of an extrusion unit for the deposition of paraffin wax in Fused Deposition Modelling (FDM) instead of the conventional polymeric materials. Among the benefits and brought by the use of paraffin wax in such system are: the possibility to make highly complex and precise parts to subsequently use in a Lost Wax Casting process, multi-material Additive Manufacturing and the use of wax as support material during the production of complicated parts. Moreover it is believed that including waxes among the materials usable in FDM would promote new ways of using and exploring the technology and opening to new challenges. The design presented in this paper represents a step towards the development of a multi material deposition unit, able to selectively deposit specific materials on demand in the same product, according to needs. In order to achieve that, waxes and respectedesigns are tested iteratively by alternating different methods in order to find the best configuration. The use of an open source platform, namely a Reprap Prusa Mendel allows to perform quick changes to the system without significant modifications to the major frame of the machine. During the design of the new extruder principles of modularity and reconfigurability are also taken into account in order to ease up a subsequent integration with a more complex system.

Performance verification of 3D printers

Additive Manufacturing continues to gain momentum as the next industrial revolution. While these layering technologies have demonstrated significant time and cost savings for prototype efforts, and enabled new designs with performance benefits, additive manufacturing has not been affiliated with 'precision' applications. In order to understand additive manufacturing's capabilities or short comings with regard to precision applications, it is important to understand the mechanics of the process. GE Aviation's Additive Development Center [ADC] is in a unique position to comment on additive metal processes and their dimensional capabilities. The former Morris Technologies has been producing Direct Metal Laser Melted parts since 2005 for a wide variety of industries. The retooled ADC now specializes in aerospace applications including GE's first production application: the LEAP fuel nozzle. This paper and presentation will take a deep dive into the hardware and mechanics of the modern-day DMLM machine from three of the largest equipment manufacturers. We will also look at typical post processes including the heat treats that are commonly applied to DMLM metal parts. Along the way, we'll mention several surface finish technologies that have been investigated including one that is known as MMP [micro-machining process] which has been used to controllably remove microns of material. Finally, the research will reveal one or two examples of techniques that have used to achieve tight tolerances at the ADC. These methodologies were employed to manufacture direct parts, where tolerances are not as tight as the conventional tools that would be used to produce such parts. Readers and attendees should walk away with a better understanding of Additive Manufacturing, specifically direct metal parts, and the tolerances obtainable today. It is believed that this background information can help engineers and tool makers make better decisions about when to pursue Additive Manufacturing in their industry.
Rendering of surface-geometries at job-generation level for camouflaging the layered nature of Additively Manufactured parts

The layered nature of Additive Manufactured parts, specifically those given from the Fused Deposition Modelling (FDM) process, exhibit a distinct surface definition. The origin of this is from the 2.5D deposition scheme, which leaves the seam between the individual layers clearly visible.[1] It is proposed to camouflage these layers in order to produce parts with a better visual appeal, and to add functional surface structures. In order to generate such surface structures without adding a challenging computational overhead at job-generation, inspiration from Computer Generated Imaging (CGI) is found. An often used method for visualization of complex geometries within CGI is by producing a geometrical primitive after which the primitive is passed through a renderer.[2] Examples can be geometries with hair, leather structure and their like. Should the entire geometry including surface definition sought to be modelled as one three dimensional surface, the geometrical complexity of this would be of intangible proportions and force even the most modern computer clusters to depletion of computing power. The task is therefore handled with an abstraction layer between 3D geometry and texture. It is here the renderer handles the task of adding the surface to the geometry, as a part of the workflow of generating a deflated 2D image[3].

Additive Manufacturing: Multi Material Processing and Part Quality Control

This Ph.D dissertation, Additive Manufacturing: Multi Material Processing and Part Quality Control, deal with Additive Manufacturing technologies which is a common name for a series of processes that are recognized by being computer controlled, highly automated, and manufacture objects by a layered deposition of material. Two areas of particular interest is addressed. They are rooted in two very different areas, yet is intended to fuel the same goal. To help Additive Manufacturing technologies one step closer to becoming the autonomous, digital manufacturing method of tomorrow.

Vision systems
A paradox exist in the field of Additive Manufacturing. The technologies allow for close-to unrestrained and integral geometrical freedom. Almost any geometry can be manufactured fast, efficiently and cheap. Something that has been missing fundamental capability since the entering of the industrial age. Now, with the geometrical freedom given back to the designer and engineer, a technology stale-mate keep us from benefitting from this freedom. Parts can easily be designed and manufactured beyond the capabilities of all common industrial measurement and verification methods, the designer and engineer is left to design parts that from a geometric metrology point of are view possible to verify the tolerances of. A proposal of a method for altering the stale-mate to a check-mate is given. An inline vision system is
developed that allow for verification of parts of a complexity that leave the only industrial alternative to the field of CT scanning. The background knowledge to develop such system is synthesized from an analysis of existing additive manufacturing processes and vision systems. The system is implemented and benchmarked throughout the scope of this Ph.D dissertation.

The proposed inline vision system has been put through several tests against several additive manufacturing systems. Till now the system has proven to be up to the task of reconstructing geometries otherwise only possible by CT scanning. The system outperformed a reference CT scan of a large metal part by an indisputable degree. The system finally showed promising results when applied indirectly to reconstruct geometries from a DLP system. In general, the system has a potential for being implemented in different AM machines and processes and provides traceable measurements of the complex parts. As the technology of inline layered reconstruction of additively manufactured parts has just been proposed within this thesis, the technology is at a dawning level, and there is an abundance of open questions to be answered and much yet to be investigated. It is impossible but leaving this part of the project open-ended. What is to hope is that future research will tie these ends with the emerge of a fully developed system.

**In-process 3D geometry reconstruction of objects produced by direct light projection**

Additive manufacturing allows close-to unrestrained geometrical freedom in part design. The ability to manufacture geometries of such complexity is however limited by the difficulty of verifying the tolerances of these parts. Tolerances of features that are inaccessible with traditional measuring equipment such as coordinate measuring machines cannot be verified easily. This problem is addressed by developing an in-line reverse engineering and 3D reconstruction method that allows a true-to-scale reconstruction of a part being additively manufactured. In earlier works (Pedersen et al. 2010; Hansen et al. 2011), this method has shown its potential with 3D printing (FDM) and selective laser sintering additive manufacturing processes, where it is possible to directly capture the geometrical features of each individual layer during a build job using a digital camera. When considering the process of direct light projection (DLP), the possibility of directly capturing the geometrical features of the object during a build job is limited by the specific machine design and the fact that photoinitiated monomers often do not change optical characteristics in the polymerization process. Therefore, a variant of the previously tested and verified method has been implemented on DLP machine, where instead of capturing the geometrical features of the produced objects during the build job directly, these features are captured indirectly by capturing the reflection of the projected light projected during the build job. Test series were made, and a reconstruction of two octave spheres were produced and compared with the input CAD file and scans of the produced objects. The comparison showed a good
correlation between the reconstructions and the scans considering the resolution of the images used for the reconstruction, and it was thereby concluded that the method has a promising potential as a verification method for DLP machines.

**General information**

**State:** Published

**Organisations:** Department of Mechanical Engineering, Manufacturing Engineering

**Authors:** Andersen, U. V. (Intern), Pedersen, D. B. (Intern), Hansen, H. N. (Intern), Nielsen, J. S. (Intern)

**Publication date:** 2013

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- Web of Science (2009): Indexed yes
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- Scopus rating (2008): SJR 0.509 SNIP 1.011
- Web of Science (2008): Indexed yes
- Scopus rating (2007): SJR 0.436 SNIP 0.73
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- Scopus rating (2006): SJR 0.484 SNIP 1.103
- Web of Science (2006): Indexed yes
- Scopus rating (2005): SJR 0.621 SNIP 0.968
In-line monitoring and reverse 3D model reconstruction in additive manufacturing

Additive manufacturing allows for close-to unrestrained geometrical freedom in part design. The ability to manufacture geometries of such complexity is however limited by the fact that it proves difficult to verify tolerances of these parts. Tolerances of features that are inaccessible with traditional measuring equipment such as Coordinate Measurement Machines (CMM's) can not easily be verified. This paradox is addresses by the proposal of an in-line reverse engineering and 3D reconstruction method that allows for a true to scale reconstruction of a part that is being additively manufactured on 3D printing (3DP), or Selective Laser Sintering (SLS) equipment. The system will be implemented and tested on a 3DP machine with modifications developed at the author's university.

General information
State: Published
Organisations: Department of Mechanical Engineering, Manufacturing Engineering
Authors: Pedersen, D. B. (Intern), Hansen, H. N. (Intern), Nielsen, J. S. (Intern)
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Main Research Area: Technical/natural sciences
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Rapid prototyping, Reverse engineering, Additive manufacturing, Geometry reconstruction
Source: orbit
Source-ID: 271583
Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

A profiling platform at 915, 1075, and 1090nm

General information
State: Published
Organisations: Manufacturing Engineering, Department of Mechanical Engineering, Institute for Product Development
Authors: Pedersen, D. B. (Intern), Hansen, K. S. (Intern), Nielsen, J. S. (Intern), Olsen, F. O. (Intern), Hansen, H. N. (Intern)
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Source: orbit
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Publication: Research › Article in proceedings – Annual report year: 2009

Mode profiling of optical fibers at high laser powers

This paper describes the development of a measuring equipment capable of analysing the beam profile at high optical powers emitted by delivery fibers used in manufacturing processes. Together with the optical delivery system, the output beam quality from the delivery fiber and the shape of the focused spot can be determined. The analyser is based on the
principle of a rotating wire being swept though the laser beam, while the reflected signal is recorded [1]. By changing the incident angle of the rotating rod from 0° to 360° in relation to the fiber, the full profile of the laser beam is obtained. Choosing a highly reflective rod material and a sufficiently high rotation speed, these measurements can be done with high laser powers, without any additional optical elements between the fiber and analyzer. The performance of the analyzer was evaluated by coupling laser light into different fibers, and measuring the output beam profiles. Fibers with different core diameters and different surface qualities were tested.
Pedersen, David Bue (Intern)
Main Supervisor:
Spangenberg, Jon (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet
Project: PhD

Powder Technologies for Additive Manufacturing
Department of Mechanical Engineering
Period: 01/06/2017 → 31/05/2020
Number of participants: 3
Phd Student:
Andersen, Sebastian Aagaard (Intern)
Supervisor:
Pedersen, David Bue (Intern)
Main Supervisor:
Hansen, Hans Nørgaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet
Project: PhD

Industry 4.0 Digital Technologies For High Added Value Zero Defect Manufacturing
Department of Mechanical Engineering
Period: 01/05/2017 → 14/12/2017
Number of participants: 5
Phd Student:
Charalambis, Alessandro (Intern)
Supervisor:
Calaon, Matteo (Intern)
Hansen, Hans Nørgaard (Intern)
Pedersen, David Bue (Intern)
Main Supervisor:
Tosello, Guido (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet
Project: PhD

New production paradigms for wind turbines
Department of Mechanical Engineering
Period: 01/09/2015 → 31/08/2018
Number of participants: 5
Phd Student:
Jensen, Mathias Laustsen (Ekstern)
Supervisor:
Haahr, Arne (Ekstern)
Pedersen, David Bue (Intern)
Skjølstrup, Carl Erik (Ekstern)
Main Supervisor:
Hansen, Hans Nørgaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Industrial PhD
Project: PhD

**Computer Vision based geometrical and textural control for 3D print and injection moulding processes**

Department of Applied Mathematics and Computer Science
Period: 01/12/2013 → 29/09/2017
Number of participants: 6
Phd Student:
Eiríksson, Eyþór Rúnar (Intern)
Supervisor:
Pedersen, David Bue (Intern)
Main Supervisor:
Aanaes, Henrik (Intern)
Examiner:
Carstensen, Jens Michael (Intern)
Krüger, Norbert (Ekstern)
Taylor, John (Ekstern)

**Financing sources**
Source: Internal funding (public)
Name of research programme: Offentlig finansiering

**Relations**
Publications:
Computer Vision for Additive Manufacturing.
Project: PhD

**Advanced Process Chains for Prototyping and Pilot Production based on Additive Manufacturing**

Department of Mechanical Engineering
Period: 01/11/2013 → 31/10/2017
Number of participants: 7
Phd Student:
Mischkot, Michael (Intern)
Supervisor:
Hansen, Hans Nørgaard (Intern)
Pedersen, David Bue (Intern)
Main Supervisor:
Tosello, Guido (Intern)
Examiner:
Islam, Aminul (Intern)
Harder, Ronen (Ekstern)
Qian, Jun (Ekstern)

**Financing sources**
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

**Additive manufacturing technology - process and product quality control**

Department of Mechanical Engineering
Period: 01/01/2010 → 04/04/2013
Number of participants: 5
Phd Student:
Pedersen, David Bue (Intern)
Supervisor:
De Chiffre, Leonardo (Intern)
Main Supervisor:
Hansen, Hans Nørgaard (Intern)
Examiner:
Lenau, Torben Anker (Intern)
Andreasen, Jan Lasson (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: DTU, Samfinansiering
Project: PhD