Novel Nanoparticle Enhanced Digital Materials for 3D Printing and their Application Shown for the Robotic and Electronic Industry

Introduction on the DIMAP project

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Abstract— **In this paper the general idea of the DIMAP project is presented. The ultimate goal of the project is to fabricate innovative applications using new additive manufacturing technologies. In order to do so, four new materials and a new generation of 3D printers are developed. The eight main objectives of the project are described, in order to present the backbone of the concept. Then a status of the project is given and the future work is explained. The DIMAP project is application-driven and intends to lead to advances in additive manufacturing technologies, therefore this paper is strongly relevant to the ADAAM symposium.**

Keywords: Digital Material, 3D Printing, Robotic, Electronic, Nanoparticule

I. INTRODUCTION

The here described DIMAP (Novel nanoparticle enhanced Digital Materials for 3D Printing and their application) idea focuses on the development of novel ink materials for 3D multi-material printing by PolyJet technology [1]. The state-of-the art of Additive Manufacturing (AM) will be advanced through modifications of the fundamental material properties, mainly by using nanoscale material enhanced inks [2, 3]. This widens the range of current available additive AM materials and implements functionalities in final objects. Therefore, applications will not be limited to rapid prototyping but can be used directly in production processes. DIMAP will show this transition in two selected application fields: the production of soft robotic arms/ joints and customized luminaires. In order to cope with these new material classes, the existing PolyJet technology [4] is further developed and therefore improved. The DIMAP project has the following objectives: additive manufactured joints, additive manufactured luminaires, ceramic enhanced materials, electrically conducting materials, light-weight polymeric materials, high-strength polymeric materials, novel multi-material 3D-printer and safe by design. With the development of novel ink materials based on nanotechnology improvement of the mechanical properties (ceramic enhanced and high strength polymeric inks), the electrical conductivity (metal enhanced inks) and the weight (light-weight polymeric materials) are achieved. Based on the voxel printing by PolyJet, these new materials lead to a huge broadening of the range of available digital material combinations. Further focus points during the material and printer development are safe by design approaches, work place safety, risk assessment, collaboration with European Union (EU) safety cluster and life cycle assessment. An established roadmap at the end of project enables the identification of future development needs in related fields order to allow Europe also in the future to compete at the forefront of the additive manufacturing revolution. In Section II, the eight main objectives of the project are described. A status of the project is given in Section III. At the end, in Section IV, the future strategy is explained.

II. THE EIGHT DIMAP OBJECTIVES

The DIMAP project intends to implement an idea born among various industrial and research centers across Europe. The overall objective is to enhance digital materials with novel nanoparticles for 3D Printing. Four different inks are investigated, electrically conductive inks, ceramic inks, high strength polymeric inks and lightweight polymeric inks. The idea is to implement those materials into two concrete demonstrators (luminaires and bio inspires robotic joints) requiring specific processes. In parallel to the ink and process developments, safe by design and work place safety approaches are conducted in order to minimize the risk due to nanoparticles use. The whole concept can be differentiated into 8 objectives, summarized in Figure 1.

A. *Objective 1: Additive manufactured joints*

Environmental interaction, the so-called man-machine interaction, is a great challenge for mechanical devices and modern robot design. Currently, research suggests "low impedance" as key strategy and an approach is provided by bionics [5]. Flexibility and low weight are two main aspects of reducing impedance that are perfectly realized in biological systems. 3D Printing technologies offer freedom of design to manufacturing and therefore are predestined for

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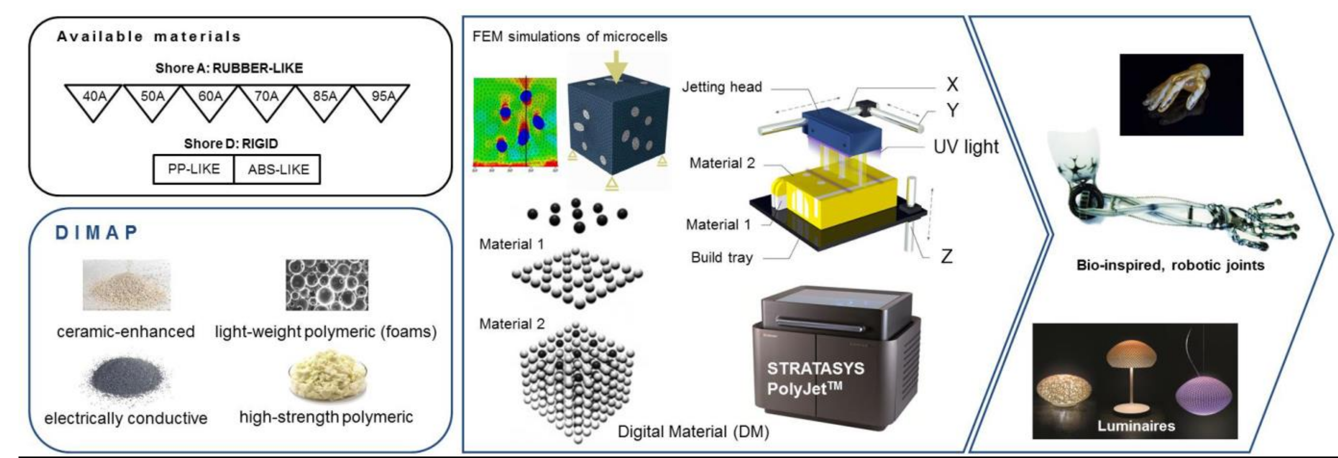

Figure 1. Concept for novel nanoparticle enhanced Digtial Materials for 3D Printing and their application shown for the robotic and electronic industry

the production of bio-inspired solutions, which are the prime example for such designs. Significant limitations in AM technologies are found in available materials, in particular functional materials to solve above-mentioned technical questions. Within DIMAP the manufacturing of bio-inspired joints, solutions derived from arthropod "jointed legs", will show novel solutions in robot design and man-machine interaction. These innovations will be reached with the development of aforementioned functional materials and technical improvements to the 3D-printer, e.g., combined thermal and Ultraviolet (UV) curing strategies, to be able to print the novel materials.

B. Objective 2: Additive manufactured luminaires

One of the main drawbacks in the development of lightning applications is the lead time, which can take up to 6 months. This is due to the use of injection molding that also adds high costs for the required tooling (up to 1.5 million Euros) and limits the applicability to customized small series production. The implementation of AM is expected to increase the ability of companies to introduce new and improved products at accelerated rates as well as addressing the market for customization due to highly value added product diversity. Within DIMAP the material portfolio for the PolyJet Printing will be expanded to achieve higher mechanical strength, electrical conductivity and flexibility in order to be able to manufacture a lighting application with movable parts for a user-controllable light orientation. DIMAP will show that the new developed ink systems and improvements to the printing process are able to lead the way to manufacturing small to medium series of customized luminaires.

C. Objective 3: Ceramic enhanced materials

The addition of ceramic particles allows the addition of new functionalities in products. The mechanical, electrical or magnetic properties of the resulting polymer matrix after solidification can be tailored. In the last couple of years, ceramic filled photo-curable inks have been used in stereolithography (SLA). Here solid loading up top 50 Vol% have been reported [6]. Based on the structuring method higher viscosities in the range of several 1000 mPas are acceptable in this case. In order to use the advantage of creating digital materials with PolyJet Printing the requirements in terms of viscosity are different: an ink viscosity below 100 mPas is crucial. However, high nanoparticle loading is necessary to enable huge property adjustments. Within DIMAP this will be achieved by using nanoparticles not smaller than 100 nm as smaller nanoparticles come along with larger specific surface areas leading to a significant viscosity increase. In addition higher solid loadings (up to 50 Vol% without solvent) retaining low viscosity values should be achieved via selection of suitable additives such as liquefiers and dispersants.

D. Objective 4: Electrically conducting materials

Nowadays, electric conductors are made in industrial environment mainly by screen printing or photolithography which carry severe environmental concerns due to the low metal ink yield and the large quantity of hazardous waste as well as limited applicability for customization. Electrically conductive inks for digital inkjet conductive printing are a challenge as its necessary to balance several counter influence properties, such as: high metal content, low viscosity, small non agglomerated particles, surface tension properties compatible with the print heads and substrates. The only viable way to achieve this balance of properties is by formulating inks with nano-metal particles. Such inks for digital conductive 3D Printing are currently not available on the market. Within DIMAP UV curable inks will be developed which address these issues - printed paths containing a monomer will be cured (polymerized) while at the same time keeping suitable conductive properties (e.g., resistivity below 10 $\mu\Omega\cdot$cm). These goals will be achieved by a selection of suitable monomers, optionally solvents and photo initiators in metallic nanoparticle ink formulation.

E. Objective 5: High strength polymeric materials

Since both demonstrators may be exposed to mechanical stresses a high strength material will be part of the material development. Also, a high temperature tolerance is favorable, especially in case of the lighting device. Therefore, a new thermoplastic material will be added to the portfolio of PolyJet materials, opening up new possibilities in functionality and mechanical strength. Strategies to realize 3D Printing of these materials are based on the preparation of highly filled 3D-inks made of soluble polymer particles or by developing reactive 3D-inks based on precursors.

F. Objective 6: Light weight polymeric materials

Various polymers can be designed to uptake high mechanical forces comparable to metal, glass and ceramics used in industrial application. A further reduction of weight from the solid polymeric object can be achieved with foams and foam-like structures. The strength of hard foams is found in the combination of different positive properties e.g., their light-weight structure and at the same time possessing high mechanical load capacity. Currently, 3D Printing of foam-like structures requires several working steps, e.g., Fused Deposition Modelling (FDM) printing and adjacent leaching in water for several days, obtaining soft foam-like objects. 3D Printing of foams with PolyJet technologies has not been realized yet. Within DIMAP printing of hard foams in one production step will be implemented to PolyJet 3D Printing. Thus, especially designed 3D-printable ink based on foamable core-shell particles and enhancements concerning the PolyJet-3D-printer will be developed. Printing of hard, closed foams will enable several new possibilities in AM including the print of light-weight, highly mechanically robust objects or the use of the closed foam as supporting material that allows printing on top of “hollow” objects, e.g., the top-surface of a 3D-printed cube.

G. Objective 7: Novel multi-material 3D-printer

The PolyJet technology is based on a multi-jet and multi-head inkjet technology where objects are constructed layer-by-layer. PolyJets’ uniqueness among other AM technologies is its ability to control the material deposition for building an object to the level of a single voxel allowing a precise control of the structure and of the properties of object printed. In order to address new markets widening the range of available materials and implementation of functions into the printed objects is crucial. As shown on the two applications this will allow SMEs to manufacture functional objects with tabletop multimaterials printers. In addition to the novel materials mentioned before a further development of the technology in order to cope with the ink requirements is needed. DIMAP will perform investigations and integration of novel printhead systems for higher ink viscosities (100 mPas at printing temperature) including ink circulation systems. Furthermore, an inline control of the printing process is needed to investigate the quality of the joint between already hardened drops and new deposited drops to be able to predict the toughness of the final 3D printed product. Thermographic flash method is known as a proper method for the investigation of the mechanical consistency of manufactured parts. DIMAP will investigate the appropriateness of this method for PolyJet 3D Printing.

H. Objective 8: Safe by design

Nanotechnology is a key enabling technology for the development of innovative products of a large variety of industries. Impact and interaction of nanomaterials on environment and human health is a widely discussed question. Considering ink-formulations as proposed within DIMAP the handling of the base materials prior to ink formulation and excess materials after the printing process are the main challenges. In DIMAP a concern-driven guidance for investigating potential risks of engineered nanomaterials (ENM) will be established according to the NanoSafetyClusters’ Research strategy 2015 – 2025. This allows a focused research on exposure levels and exposure routes, material properties, various in silico models as well as hazard and biokinetic data [7, 8]. In order to reach a Safe-by-Design approach for the process chains proposed within DIMAP assessment of the exposure rates during the manufacturing processes, usage time and end of life will be carried out. Furthermore, the implementation of a highly efficient risk management system will be targeted. Based on the data of existing databases and studies the process chain and materials will be evaluated and potential hazards will be identified. In combination with assessment of exposure rates mentioned above a strategy for the control and reduction of exposure rates will be proposed to reach a less hazardous product life cycle. The information gathered within DIMAP will be shared with the scientific community to further improve the knowledge base.

III. CURRENT STATUS

During the first six months of the project, the main focus of the consortium was on the assessment of requirements for the demonstrators, materials and processes that will be used throughout the runtime of DIMAP. The base information needed for the developments within the project were the envisaged properties of the robotic arm and the luminaire system. Therefore, the main mechanical, electrical and thermal properties of the products themselves as well as the operating conditions and the limitations given by the current state of the PolyJet technique were collected. Based on these assumptions the development for the novel material classes and improvement of the printing technology is currently performed.

In close cooperation with a powder supplier (*TECNAN S.L.*)[9] the development of ceramic filled inks at the *Karlsruhe Institute of Technology (KIT)* is currently focusing on selecting the most suitable components. Ceramic nanoparticles for mechanical stability (Al_2O_3 or ZrO_2) or thermal conductivity (AlN or BN) are currently customized in order to adapt the particle size distribution and surface properties. Additionally, a wide variety of binder materials and surfactants will be examined for their suitability to reduce the ink viscosity to a processable level.

PVNanoCell Ltd. [10] develops conductive materials, mainly conductive inks for digital conductive printing based on silver nanoparticles. Silver-based inks will be used for printing conducting paths that are required in both applications. Currently, the main focus of the research is on the composition of the ink, as well as on the stability of the ink, reducing the percolation of the dense silver particles. In parallel, first printing test will be performed in the near future using the first promising ink compositions available.

As described above, the use of a new class of thermoplastics as a high strength polymer is a completely new approach in context of the PolyJet technology. Therefore, investigations at the *Soreq* [11] research center had to start from scratch by determining the most promising approach to create a suitable ink. Two different routes were evaluated, one using pre-polymer powders and the second by cross-linking low-molecular weight oligomers. At the current state, the second approach seems to show better compliance to the desired properties, which is why this route will be followed.

The last material is the foam-like material for the bone structure. At the *Johannes-Kepler University of Linz* and *Borealis AG* two different types of foams will be analyzed. The first type is a closed cell foam based on the principle of blowing agents that are dispersed in a polymer matrix and that forms voids with a outer shell upon UV- or heat treatment. The second type is an open cell foam that is produced by using organic blowing agents within the ink matrix.

All developments on the ink systems are carried out in close cooperation with *TIGER Coatings GmbH & Co KG* [12], who are focusing their work on the composition of the ink matrix, and *Profactor GmbH*, that are responsible for the ink curing strategies, that have to be individually adapted for each material. Finally, the practical test and printer development is done by *Stratasys Ltd* [13]. since some materials may not be fitting to the current PolyJet standards and may require new generation print heads or combined dispensing techniques.

IV. Conclusion and future Work

DIMAP will provide a new range of materials as well as significant improvements concerning the dispensing technique to the PolyJet Printing within the runtime of the project. Two exemplary applications will be produced to show the capabilities of the development of the process chain. Although the project has just been running for 6 months, significant steps have already been made by defining the material and product properties in detail and first investigations in the field of ink development with very promising results so far.

The next steps are the development of suitable ink formulations using the designated nano materials defined in the previous months, ink stability testing and, in some cases, also first printing and modeling trials using the newly developed materials.

The printing technology has to be adapted for the expected higher values of viscosity. Therefore, the print heads used in the inkjet printer will be changed to upgrade the capability for higher viscous inks wherever it is needed. In addition, a possible combination with other dispensing techniques is currently thought of, depending on the properties of the final inks.

For the safety aspect, personal monitoring devices that measure workplace exposures will be implemented in the ink production processes to determine the possible influence of nano materials in the workplace safety.

References

[1] http://www.stratasys.com/3d-printers/technologies/polyjet-technology [accessed June 2016]

[2] T. Hanemann, D.V. Szabó, “Polymer-Nanoparticle Composites: From Synthesis to Modern Applications”, Materials, 3, pp. 3468-3517 (2010), doi: 10.3390/ma3063468.

[3] R. Zichner, E. Sowade, R. R. Baumann, “Inkjet printed WLAN antenna for an application in smartphones”, Jpn. J. Appl. Phys. 2014, 53, 05HB06.

[4] http://www.stratasys.com/fr/imprimantes-3d/technologies/polyjet-technology

[5] S. P. Buerger, “Stable, high-force, low-impedance robotic actuators for human-interactive machines”, Massachusetts Institute of Technology, 2005.

[6] C. Provin, S. Monneret, H. Le Gall and S. Corbel, “Three-Dimensional Ceramic Microcomponents Made Using Microstereolithography”Adv. Mater. 2003, 15, pp. 994–997.

[7] A. G. Oomen et al., “ Concern-driven integrated approaches to nanomaterial testing and assessment – report of the NanoSafety Cluster Working Group 10”, Nanotoxicology 2014, 8, pp. 334–348, doi: 10.3109/17435390.2013.802387

[8] V. Stone et al., “ITS-NANO – Prioritising nanosafety research to develop a stakeholder driven intelligent testing strategy”, Particle and fibre toxicology, 2014, 11, 9, doi: 10.1186/1743-8977-11-9

[9] https://tecnan-nanomat.es/ [accessed June 2016]

[10] http://www.pvnanocell.com/ [accessed June 2016]

[11] http://soreq.gov.il [accessed June 2016]

[12] http://www.tiger-coatings.com/ [accessed June 2016]

[13] www.stratasys.com [accessed June 2016]