Nano Inks for Additive Manufacturing – A Safe-by-Design-Approach

Katja Nau[1], Tobias Müller[1], Daniel J.B.S. Sampaio[2], Steffen G. Scholz[1]

[1]Institute for Applied Computer Science
Karlsruhe Institute of Technology
Karlsruhe, Germany
e-mail: nau@kit.edu

[2]School of Engineering – Guaratinguetá
São Paulo State University (Unesp)
Guaratinguetá, Brazil
e-mail: dsampaio@feg.unesp.br

***Abstract*—Additive manufacturing (AM) enables a new manufacturing paradigm, such as the rapid, distributive manufacture of complex 3D objects. Nanoparticles are in particular suitable for ink formulation of novel PolyJet inks to obtain functionalities embedded in the AM process. However, the impact and interaction of nanomaterials on environment and human health is widely discussed today. This paper deals with a safe-by-design-approach that is developed in this context.**

Keywords-additive manufacturing; nano safety; safe-by-design; human-centred industrial technologie.

I. INTRODUCTION

Additive manufacturing (AM) is a technique for creating 3D objects by building up material, layer by layer, with the control of a digital design. The term 3D printing is often used to refer to AM but it is important to keep in mind that 3D printing is actually one of the several AM processes. 3D printing was developed by a Massachusetts Institute of Technology team led by Emanuel Sachs in the late 1980s [1]. AM processes have some important advantages over traditional manufacturing techniques. The design of products is more flexible because of its additive approach, permitting a range of geometries beyond the capabilities of other methods. The development of new products is also faster because of the ease of moving from design to prototyping and then to production since it takes place directly on the basis of digital 3D data. It is possible to create functional parts without the requisite for assemblage [2].

Nanotechnology is science, engineering, and technology conducted at the nanoscale, which is about one to 100 nanometers, and involves the ability to see and to control individual atoms and molecules [3]. When shrinking the size scale from macro to nano, materials can change their fundamental properties, exhibiting unique optical, thermal or electrochemical properties that differ from the properties of the bulk material. These properties strongly depend on the size and the shape of nanostructures [4][5]. The integration of nanotechnology with AM can complement existing techniques and create entirely new nanocomposites having unique properties that can lead to expansion of AM application areas and reduce some of the AM limitations. Investigations have shown that the introduction of inorganic nanostructures such as carbon nanotubes, metal nanoparticles, and ceramics can meaningfully affect sintering features and final mechanical properties of the produced parts [6].

The addition of metal nanoparticles generally decreases sintering temperatures, improves part density, and decreases shrinkage and distortion of printed parts in comparison to micro-scale fillers [7]. Metal nanoparticles embedded into polymer materials can also provide improved electrical conductivity in fabricated objects [8]. Incorporation of carbon nanotubes in printing media offers a potential route to improving mechanical properties of the final parts and to increasing electrical and thermal conductivities [9]. The addition of carbon nanotubes in bio-scaffolds can yield excellent enhancement of cell proliferation. Adding semiconductor and ceramic nanoparticles to printing media can lead to improvements in mechanical and wear properties of the final parts. In addition, ceramic nanoparticles can be effectively used for bone tissue engineering. Even with the mentioned design, material and environmental advantages, the adoption of AM as a means for fabricating end-use components has been limited by the narrow choice of materials that can be used with this technology and challenges in the fabrication like nozzle clogging/wear, aggregation within printing media and rough surface finish of printed parts. Additionally, differences in built process parameters and/or in some AM processes parameters, like ambient conditions, can result in variations in properties and dimensions between parts built on different machines of the same kind. Overcoming these issues will require advances in both process control methods and material diversity [10].

One of the initiatives that intends to lead to advances in AM technologies is a EU-funded project called DIMAP (novel nanoparticle enhanced **DI**gital **MA**terials for 3D **P**rinting) [11] that, based in an idea born among various industrial and research centres across Europe, aims to develop applications not only limited to rapid prototyping but that address production processes, enhancing digital materials with novel nanoparticles for 3D printing in order to increase design possibilities and handling with needs for adapting and updating actual printing technology components.

Another important point is that DIMAP is also taking in account the risks of today's nanoscale technologies [12]. These nano related risks cannot be treated the same as the risks of longer-term molecular manufacturing, it would be wrong to put them together and make the same policy considerations since they offer different problems and therefore require special solutions. Nanotechnology manufacturing can bring unfamiliar risks and new classes of problems, consequently the impact and interaction of nanomaterials on environment and human health is widely discussed today [13].

This paper presents work of the EU project DIMAP as shown in Section II. Section III shows the safe-by-design approach, based on the prior knowledge of the used chemicals and nanomaterials that is going to be validated using two concrete demonstrators, an additive manufactured robotic arm and additive manufactured luminaires. Current work on nano safety aspects is presented in Section IV.

II. OVERALL APPROACH OF DIMAP

The overall objective of the DIMAP project is to enhance digital materials with novel nanoparticles for 3D printing in order to increase design possibilities. In order to develop these two specific innovative demonstrators, four novel digital materials, novel multi-material 3D printer and a safe-by-design approach should be investigated in parallel and developed as shown in Figure 1.

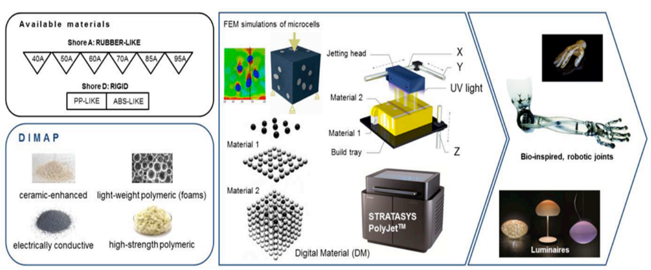

Figure 1. Concept for novel nanoparticle enhanced Digital Materials for 3D Printing

The challenges created by the selected applications require the development of novel ink systems with incorporated nanoparticles, with four different inks being in the scope of the project: electrically conductive inks, ceramic inks, high strength polymeric inks and lightweight polymeric inks as shown in Figure 2. In order to cope with these new material classes, the existing PolyJet technology should be further developed and therefore improved.

Material	Type	Particle properties
Ceramic enhanced	Al_2O_3 ZrO_2 AlN BN	15 - 100 nm
Electrically conductive	Ag	~ 70 - 80 nm
Low-weight structures	Polyolefines, Blowing agents	non particulate
High strength polymeric	Polyimides	non particulate

Figure 2. Selected materials to enhancement inside DIMAP

A safe-by-design and work place safety approach is carried out in parallel with the purpose of minimizing the risk due to the use of nanoparticles. This is shown in more details in the next section.

III. SAFE-BY-DESIGN APPROACH

The growing of nanotechnology-based products is increasing together with the conscience that some nanomaterials can bring unsafe effects and in order to try to control the risks, safe-by-design approaches are gaining attention and importance as tools to develop safer products and production processes [14]. It is important to first define what is included in the design process and then think about the safety aspects. There is no agreement in the literature about a clear boundary of the design process [15].

In this work, a proposed safe by design methodology for 3D printed nano-based products is presented centred in a systematic design analysis that can detect exposure scenarios and present the solutions to control the possible risks, endorsing possible barriers to reduce or even block them. The Figure 3 shows an overview of the proposed approach indicating all the elements that are encompassed and also the possible exposures for each element, emphasizing the importance of a safe-by-design approach.

The approach starts with the knowledge of all necessary chemicals and nanomaterials used during all process steps because their properties are used as basis to understand the toxicity of each production stage and final nanotechnology-based product. Each used material is evaluated and for each a very detailed Safety Data Sheet (SDS) has to be filled. This first step is very important since the SDS is the basis for the analysis made inside the methodology.

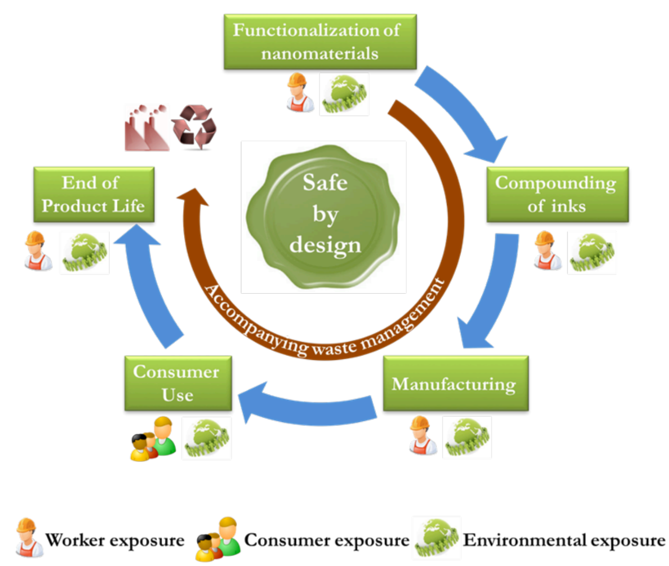

Figure 3. Safe by Design approach based in a systematic design analysis

The next step is the potential risk investigation where personal monitoring devices should be used to measure and analyse exposure to nanoparticles during the material

 ISBN: 978-1-61208-538-8

preparation and printing steps. A life cycle assessment should be also carried out to determine the impact of the printed product throughout the whole production, usage and disposal. Assessment of the exposure rates during manufacturing, usage and end of life are then carried out. The waste produced starting from the synthesis of each used material until the end of life of the final product is also analysed and considered in this assessment. As last step, solutions are given for the detected exposure scenarios that should be applied to reduce or even eliminate the found risks and re-evaluated after application.

IV. CURRENT WORK

Within the DIMAP project various nanomaterials are used in inks for 3-D printing. The safe-by-design approach started with the determination of the composition of the inks on the one hand and the potential exposure hotspots within the DIMAP work packages on the other hand. Material safety datasheets were analysed or generated for each new or modified material. Another aspect of the safe-by-design approach is, as mentioned above, the exposure of humans to nanoparticles during the whole process of AM. At present, little is known about the release of nanomaterials from 3D printers. But the potential exposure to airborne nanomaterials from these printers needs to be measured in the personal breathing zone using nano-specific personal samplers or monitors.

Within DIMAP, such a small and easy to use sampler is currently applied to determine the particle release at, in and around the printer. Measurements are carried out in ambient conditions, as well as with the printer running, being able to compare different materials, different printing techniques, printer models and, to a limited extent, the dependence of exposure on different manufacturing parameters.

V. CONCLUSION AND FUTURE WORK

The main aim of the DIMAP project is to develop novel multi-material systems for PolyJet inks. Therefore, DIMAP will improve and advance the current technology by widening the range of available materials. However, the impact and interaction of nanomaterials on environment and human health is widely discussed today. Work is currently at an early stage concerning the measurement of (nano)particles in the process chain of AM. Different work place scenarios will to be analysed. The release of (nano)materials during work process, exposure to workers, potential hazard and a potential risk have to be assessed.

As an outcome of the project a safety guideline will be established in order to support the industry in applying AM in an even wider spectrum.

ACKNOWLEDGMENT

The DIMAP project is funded by the European Union's Horizon 2020 Program for research and innovation under Grant Agreement No. 685937.

REFERENCES

[1] E.M. Sachs, J.S. Haggerty, M.J. Cima, and P.A. Williams, "Three-dimensional printing techniques", U.S. Patent No. 5,204,055. Washington, D.C.: U.S. Patent and Trademark Office, 1993

[2] A.M. Dollar and R. Howe "Joint coupling design of underactuated hands for unstructured environments" 30 (9) pp. 1157-1169 2013. DOI: 10.1177/0278364911401441

[3] M.C. Roco, R.S. Williams, and P. Alivisatos, Nanotechnology Research Directions: Iwgn Workshop Report. Vision For Nanotechnology R&D In The Next Decade. National Science And Technology Councilarlington Va, 1999

[4] Y.W. Jun, S.M. Lee, N.J. Kang, and J. Cheon, "Controlled synthesis of multi-armed CdS nanorod architectures using monosurfactant system", Journal of the American Chemical Society, 123(21), pp. 5150-5151, 2001.

[5] C. Burda, X. Chen, R. Narayanan, and M.A. El-Sayed, "Chemistry and properties of nanocrystals of different shapes", Chemical reviews, 105(4), pp. 1025-1102, 2005.

[6] S. Chaturvedi and P.N. Dave, "Design process for nanomaterials", Journal of Materials Science, 48(10), pp. 3605-3622, 2013.

[7] W. J. Sames, F. A. List, S. Pannala, R. R. Dehoff, and S. S. Babu, "The metallurgy and processing science of metal additive manufacturing", International Materials Reviews, 61:5, pp. 315-360, 2016, doi: 10.1080/09506608.2015.1116649

[8] S. Schlabach, R. Ochs and T. Hanemann, and D.V. Szabo, "Nanoparticles in polymer-matrix composites", Microsystem Technologies, 2011, 17, pp. 183-193, doi: 10.1007/s00542-010-1176-8.

[9] M.F. De Volder, S.H. Tawfick, R.H. Baughman, and A.J. Hart, "Carbon nanotubes: present and future commercial applications", science, 339(6119), pp. 535-539, 2013.

[10] O. Ivanova, C. Williams, and T. Campbell, "Additive manufacturing (AM) and nanotechnology: promises and challenges", Rapid Prototyping Journal, v. 19, n. 5, pp. 353-364, 2013.

[11] http://www.dimap-project.eu [retrieved Feb 2017]

[12] S. Scholz, A. Brunet., T. Müller, and A. Fuchsbauer, "Novel Nanoparticle Enhanced Digital Materials for 3D Printing and their Application Shown for the Robotic and Electronic Industry", proceeding of the CENICS 2016 conference.

[13] P.C. Ray, H. Yu, and P.P. Fu, "Toxicity and Environmental Risks of Nanomaterials: Challenges and Future Needs", Journal of environmental science and health Part C, Environmental carcinogenesis & ecotoxicology reviews. 2009; 27(1): pp. 1-35. doi:10.1080/10590500802708267.

[14] F. Silva, P.M. Arezes, and P. Swuste, "Systematic design analysis and risk management on engineered nanoparticles occupational exposure", Sho2015: International Symposium on Occupational Safety and Hygiene, pp. 350-352, 2015

[15] A. Hale, B. Kirwan, and U. Kjellén, "Safe by design: where are we now? Safety science, v. 45, n. 1, pp. 305-327, 2007

 ISBN: 978-1-61208-538-8