Dutch Research Council (NWO)

NWO Domain

Applied and Engineering Sciences (AES)

Open Technology Programme 2022

Project Title:

**T**ailoring **O**ptimized **P**olymer **Foam**s via   
rapid high-resolution 3D printing   
[**TOP-FOAM**]

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# Title

Tailoring optimized polymer foams via rapid high-resolution 3D printing [TOP-FOAM]

# Keywords

Foam, additive manufacturing, 3D printing, polymer, sustainability, bubbles, fluids

# Summary

# Scientific Summary

Direct bubble writing (DBW) is a novel technology for the 3D-printing of polymer foams. This versatile platform enables the manufacture of materials with well-controlled and uniform cell sizes, and renders possible locally tailored properties such as gradients in cell size, density, and open- or closed-cell regions. The foams are printed to shape in a single step, preventing cutting waste or fabrication of complex molds. Surfactant-free and solvent-free formulations with only few components are available. These unique feats are achieved by ejecting bubbles from a core-shell nozzle into the air, assembling them into a porous material, and solidifying them in-situ by photopolymerization. The process is operated at medium/high throughput and can be scaled by parallelization, providing industrial output that matches target markets (e.g. footwear, bedding, and casting). However, up to now, DBW was optimized for either structural control, mechanical properties, *or* reduced environmental impact. TOP-FOAM aims for the next-generation foams that will bring all these elements together by advancing our understanding in three key areas:

* *WP1 - Bubble formation*. The key mechanisms behind bubble formation from core-shell nozzles will be investigated as a function of the nozzle geometry, liquid properties, and flow rates via high-speed imaging, numerical modeling, and dimensional analysis. This knowledge will deepen our understanding of the fluid mechanics of DBW, which is still a black box, to enable the formulation of a wider range of resins.
* *WP2- Resin formulations*. We will systematically investigate resin formulations to maximize control over the mechanical properties (e.g., stiffness, toughness, cycling behavior) and to minimize the environmental footprint. A range of monomers and solidification methods will be assessed in an iterative fashion. The resulting foam samples will be characterized chemically, optically, mechanically, and structurally.
* *WP3 - Applications*. Advanced foam samples will be manufactured and tested against user standards, in close collaboration with the consortium partners. Subsequently, functionally graded porous parts will be 3D-printed and assessed for application in target markets (footwear, bedding, metal casting).

# Public Summary NWO Domain AES website and online in ISAAC

Direct bubble writing is a novel technology for the 3D printing of polymer foams with tunable and well-defined internal gradients, at higher throughput than typical 3D-printers. The concept was proven for a range of polymers, shapes, and foam densities, and has already enabled added functionalities such as pressure sensing, shape memory, and tailored bending. In the TOP-FOAM project we will advance the understanding of the process and materials, to enable the next leap towards strong and durable foam components using eco-friendly (bio-sourced/recyclable) formulations. Applicability in footwear, bedding, and metal casting will be demonstrated.

# Problem statement

**The problem**:

***Current foams***: Polymer foams are ubiquitous in our everyday lives (e.g., seat, shoes, wall insulation), and represent a vast market (Facts&Factors). However, current manufacturing processes have significant limitations: Production is mostly done in bulk, which then necessitates transportation of these cumbersome materials. Foams need to be cut to their final shape which makes customized designs difficult and generates a large amount of waste. Adapting production techniques towards bio-sourced and biodegradable materials is still in its infancy. The text box highlights the impact of these challenges on the products and processes of our industrial partners.

***Our users on their foam-related challenges***

***Adidas***: “Current midsole foam technologies do not enable tuning towards specific performance needs of a sport or individual. Additionally, environmentally friendly polymer foam solutions are a key requirement for the consumer goods supply chains of the future.”

***Auping***: “Mattresses with different densities and firmness are desired for supporting specific parts of the body or body types. Typically this is now achieved by post processing; cutting and reassembling. This limits design freedom, is labor intensive, and produces waste.”

***Atlas Copco***: “Our company uses lost foam casting for manufacturing highly complex metal geometries. Gradients in the foam density would optimize the casting process and quality of our parts, but these are hard to achieve. Our current foam parts also need expensive and complex-shaped molds, require a gluing process to combine several foams, and produce toxic fumes during casting.”

***Technological:*** In contrast, ideal foam materials would exhibit *gradients* in their structure or density, mimicking cellular materials found in nature (*1*). However, current bulk foaming technologies cannot create such functionally graded or partially void structural parts (such as lattices). Molding techniques require expensive prototyping and still fail to incorporate tailored gradients (*2*). Some recent technologies proposed to alleviate this problem but are not scalable. For example, additive manufacturing is mostly limited to small parts as every cell in the foam is created from multiple layers, or provides poor control over the cell size if each cell is nucleated (*3*). Microfluidic chips only operate at low-throughput (*4*). Therefore, optimized functionally graded parts remain essentially out of reach.

***Environmental***: Changing to more eco-friendly foam compositions requires scaling of bulk reaction processes that prevent harsh chemicals and surfactants, eliminate waste, and reduce transport. Current foaming agents must also be replaced, as these expose a high global warming potential. Meeting these targets with conventional bulk processes is challenging, since tens of control parameters interact in escalating levels of complexity during foam formation. Therefore, processes that separate different steps in the foaming process in time or space, such as direct bubble writing, are highly attractive for analyzing, testing, and producing foams with new eco-friendlier chemistries.

***Societal****:* Current foams (with no gradients) are underperforming in terms of strength, shape, dynamic response, acoustic and thermal insulation, or sensory response (touch, feel, appearance, acoustics). Consequences may include increased safety and health risks (e.g., by collision shocks, exposure to loud sounds or sharp temperature gradients). Adding weight to mitigate these issues results in excess use of resources along the supply chain, such as mining and transport, e.g. increased fuel consumption and fine-particle pollution via tires wear and exhaust emissions. Adding weight also reduces comfort and risk of injury upon use. Economically, the Netherlands (and EU) are exposed to the real risk of losing its ability to manufacture advanced materials. Connecting fundamental research and new technologies with the development of applications was identified as a key weakness of materials science in The Netherlands (“engineering gap” and ”innovation gap” as detailed in the Dutch Materials report (*5*)). Developing solutions for the above-described problems would directly benefit our academic-industrial ecosystem, yield job creation, and help to retain a leadership position.

# Scientific description

# Research contents / Introduction

# 4.1.1 Introduction & state of the art

Polymer foams are functional materials providing thermal insulation, sound or shock absorption, cushioning, and exceptional structural performance. Consequently, foams are broadly applied in among other footwear, helmets and cushioning (*6*), furniture, tissue engineering (*7*), biomedical implants (*8*), micro-filtration (*9*), catalysis (*10*), and pressure sensing (*11*). The functional properties of these foams are defined by the constituent material, the porosity (void fraction), the cell size, and the cell interconnectivity (i.e., the transition between open-cell and closed-cell regions) (*12*, *13*). **Therefore, realization of optimized foams with functional gradients requires foam fabrication methods that control these properties at the local (cell) level. The shape, size, and gradients within these foams should be created in one step to eliminate cutting waste and complex post-processing. Solvent-free and surfactant-free processing of eco-friendly resins would be highly beneficial, as there is no satisfactory solution for foams’ end-of-life. However, this level of control is beyond current foaming techniques** (*14*, *15*)**.**

Recently, we invented a technique coined Direct Bubble Writing that provides (*16*, *17*):

1. One-step additive manufacturing of shape-controlled porous materials at high throughput (20 to 300 mL/min and scalable via parallelization). Filaments, vertical pillars, and overhangs were printed.
2. Smooth predictable gradients in cell size, open-to-closed cell transition, and density. For example, relative densities from 10% (90% gas) to 100% (pure solid) were locally applied within single printed construct, providing a gradient that enabled a non-trivial lock-in-place response from a spherical cap (*16*).
3. Solvent-free and surfactant-free processing (*17*), no cutting of parts (preventing waste) (*16*), and simple formulations (few components required) enabling rapid iterations towards further eco-friendliness.

The goal of TOP-FOAM is to integrate and extend these feats by exploring key scientific questions behind this platform technology. This challenging goal is urgent and relevant from academic, societal, and industrial (commercial) perspectives, as detailed below. The knowledge is applicable to other technologies relying on core-shell nozzles (e.g. in-air microfluidics (*18*) and target formation (*19*)), and the curing of sustainable resins for 3D-printing (*20*), and it will provide a pathway towards the highly desired functionally graded polymer materials (*14*).

**The state of the** **art** is divided in (1) existing bulk foaming techniques, (2) recent foaming techniques including additive manufacturing, and (3) direct bubble writing and its key opportunities that will be the focus of TOP-FOAM.

In **bulk chemistry**, foam properties are determined by the foaming dynamics, including nucleation and growth of cells, drainage and rupture of cell walls, internal heating, and gravitational translation of bubbles. As these dynamics occur simultaneously in bulk, resin modification towards sustainability easily affects all foam properties. Similarly, introducing tailored gradients in 3D is hardly possible. Therefore, foam parts with different properties are glued together, reducing the performance and inducing delamination and cracking risks (*21*–*23*).

**Additive manufacturing** (AM) of foams provides full control over the local architecture, including gradients and multiscale architectures that mimic natural materials. However, AM is mostly limited to open-cell foams and is relatively slow, since each cell consists of multiple layers. Therefore, only a few thousand cells are typically incorporated in a single piece (*24*–*26*). Recent AM processes that exploit bubbles or cell precursors in the extruded material, such as porous inks,(*27*, *28*) high-internal phase emulsions,(*29*, *30*) or leachable inks (*31*, *32*) attempt to address these limitations, but here the cell size is not locally tunable. Microfluidic chips were also used to generate controlled bubbles and convert these into highly controlled foams. However, microfluidic chips are prone to clogging as solidification starts on-ship, and exhibit a low throughput of typically up to ~1 mL/min (*4*, *15*, *33*–*36*).

A picture containing graphical user interface

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Figure 1: Principle of operation of direct bubble writing. (a) Ink and gas are flown through a core-shell nozzle, resulting in a directed stream of bubbles that is solidified in-situ upon impact. (b) Photograph of the x-y-z movable nozzle head while printing a 3D-disk. On top the tubing for air and resin and the optical fibers for UV light are visible; the vertical line is the bubble train. (c) Close-up of the cell structure within the foam.

**Direct bubble writing** is a novel fluidic technique for foam printing that was developed during the post-doctoral Rubicon fellowship of C.W. Visser. Here, a continuous stream of monodisperse bubbles is formed by coaxial injection of gas through the core of a core-shell nozzle and a liquid ink through the shell, as shown in Figure 1a. The bubbles, ejected through the air, are deposited onto a substrate while being exposed to UV-light to polymerize and solidify upon deposition. Each bubble solidifies as one cell. By mounting the nozzle and light sources onto a 3D robotic stage, foams are printed in programmable shapes (a cylinder is shown in Figure 1b) and with a well-defined cell size (Figure 1c). Increasing the gas pressure applied to the nozzle during printing results in a higher gas content in the foam, which translates into softer areas in the printed construct with larger cells. Switching the gas type between nitrogen and air results in a switch between closed-cell and open-cell sections of the foam, respectively, since air (oxygen) diffuses into the still-liquid resin and inhibits solidification of the cell walls. Advanced functional foams for pressure sensing, mechanical deformation, local chemical patterning, and shape memory were demonstrated (*16*, *17*), and preliminary work showed promise for filtration, acoustics, catalysis, and heat storage materials. The direct bubble writing platform was transferred from Harvard University to the University of Twente (UT), where a setup (unique in the world), a dedicated new lab, and IP rights are now in place.

However, direct bubble writing is not yet commercially applicable, since:

1. Current foams are soft and prone to cracking. Most applications require stronger, tougher materials.
2. Our current resins are based on poly(ethylene glycol)-diacrylate (PEG-DA) or thiol-ene chemistries, which are not bio-sourced, not recyclable, and poorly biodegradable.
3. Simultaneous control over individual foam properties is still out of reach. For example, when printing a foam with a low density, the tight control over the cell size is lost.

Diagram, text

Description automatically generatedThe next generation of foams must be stiffer, more robust, eco-friendlier, and have a reproducible architecture for a range of densities. Achieving this with trial-and-error is not sensible, as the control parameter space is enormous. For example, “simply” transitioning from PEG-DA resins to thiol-ene resins resulted in promising surfactant-free and solvent-free foam formulations, but required hundreds of trial-and-error formulation attempts (*16*, *17*). To accelerate development, we must rather *understand* the links between polymer properties, bubble generation and polymerization kinetics, and properties of the final foam part (e.g. mechanical), as indicated by the question marks in **Error! Reference source not found.**. Already, in MSc projects, bubble formation and impact were visualized with high-speed imaging and new nozzles and new chemistries were tested. However, these projects are too limited to make a leap in understanding that would diminish the iterations needed towards relevant foams. **The aims and objectives of the TOP-FOAM project are therefore to investigate the *physical mechanisms observed in direct bubble writing* (WP1) hand in hand with *selection and testing of new high-potential material formulations* (WP2). Based on this understanding, we will *demonstrate the first functional foam samples with application relevance* (WP3).** This next-generation of foams will integrate eco-friendliness, optical appearance, resolution and reproducibility, and locally tunable mechanical properties.

Figure 2: Structure of the TOP-FOAM project

Achieving these goalswould contribute to the **global UN sustainability goals 3** (good health and well-being, e.g. via personalized mattresses for hospital patients, recyclable shoe soles, or lower resin toxicity), **9** (industry and innovation), and a “clean world” [goals **6, 7, 12-15]** by minimizing environmental impact and preventing surfactants and solvents in foaming. For maximum impact, we decidedly need to achieve our aims *before* the DBW technology is scaled.

# 4.1.2 Proposed research

This far-reaching proposal is divided in three work packages, as shown in **Error! Reference source not found.** and described below:

**WP 1. Bubbles formation from core-shell nozzles**

Research since the 1970s has shown that core-shell nozzles can generate monodisperse bubbles for a wide range of liquids including water (*37*), tin, lead (*38*), copper (*39*), gold (*39*), and polymers (*7*, *39*, *40*). Figure 3f-h show useful closed-bubble regimes including monodisperse , multidisperse , and “snaking”, as observed if the control parameters are set appropriately (including gas pressure, liquid flow rate, fluid properties, and nozzle geometry). The phase diagram (Figure 4a) shows that these closed-bubble regimes only occur for narrow regions of the parameter space (*7*, *41*). In contrast, spraying (Fig. 3i) is observed if the control parameters are not optimized.

Up to now, the different ejection phases were classified in phase diagrams (*16*, *42*) and some phase transitions were successfully described by dimensional analysis (the green lines in Figure 4a, unpublished). However, key phase transitions between bubble regimes and spraying as displayed in blue, red, or black color in Fig. 3 and Fig. 4 are not yet understood. Therefore, trial-and-error remains the only option to identify relevant regimes for direct bubble writing and other applications (*38*, *43*, *44*). For example: for viscous resins we can obtain monodisperse bubbles, but for slightly different formulations or a different nozzle design or surfactant concentration we observe (useless) spraying. Finding the relevant regime without knowing the physical mechanism behind phase transitions is challenging, but even more problematic is that *we do not even know* whether useful bubbles with a particular resin are possible in the first place, which could lead in endless attempts.

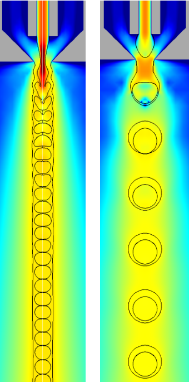
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Description automatically generated*Figure 3: Ejection regimes from core-shell nozzles. (a) Transparent core-shell nozzle. (b) Detail of the nozzle tip. (c-i) Images of gas/liquid ejection from the nozzle. Shown are: Dripping (c), build-up (d), pure-liquid jetting (e), snaking (f), bidisperse bubble ejection (g), monodisperse bubble ejection (h), and spraying (i). (j,k) show simulations in Gerris of the snaking and monodisperse regimes, respectively. Question marks: examples of non-understood phase transitions. Markers (on top) and question marks correspond to Figure 4a.*

**?**

**?**

**?**



j

k

**The objective of WP1 is: Explaining the unknown phase boundaries of monodisperse and polydisperse bubbling with experimental, theoretical, and numerical methods.** For example, the results will be used to predict stable bubbling at maximal gas/liquid ratios if exceptionally low-density foams are needed. From there, fine-tuning and optimization can start. Our preliminary results show promise for dimensional analysis, that we will extend aided by systematic experiments (WP1.1) and numerical flow solutions (WP2.1). The influence of surfactants and solvents will be explored in WP1.3.

Chart, scatter chart

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*Figure 4: (a) Phase diagram of the ejection regimes as a function of the gas pressures and liquid flow rate; markers as shown in figure 2.* ***The incidence of key regimes for direct bubble writing is unknown, and the focus of WP1. We will investigate the incidence of monodisperse bubbles (Red), snaking (Blue), and the transition to spraying at high pressure (Black).*** *Green lines: phase transitions that we recently captured in dimensionless terms. (b) Indicative high-speed images of the transition to spraying, showing that bubbles burst (time between images is 0.2 ms). (c) For a slightly lower pressure, the bubbles stay intact and a useful regime for direct bubble writing (bidisperse with one big and one small bubble) is observed (time between images is 0.4 ms).*

In **WP1.1**, we will visualize the key unknown regime transitions (indicated by “**?**” Figure 4a) with **high-speed imaging** to guide hypothesis of key underlying mechanisms. For example, preliminary high-speed imaging of the transition from multidisperse to spray (Figure 4b,c) suggest that bubble bursting might be the mechanism behind this transition, rather than immediate ejection of pure-liquid micro-droplets from the nozzle. With **3D-printed transparent nozzles** (preliminary results in Figure 4b,c), the flow inside the nozzle will be visualized to further strengthen this effort. **Dimensional analysis** based on these hypotheses will be experimentally validated by changing the nozzle geometry or liquid properties in relevant parts of the dimensionless control parameter space. The viscosity will by controlled by water-glycerol mixtures; the surface tension by using model surfactants (e.g., Tween 20) and solvents (e.g., isopropanol, ethanol), and the nozzle geometry by 3D-printed nozzle designs.

In **WP1.2**, we will **numerically model the local flow with Gerris**, a well-validated volume-of-fluid solver that we previously used for small-scale incompressible flow (*45*, *46*). A Gerris model of our system was already realized by an MSc student in our team, in collaboration with the Physics of Fluids group at UT (see Figure 3j,k). Knowledge of the flow field will reveal **details of the bubble formation mechanism** that would be difficult to obtain with optical methods, since optical access is blurred by rough and curved nozzle surfaces. Furthermore, numerical modeling allows testing of hypothesis via **direct scans of dimensionless control parameters**.

In **WP1.3, the influence of surfactants on bubble formation and breakup will be experimentally assessed** for different types and concentrations of both solvents (water, ethanol) and surfactants including Tween 20, Span 80, SDS, and PVA. Special attention will be paid to ultra-stabilizing surfactants (SAI 1035 BFS (*42*)) and biodegradable surfactants based on lecithin or lignin sulfonate. We will perform the analysis with one water-based and one non-aqueous monomer. In order to be knowledgeable about the state of the art in this field, we will start with a concise literature review on the role of surfactants in bubble breakup mechanisms. The experimental and literature results will be discussed with existing contacts and experts in the field (e.g., Prof. Emmanuel Villermaux).

**WP2: Resin formulation for designer foams**

DBW was demonstrated with resins based on poly(ethylene glycol)-diacrylate (PEG-DA) (*47*). With this approach, soft foams could be produced, but they remained brittle. Thiol-ene based resins later exhibited superior mechanical performance (*17*). Solvents and surfactants could also be eliminated. However, a broader range of compositions and structures is required to enable competitive mechanical performance, advanced functional properties, and a low environmental impact. As illustrated in Figure 2, we aim in **WP2** to broaden the scope of DBW by investigating a wider range of resin formulations and proposing novel chemistries. In **WP2.1**, we will first screen suitable resin formulations by varying the structure and composition of the monomers, the type of additives, and solvent content. Then we will proceed in **WP2.2** by enhancing our fundamental understanding of the photopolymerization mechanisms, and suggest novel polymerization strategies. Lastly, in **WP2.3** we will evaluate the materials properties and performance to produce advanced foam materials.

**WP2.1 Resin formulations.** We will start by screening and selecting a broad range of resin candidates, and evaluate their printing performance. *(Meth)acrylate-based poly(ethylene glycol*) macromonomers will first be investigated (figure 6a). Compounds featuring short chain lengths, and a higher functionality will be considered to promote a high crosslinking density, and stiffer materials. Introducing intermolecular hydrogen bonding and aromatic segments may be also beneficial to the mechanical properties. Comparable considerations will be applied to *thiol-ene* (click) systems (Figure 6b), which exhibit benefits in terms of biocompatibility and biodegradability (Mautner, 2013).

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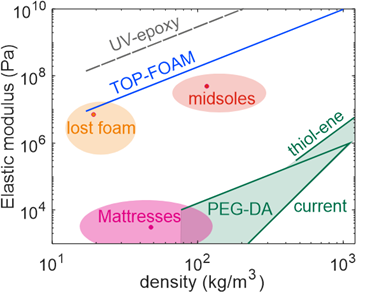
Figure 5 Selection of (a) (meth)acrylate and (b) thiol ene/yne monomers and oligomers for the preparation of 3D printed polymer foams.(Adapted from ref. (48).)

The availability of *biodegradable resins* for photopolymerization remains limited. We will therefore investigate novel sustainable approaches, and synthesize macromonomers and surfactants specifically designed for DBW. Candidates include PEG and poly(lactic acid) (PLA) triblock macromonomers with (meth)acrylate functionalities.(*49*) Other candidates are based on poly(caprolactone) (PCL), polyhydroxyalkanoates (PHA), PLA-poly(glycolic acid) copolymers (PLGA), lignin, and cellulose derivatives. Noteworthy, the SPC group has upscaled the synthesis methods for the preparation of biodegradable synthetic and biobased resins to the kilogram scale. Modification with olefins or thiol groups is also established. *Recyclable solutions* will be proposed, based on reversible polymerization strategies. One promising approach will be based for instance on PEG chains functionalized with furan, maleimide, and coumarin groups.

**WP2.2 Polymerization mechanism.** We will advance our existing polymerization models to quantify the reaction dynamics as a function of UV exposure time and intensity, and of formulation composition.(*50*) Our goal is to elucidate how the mechanical properties and the morphology of foams depend on the polymer chains structure and composition, and on the polymerization reaction mechanism and kinetics. Specifically, we will perform in depth molecular and structural characterization of the polymers using several techniques available in our groups (e.g., size exclusion chromatography (SEC), nuclear magnetic resonance (NMR), infrared spectroscopy, transmission electron microscopy (TEM)). Simulation tools will also be evaluated .(*51*)

Furthermore, *non-photopolymerization strategies* will be pursued. We have already fabricated bio-sourced and bio-degradable foams based on alginate (unpublished). *Cationic photopolymerization* was shown suitable for the 3D printing of epoxy materials (*52*). We will also explore the extension of DBW by utilizing already polymerized *thermoplastic* materials, which we have recently successfully processed via liquid jetting. Resins of particular interest include PLA, PET, PP, PA, epoxy resins,(*53*) and biopolymers.(*54*)(*55*)

**WP2.3 Foam properties**. Materials properties depend on both the polymer matrix characteristics and the structure of the cellular architecture.(*56*, *57*) Two main types of architecture are possible, *viz*. open and closed cell structures, with different control parameters involved.(*13*) Generally, 3D-foam structures will be obtained by micro-computed-tomography (micro-CT) scans. Mechanical testing (compressive and shear) will be performed on foam specimens. The SPC group is equipped to perform degradation studies, and (chemical) recycling evaluation.

**WP3: Manufacture of 3D samples for target applications**

In WP3, in collaboration with the consortium partners, we will optimize foam samples for industrial applications and perform tests according to industry standards. Specifically, we will offer tailored solutions for shoe midsoles (**WP3.1**), bedding materials (**WP3.2**), and sacrificial casting molds (**WP3.3**). Figure 8 shows the targets of our partners (colored dots). The green areas indicate that foam densities below 100 kg/m3 are in reach (*16*) and that thiol-ene-based resins enable improved mechanical properties (*17*). Using low-viscosity, UV-curable epoxy-based compositions that we recently developed, we aim to further increase foam strength by several orders of magnitude (grey dashed line) (*50*). Subsequently, Initial tests towards scale-up will be pursued (**WP3.4**). WP3 will enable rapid validation or rejection (go/no-go) for specific product-market combinations.

Figure 8: Elastic modulus and density ranges of current (green) and targeted (blue) 3D printed foams, and of an epoxy resin (grey). The dots indicate target specifications per application.

**WP3.1 Footwear (midsoles)**. Midsoles with locally tunable stiffness benefit comfort and performance. Therefore, customized graded structures will be investigated, building on adidas’ expertise on the design, testing and evaluation of 3D printed shoe midsoles (e.g., 4DFWD and Futurecraft 3D). *Test specimens*. We will employ both standard and company-specific testing methodologies to characterize foam samples. For instance, shock attenuation, absorbed energy loss, peak pressure, elongation at break (ideally > 250%), and stiffness will be evaluated according to method ASTM F 1614. Compressive cyclic loading will provide information on the foam hysteresis properties (ideally < 30% loss), and compression set. *Midsole prototypes.* 3D printed foam midsoles will be subject to comparable tests performed on the specimens. Additional testing on footwear performance will be conducted at adidas. Microstructural information will also be used to characterize deformations taking place, and establish structure-property relationships. *Chemical composition*. Chemical compositions developed in WP2 will be optimized towards footwear. Non-emission of hazardous compounds and compliance with company standards and local environmental regulations will be assessed by the University of Twente and at an independent certified laboratory.

**WP3.2 Bedding (mattress).** *Circularity* of mattresses is a key aim of Auping. Therefore, recyclable materials developed in WP2 will be implemented and evaluated. *Graded structures* will be manufactured to provide different level of firmness within one mattress, enabling smoother gradients that benefit comfort and health as well as personalization. The hardness, hysteresis and compression will be measured according to ISO standards 2439 and 1856. *Flame retardancy* will be evaluated to prevent hazardous mattresses. For instance, several phosphorus-containing polymers have been reported by the SPC group. Incorporation of such materials during foam printing, or use of phosphorus-containing additives, will be evaluated.

**WP3.3 Molding (lost foam casting).** The *structure* of the printed foam is critical to the molding process: The outer surface will be made of closed-cells that provide stiffness and a smooth surface. In contrast, the core of the foam will contain open-cells to promote metal flow. We will first prepare specimens exhibiting such mixed cell-structures. The *thermal properties* of foams for lost casting should meet 3 demands: (1) Shrinkage must be prevented upon exposure to high temperatures, ensuring casted parts with the desired dimensions. (2) After metal casting and pyrolysis ca. 1300-1400 °C, preference is for low ash rests (contaminants). (3) The back pressure created by the gas should remain sufficient to regulate the fill rate of the metal during casting. Foam decomposition should therefore promote formation of nontoxic volatiles. We will perform thermomechanical analysis by thermogravimetry analysis (TGA) and analyze decomposition products by TGA-FTIR. Pouring tests and lost foam casting tests will be conducted at Atlas-Copco.

**WP3.4 Scaling.** Initial studies of scaling towards multiple nozzles will be pursued together with FoamPrint3D. Systems that include 5 to 10 nozzles will be manufactured and tested, building on the results of WP1, Visser’s experience with scaling of nozzle systems, and existing knowledge of parallelized microfluidic bubble generators (*58*). These tests will further extend the high throughput of our core-shell nozzles, which is 1 to 2 orders of magnitudes higher than microfluidic chips for 3D foam printing (*4*). These initial results on parallelization will facilitate follow-up funding to develop systems with hundreds of nozzles, as necessary for market entry.

# Existing infrastructure

The **3D printer for direct bubble** writing is home-built by the **FM2 group** and placed in a separate **light-shielded** **room**, aiding formulation of light-sensitive inks. The printer integrates automated control of the liquid and gas flows (the option exists to control the gas pressure), motion of a 5-kg printhead at up to 0.5 m/s by an automated x-y-z stage, UV light focusing, and high-speed visualization. Safety measures including shielding of UV light and automated printer shut-off upon opening of the cabinet are in place. Advanced controls and measurement equipment of (LED) illumination in the UV- and visible spectra are available. Our new dedicated lab for fluid mechanics and materials science includes a rheometer, a 3D stereolithography printer (to print optically accessible nozzles), a surface tension meter, and multiple fume hoods. At the Thermal and Fluid engineering at UT, two micro-CT scanners and mechanical testing equipment are available.

State-of-the-art **chemical synthesis and polymerization/polymer modification setups** are available at the **SPC group**, including polymer characterization (SEC, DSC, TGA, etc.), SEM, and AFM. Molecular design and modifications can be characterized in detail to tune the polymerization kinetics using advanced NMR spectroscopy. Detailed biodegradation studies can be conducted by respiratory setups following European Standards. Chemical Recycling of the produced materials, i.e. depolymerization to the monomers, will be studied spectroscopically.

# Time plan and division of tasks

Table

Description automatically generatedThe Gantt chart shows the planning in time for the PhD student (in blue) and the Post-doc (red). A 4-year post-doc is planned as effective formulation is a complex tasks that requires PhD-level training. Company visits in Q3 and the user meetings will ensure early and tight connections to the industry partners. Although industry collaboration will be closest in WP3, all partners are eager to interact and contribute in all stages of the project.

# Consortium

# Composition of the research group

The research will be carried out by the FM2 group and the SPC group in close collaboration with all partners. **Work package 1** will be led by the FM2 group, where a PhD student will be trained. FM2 builds on a strong track record in fundamental fluid mechanics (*45*, *46*, *59*) and 3D printing (*60*–*63*); the numerical modelling will be performed with the well-validated Gerris or Basilisk software, in collaboration with Dr. Vatsal Sanjay at the Physics of Fluids group (UT). **Work package 2** will be led by the SCP group, where a post-doctoral researcher (PD) will be appointed and further trained as a formulation chemist (N.B.: such high level skills require PD expertise and training). **Work Package 3** will be led by the PD, in close collaboration with industry partners who are responsible for support in terms of discussion time, guidance, and testing. WP1,2,3 are closely connected and linked to other projects in FM2, so the PhD student and PD will join the weekly meeting of FM2. **Dr. Ir. Visser will formally lead the project**, building on academic research experience (since 2011, at the UT and at Harvard University) as well as industrial research experience (as research project leader at Tata steel 2006-2011 and as CSO of IamFluidics since 2018). The industry partners all have extensive experience with Academically-led R&D projects, have capacity to interact during the project, and have a strong desire to adopt improved foam manufacturing technologies.

# Potential users / User committee

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Company/Institute | Contact | Full contact details | Company size (empl) | User comm. yes/no | Support letter yes/no | Contribution  yes/no |
| Adidas Innovation | Mr. M. Kormann | Adi-Dassler-Strasse 1, 91074 Herzogenaurach, Germany Phone: +49 (0)9132 84 -5267 [marco.kormann@adidas](mailto:marco.kormann@adidas).com | >250 | Yes | Yes | Yes |
| Auping | Geert Doorlag | Maagdenburgstraat 26 7421 ZC Deventer, Netherlands  m +31 (0)6 51 30 27 91  [g.doorlag@auping.com](mailto:g.doorlag@auping.com) | >250 | Yes | Yes | Yes |
| Atlas-Copco, Airtec Division | Mr. E.Schepers | Boomsteenseweg 957  2610 Wilrijk, Belgium  Phone: +31 6 82349028  ernst.schepers@atlascopco.com | >250 | Yes | Yes | Yes |
| FoamPrint3D | Dr. Olivier J. Nguon | H.J. van Heekplein 80-23  7511 HN Enschede, Netherlands  +31 (0)63 866 2504  o.j.nguon@utwente.nl | <250 | Yes | Yes | No |

# Knowledge utilisation

# Utilisation plan

**Market potential**. TOP-FOAM focuses on markets that combine high added value with moderate throughput, including footwear, high-end bedding, and sacrificial molding. Subsequently, developments towards either larger markets (construction, automotive, packaging, furniture, and wind) or towards specialty foams (e.g. ,medical footwear, implants, or fire-retardant coatings) will be explored. The potential is huge, as the market for polymer foams is USD 84 billion (2018), growing at 6% per year (researchandmarkets.com).

**Per partner:** For *Adidas*, development and processability of sustainable materials is a key outcome of TOP-FOAM, as it will determine the commercial exploitation of the foam printing technology. The long-term goal is offering a tunable product that extends the advantages of existing foam materials (high performance, low density). For *Auping*, Insights from the project will be used for evaluating the technological feasibility of a print to order, tailor-made mattress. Furthermore, the knowledge will be used in our innovative sleep technology roadmap, specifically in soft robotics, with Somnox ([www.somnox.nl](http://www.somnox.nl)) being a first example. For *Atlas Copco,* the objective is to improve the Lost Foam casting process for intricate castings. Lost Foam casting is already a relatively clean casting process, but this development could prevent the high energy consuming particle foam process, preventing harmful emissions in the casting process, and create a huge flexibility in shaping geometries by removing the need for expensive tooling (molds). *FoamPrint3D* will develop the most promising by bridging the scaling and commercialization gap between the UT and industry.

**Utilization time** 🡪 **Commercial product in 2028 is our goal**. TOP-FOAM is part of a broader technology roadmap directed towards utilization of the DBW platform technology in multiple application areas. The following timeline was established together with industry partners:

|  |  |  |
| --- | --- | --- |
|  | **In TOP-FOAM project** | **In parallel** |
| Up to mid-2022 | Current preparation | NWO take-off 1, TTT voucher, industry funding secured (total: 140k€) |
| 2023 | Continued R&D 🡪 mechanically strong eco-friendly foams + team growth. | Raise funding for FoamPrint3D to explore markets and protect IP. |
| 2024 to 2025 | Continued R&D; product prototypes | Apply for additional applied grants |
| 2025 and 2026 | Reproducible process (TRL5), Explore parallelization (~10x) | Industry-grade systems, nozzles made of resistant materials (e.g. stainless steel). |
| 2027 and 2028 |  | Scale ~100x (pilot-scale), then 1000x (commercial) |

**Scaling** requirements were discussed with consortium partners. For example, printing 1 mattress per minute for Auping (a commercially feasible rate) would require ~1000 nozzles which seems reasonable, as scaling in inkjet printing or microfluidic chips was achieved for thousands of nozzles. For a substantial production in athletic footwear (adidas), scaling is limited to ~400 nozzles.

**How does TOP-FOAM address the problem?** TOP-FOAM will realize (1) a bubble generation system for tunable, eco-friendlier foams, (2) develop resins that combine mechanical strength with a minimal environmental footprint, (3) stack and polymerize these bubbles into foams with controlled shapes and locally controlled mechanical properties in one step, and (4) thereby establish DBW as a relevant platform for foams that are controlled at cell level. **TOP-FOAM will benefit the Twente area as a hub for pioneering research, development, and production of new advanced materials** (and thereby the Netherlands and the EU). For example, eco-friendly resins (WP2) will also benefit inkjet printing, stereolithography, and coating technologies. All our industry partners are actively innovating towards eco-friendly polymers. **TOP-FOAM will combine and advance high-quality academic and industrial know-how, and is therefore well-positioned in the OTP program**.

# Past performance

Highlights of our track record: the UT combines outstanding research with a #1 position in education (‘Beste Technische Universiteit 2021’, Keuzegids Hoger Onderwijs) and was awarded the Most Entrepreneurial University since 2014 (ScienceWorks). Dr. Ir. Visser has founded and spun out a company from the UT (IamFluidics B.V., now 22 people), holds three patents and has published in e.g. Nature, Advanced Materials, and Science Advances. Prof. Dr. F. Wurm has published more than 200 papers and his research was awarded several times, e.g. with the Reimund Stadler Award of the German Chemical Society (2016), the “Dozentenpreis des Fonds der deutschen chemischen Industrie” (2017) and Polymer Chemistry Lectureship (2019). Adidas drives innovating athletic footwear. Auping is the #1 mattress producer in the Netherlands, focusing on circularity. Atlas-Copco is leading developments in lost-foam casting. FoamPrint3D will bridge the step from UT (which is not positioned for technology scaling) to users (which are not focused on foam printing). We are very excited to bring together this new, technologically strong consortium of the UT and high-tech companies!

# Intellectual property

# Contracts

Research contract UT-Adidas (2021-2022). Any generic IP from this bilateral collaboration goes to UT with an option for Adidas to obtain a licence; athletic-footwear-specific IP goes to Adidas with free use by UT.

# Patents

WO2020033243A1 - Method of 3d printing a cellular solid. Umbrella patent that covers the DBW technology. Expectation is that any new IP is useful only under this patent. Owned by the UT.

# Positioning of the project proposal

# Uniqueness of the proposed project

**Technology**: The Direct Bubble Writing technology (lab, setup, expertise, and IP) is uniquely available at the UT.

**New research questions**: This project drives new fundamental understanding on high-throughput bubble formation from core-shell nozzles, an emerging topic in printing, biofabrication, flow visualization, and in-air microfluidics . Testing and optimizing our functionally graded foam parts with 104 to 106 well-defined unit cells will break new ground in materials science, where such materials are hardly in reach.

**Consortium**: A new consortium is formed. Connections to groups at UT (Prof. Lohse), Germany (Max Planck institute, Mainz), and France (Prof. Villermaux, Marseille) ensure access to relevant world-class knowledge.

**Utilization potential**: Direct bubble writing has the potential to revolutionize foam fabrication, providing a unique opportunity for research and commercialization.

# Embedding of the proposed project

DBW is a core research topic of the FM2 team. Cross-fertilization with Dr. Ir. Visser’s other research line (in-air microfluidics, including on-the-fly photopolymerization) is foreseen. Core research in SPC is the design of novel biodegradable polymer products. The TOP-Foam project expands the efforts of SPC on biobased and biodegradable 3D printing projects, currently running in the group.The project is aligned with the adidas bilateral project (see 6.1; follow-up project on the way), as well as valorization grants including a TTT voucher (50 k€, granted) and NWO Take-off Phase 1 (50 k€, granted). Funding for TOP-FOAM is not requested elsewhere.

# Financial planning

# Personnel positions

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *Position* | *Category1 (PhD student, Postdoc, NSS, OSS, PDEng)* | *FTE* | *Months* | *Rate (see FP)\** | | *Name (optional)* | *Bench fee*  *Yes/no* |
| 1. | PhD student | 1 | 48 | € | 253.328 |  | Y |
| 2. | Post-doc | 1 | 48 | € | 336.731 |  | Y |
| 3. | *NSS (technician)* | 0.25 | 60 | € | 75.364 | Ing. B. Siemerink | N |

# Material costs

* + 1. Project-related goods/services

Materials including optics, chemicals, nozzles, etc: €10.000/y/position (average of current foam-print PhD).

* + 1. Travel and accommodation costs for the requested personnel positions

Per PhD/PD year, €1.500 budget for 1 national + 1 international conference.

* + 1. Implementation costs

Open access publishing of 5 papers (€15.000 total).

9.2.4 Cleanroom costs

# Investments

Our high-speed camera goes up to 5000 frames per second which is too low to visualize the details of bubble pinch-off. A 20.000 fps camera is budgeted (€35.000). As the current printer is shared between several MSc and PhD students, an additional foam printer including pressure and flow control is included to ensure availability for this project (€75.000, similar to current printer in our lab).

# Knowledge utilisation

Filing of 2 patents is foreseen (€10.000).

# Internationalisation

The PhD student and PD will visit adidas (Germany) and Atlas-Copco (Belgium) sites in an early stage of the project to build their industrial and cultural awareness, and see the facilities for subsequent testing of foams. Additional travel will proceed as deemed most beneficial to achieve the project results.

# Money follows cooperation

# Contribution from users

|  |  |  |
| --- | --- | --- |
| ***User*** | ***Description*** | ***Value*** |
| Adidas | In cash (50%) + in-kind (50%) [providing materials, moulds, tests], | 100 000 € |
| Atlas-Copco | In cash + in-kind [providing materials, moulds, tests],<to be updated> | 30 000 € |
| Auping | In cash (50%) + in-kind (50%) [providing materials, tests], | 50 000 € |
| FoamPrint3D | In-kind | 10 000 € |

# Cost breakdown

|  |  |  |
| --- | --- | --- |
| Total project costs | € |  |
| Total contribution in cash | € |  |
| Total contribution in kind | € |  |
| Requested from NWO Domain AES (AES contribution) | € |  |

*The maximum number of pages (12 pages, or in the case of more than one research institute, 15 pages) ends here.\**

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# Selection of key publications of the research group

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# Expected Technology Readiness Level (TRL)

*State the current TRL and the expected TRL after the research has been completed. Tick one box in each case.\**

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| --- | --- | --- | --- |
| **Technology Readiness Level (TRL)** | Current | After | 1. basic principles observed  2. technology concept formulated  3. experimental proof of concept  4. technology validated in lab  5. technology validated in relevant environment [**process**]  6. technology demonstrated in relevant environment [**samples**]  7. system prototype demonstration in operational environment  8. system complete and qualified  9. actual system proven in operational environment |

# Abbreviations and acronyms

*Do not forget to submit the compulsory form “Declaration and signature by the main applicant” and all other compulsory annexes (letters of support, financial planning, data management section) through ISAAC together with this application form. Only fully and correctly submitted research questions will be taken into consideration.\**