Project Description – Project Proposals

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Fast dewetting and fluid-splitting phenomena between elastic surfaces

Project Description

1 State of the art and preliminary work

The interplay of elasticity of a surface with the wetting and dewetting by liquids is almost omnipresent in nature. The imbibition of liquids in porous elastic media, capillarity-driven coalescence between bendable hairs [2] and sheets [3,6] gives rise to an enormous variety of pattern formation mechanisms. Not only in the static situation but also under the action of dynamic wetting surface elasticity becomes relevant. This happens whenever the predominant forces achieve a delicate and volatile equilibrium, and drive the system towards an instability. In particular cases this even drives industrial manufacturing to the limits of technical capabilities.

Recent progress in printing and coating technologies relies on the steadily improved understanding of micrometer and millisecond scaled fluid dynamics on soft solid surfaces, namely for printing on porous, brittle, pressure-sensitive or elastic surfaces [3,13,E1-E5]. Current research of drop formation and drop impact phenomena have revealed new, highly dynamic aspects of long lasting hydrodynamic theory, and has found broad and fruitful fields of application in digital inkjet printing, in microfluidic lab-on-chip technology [3,12,E7]. The phenomena of ink splitting between rotating cylinders in coating and printing presses are less conspicuous, possibly due to the fact that it is all the more difficult to observe drops and liquid filaments. [E2,E6].

Fig. 1: A flexographic printing unit: the elastic printing plate (left) transfers printing ink (a solution of e.g. a graphic dye or an electrically conductive polymer) to a substrate sheet made of plastic foil or paper.

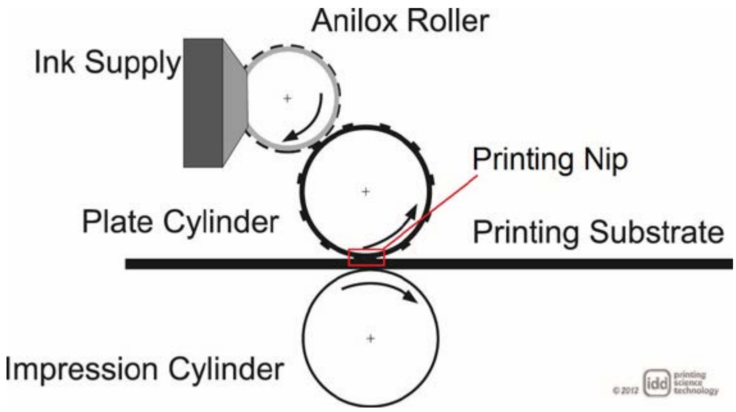

Fig. 2: Principal design of the flexographic printing unit

The very principle and kinematics of a printing press, namely of a flexographic unit, see figure 1, is depicted in figure 2. In order to reproduce a specific pattern, say, a DIN A4 sized page of a journal, with text and images, or a network of fine, electrically conductive lines for the front electrode of a solar cell, a photopolymer plate is used as the printing plate. The plate exhibits protruding and recessed parts on its surface – step hight is of order of 100 µm, lateral widths may vary between 10 µm and many centimeters – according to the desired printing pattern. The polymer plate is mounted on a rotating plate cylinder. In the printing unit the protruding parts, and only these, are wetted with the printing fluid. This is achieved by the anilox roller. A regular raster of gravure cells transfers the fluid from the ink supply to the plate. The protruding parts take fluid from the cells and transfer it to the printing substrate. Although this process bears interesting scientific questions by itself, is not the subject of our research proposal. Rather, we focus on the second solid-to-liquid contact event, the transfer of the fluid to the substrate. This is located in the printing nip, i.e. in the narrow wedges on both sides of the line where printing plate and substrate in mutual contact for a short instant.

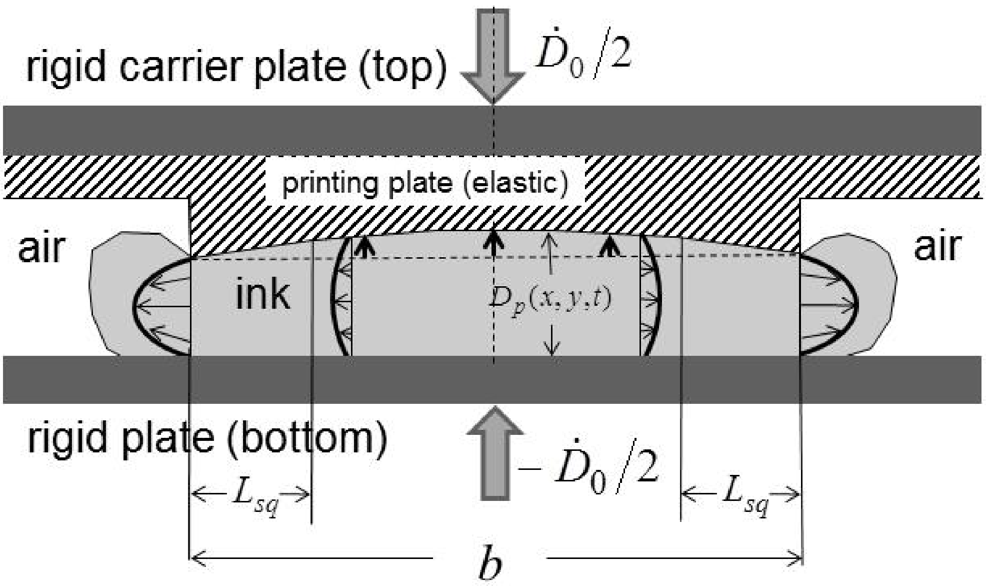

Fig. 2: Schematic view in the cross-section of the printing nip and the printing plate, with a protruding element of width *b*: by external compression (closing the gap with velocity dD_0/dt)

the fluid (ink) is squeezed out of the liquid layer, and the elastic printing plate is deformed, changing the thickness D_p of the liquid film.

Technical solutions are available in our lab for precise mechanical control of this key event, setting reproducible boundary conditions for fluid and wetting flows, and for the acting forces and pressures. However, the relevant short-time and small-scale physics of fluid transfer is not a matter of stiff machine design, but negotiated between the fluid and, specifically, the elastic surfaces alone. Recent efforts have demonstrated that there are still critical deficiencies in understanding and managing the process on the desired millisecond and micrometer scale.

Fluid flow, shear and pressure appear to be singular at the contact line of the cylinders, at least if one sticks to the assumption of unrestricted incompressibility and rigidity of the materials. Studies on ink splitting between rigid surfaces have revealed that there are quite different mechanisms which avoid the singularity [3]. The fluid meniscus forming between the cylinders is highly unstable, and air fingers can penetrate into the nip, causing a breakdown of pressure and shear forces, giving rise to collective pattern formation phenomena with on interestingly large length and time scales. Intimate relations to well-known instabilities such as those recognized by Saffman & Taylor [10], or by Rayleigh & Plateau [8] have been discovered. Moreover, a microscopic texture of the surfaces may provide nucleation points for gas bubbles and cavitation.

With the transition to elastic instead of rigid surfaces new phenomena occur. The surfaces become dynamic as well as soon as viscous and capillary forces in the liquid phase become comparable to the elastic forces in the solid. The elastic printing plate, the liquid layer, and the hard substrate could be considered as a three-layer stack which is in a delicate force equilibrium. The external pressure between the solid surfaces tends to squeeze the liquid out of the interspace. The motion of the liquid is governed by viscous and capillary forced and affects the shape of the printing plate by shifting volume. The key observation is that even if one assumes completely linear flow and elasticity equations for the liquid and the printing plate, respectively, the problem is essentially a non-linear one. Let D_p be the thickness of the liquid layer, the width of the film where viscous flows occurs under the pressure in the nip. The elastic deformation of the printing plate is linear in D_p and expresses the widening of the flow channel. The resulting fluid flow, however, is proportional to D_p^2, by Darcy's famous thin-film or Hagen and Poiseuille's pipe flow equation. This non-linearity cannot occur in the cuvette flow experiment of Saffman and Taylor, as D_p is static there.

There is evidence that the evolving flow and pattern formation phenomena are of principally different nature, and not only a variation of the phenomena readily studied on rigid surfaces. As e.g. the capillary rise of the fluid meniscus between two parallel elastic sheets as studied by Kim & Mahadevan [4], or between flexible hairs as considered by Bico, Roman et al. [1,9] is depending on the elastic properties of the wetted surfaces, also the excess volume V_{nip} of fluid that is conducted between two rotating cylinder surfaces (or between a cylinder and a planar substrate) shows such behavior. For hard surfaces the distance between the menisci at the incoming and the outgoing side of the nip, and therefore also the excess volume V_{nip}, are independent of the rotation velocity v_p, and entirely a function of the initial parameters, i.e. surface roughness and initial wetting state. Making the surfaces elastic the capillary rise of the liquid is changing, depending in the elastocapillary features. The same applies to rotating elastic cylinders. If one considers the excess volume V_{nip}, or, equivalently, the width L_{nip} of the wetted stripe before and after the printing nip, a clear dependence on the rotation velocity v_p is found. In a previous study lubrication theory has led us to the suggestion [E2] that $L_{nip} \sim Ca^{1/5}$ (which is from self-consistent perturbation theory and to be considered as preliminary). This is an important information for the design of flexographic printing units, as the excess V_{nip} of printing ink is squeezed out at the rim of printed elements, adding an undesired outline feature. Moreover, the scaling behavior of the finger instability is expected. For hard cylinders one observes that the finger width scales as $\lambda(v_p) \sim Ca^{-1/2}$, i.e. in the same manner as in the classical cuvette experiment of Saffman & Taylor [10]. For elastic surfaces we concluded that $\lambda(v_p) \sim L_{nip}^2\, Ca^{-1/2} \sim Ca^{-1/10}$ [E2] and that effect is dependent on an elastocapillary length $(\sigma d/K)^{1/2}$ (K is an elastic modulus of the substrate, d is thickness of the elastic component, and σ is the surface tension of the liquid). This implies that the finger instability that occurs in flexography changes much less as a function of printing velocity as compared to the original Saffman-Taylor experiments (which is unquestioned to apply for rigid, e.g. gravure cylinders). Interestingly, this feature has long been realized in flexographic practice, but apparently never been seriously fathomed.

The research at the Institute of Printing Science and Technology (IDD) is focused on the physical understanding and engineering of ink, or printing fluid, fluid flow and transport phenomena as related to the different printing techniques: offset lithography, gravure, screen and flexographic printing. Our paradigm is to make these fairly complex processes visible at any instant. This refers to direct observation of fluid flows, of fast wetting on solid surfaces, fluid splitting, and evaporation, film formation, and drying. As an engineering institute these studies are usually embedded in the development of manufacturing processes, in the integration of novel printing features in the production context of our industrial collaborators, and device construction. Beyond graphical arts target areas are functional printing, e.g. printable electronics, industrial joining and inline as well as offline process control. Finally, printing means the fast (i.e. in the range of several m/s) and controlled creation of complex wetting patterns with a wetting border line that is well-defined on a length scale of 10 µm, approximately.

The IDD has participated in various research projects on printed electronics [E1-E5], e.g. the leading edge research cluster initiated by the German federal department of research and technology, „Forum organic Electronics“, as well as industrial research projects with industry partners from printing and from chemical industries. In collaboration with the Karlsruhe Institute of Technology, the universities of Heidelberg and Cologne, the task here was to study the principal phenomena of solution-bases processing of ultra-thin (10-100 nm) layers or organic semiconductor materials by gravure, inkjet, and flexographic printing. The IDD contributed several new machine concepts: a lab-scale printing platform providing precise local and time-resolved monitoring and control of fluid transport on gravure and flexographic printing plates at elevated velocity. Other topics were printing and solvent evaporation under saturated vapor atmospheres, printing under the restricted conditions of a clean room, and inline optical control of liquid film dynamics and evaporation at elevated velocities.

The IDD participates in the Collaborative Research Center 1194 „Interaction between Transport and Wetting Processes“, where the enforced wetting of finely structured, mechanically rigid gravure cylinders, the filling and emptying of the surface features, the coalescence of the fluid drops in the gravure raster, and various hydrodynamic instabilities endowed with fluid splitting are studied. As a part of these studies novel optical techniques for time-resolved image-based observation of fluid flows in printing nip have been elaborated, adequate for the restricted environment in a rapidly rotation printing press. With this tool the formation of liquid films and bridges have been studied. Results have been presented in [E7]

In collaboration with the Max Planck Institute for Polymer Research, Mainz, and the Leibniz Institute of Polymer Research Dresden the effect tensides on the dynamic wetting of structured surfaces was studies. The particular focus was on the effect on the surface textures and gravure patterns on the fluid flows on the printing plate, and on the movement of the advancing wetting border line [E10].

Quantitative measurements of transport and pattern formation phenomena inside at in the vicinity of the nip of fast rotating printing units is one of the competences of the IDD, and it is one of the key concerns of inline quality control in industrial printing machine design. From the engineering point of view the challenges arise from the following features:

1. Optical access to the narrow wedge between cylinder and substrate or between to cylinders is extremely restricted.
2. Typical printing velocities of several m/s require high speed video recording and illumination techniques.
3. Mechanical vibration cannot be neglected on the µm length scale and may interfere with the fluid dynamics themselves as well as with the recording equipment.

Essentially, we found that three different inline observation methods are useful as adequate time and space resolution at reasonable signal-to-noise ratios are possible. Naturally, major amendments in machine design and construction are required:

1. Direct high-speed video recording using a moving optical shuttle which can pass the nip at printing velocity. The shuttle conducts the optical path from the participating surfaces and fluid layer to the video recording system. [E10]
2. Imaging color reflectometry (ICR): the observation of optical interference patterns within thin (1 nm – 3 µm) liquid layers, simultaneously using three (or more) different wavelengths of light (e.g. RGB). The fact of a color change in thin liquid films has been known for more than 80 years [5], and has been developed to standard inline measurement technique for thin film printing [E8], e.g. for purposes of printed electronics [E5, E6].
3. Digital scanning of dye patterns in direct succession of ink transfer and drying. This is an established technique and particularly useful in observing e.g. pattern formation phenomena under stationary conditions.

1.1 Project-related publications

1.1.1 Articles published by outlets with scientific quality assurance, book publications, and works accepted for publication but not yet published.

[E1] S. Ganz, H. M. Sauer, S. Weißenseel, J. Zembron, R. Tone, E. Dörsam, M. Schäfer, M. Schulz-Ruthenberg, *Printing and Processing Techniques* pp. 47-112, in: Organic and Printed Electronics, G. Nisato, D. Lupo, S. Ganz (eds.), Pan Stanford Publishing, Singapore 2016.

[E2] H. M. Sauer, D. Daume, E. Dörsam*, Lubrication theory of ink hydrodynamics in the flexographic printing nip,* J. Print Media Technol. Res. **4**, 163 (2015)

[E3] D. Spiehl, M. Häming, H. M. Sauer, K. Bonrad, E. Dörsam, *Engineering of Flexo- and Gravure-Printed Indium–Zinc-Oxide Semiconductor Layers for High-Performance Thin-Film Transistors*, IEEE Transactions on electron devices, **62** (9), 2871 (2015)

[E4] M. Wegener, D. Spiehl, H. M. Sauer, F. Mikschl, X. Liu, N. Kölpin, M. Schmidt, M. P. M. Jank, E. Dörsam, A. Roosen, *Flexographic printing of nanoparticulate tin-doped indium oxide nks on PET foils and glass substrates,* J. Mater. Sci. **51**, 4588 (2016), doi: 10.1007/s10853-016-9772-3

[E5] Raupp, S.; Daume, D.; Tegoglo, S.; Merklein, L.; Lemmer, U.; Hernandez-Sosa, G.; Sauer, H. M.; Dörsam, E; Scharfer, P.; Schabel, W.; *Slot Die Coated and Flexo-Printed Highly Efficient SMOLEDs*, Adv. Mat. Technol., **2**, 1600230 (2016)

[E6] N. Bornemann, H. M. Sauer, E. Dörsam, *Gravure Printed Ultra-Thin Layers of Small-Molecule Semiconductors on Glass,* J. Img. Sci. Tech. **55**, 040201 (2011)

[E7] H. M. Sauer, I. V. Roisman, E. Dörsam, C. Tropea, Colloids and Surfaces A (2018), https://doi.org/10.1016/j.colsurfa.2018.05.101

[E8] N. Bornemann, E. Dörsam, *A flatbed scanner for large-area thickness determination of ultra-thin layers in printed electronics,* Optics Express **21**, 21911 (2013), doi:10.1364/OE.21.021897

[E9] G. Hernandez-Sosa, N. Mechau, U. Lemmer, N. Bornemann, E. Dörsam, I. Ringle, M. Agari, *Rheological and Drying Considerations for Uniformly Gravure-Printed Layers towards Large-Area Flexible Organic Light-Emitting Diodes*, Adv. Func. Mat. **23**, 3164 (2013)

[E10] J. Schäfer, H. M. Sauer, E. Dörsam, *Direct observation of high speed fluid transfer phenomena in the nip of a gravure printing machine*, 45rd International Research Conference of iarigai, September 3 - 8, 2018, Warsaw, Poland

1.1.2 Other publications

none

1.1.3 Patents

1.1.3.1 Pending

none

1.1.3.2 Issued

none

2 Objectives and work programme

2.1 Anticipated total duration of the project

36 months

2.2 Objectives

In printing and packaging industries a profound technology change from oil- to water-based inks is taking place. Transparent management of energy and natural resources, recyclability of printed products have become the primary benchmarks in a highly competitive field of technology. With this development the backbone of mass printing, offset lithography, has been taken in the focus of tight criticism as is intimately committed to hydrophobic oil-based inks. Offset lithography depends on the wetting and dewetting of polar and non-polar liquids on the printed substrate. Inevitably, mineral oil residuals from the inks are not only suspected to slowly accumulate in the recyclable fraction of wasted printing products if not thorough and costly purification procedures are established on a large scale. Although this is readily the case in Western Europe and in Germany, specifically, it is far from being an international standard. More seriously, one has recognized the risk that even traces of such residuals could be responsible for irreversible harm to nature on the global scale, and to future human generations on the long run [14,15] As a technical alternative which avoids such problems flexographic printing is a quite promising. This technique is well-established in packaging technology, and is capable for printing speeds of up to 10 m/s. Printing of food packaging without the risk of migration and contamination by oil residuals, the handling of soft, porous, water-penetrable materials, the use of stretchable, extremely thin polymer foils, and of water-imbibing materials that abandon energy-consuming thermal curing, printed press production in countries without closed paper recycling systems are the key aspects. [14]

Nevertheless, flexography has still technical drawbacks at elevated printing velocities [15-20,E10]. Close inspection of the mechanics and ink dynamics in flexographic printing units as has been done in the labs of the applicant of this proposal reveals that the present limits are related to the peculiar fluid-mechanical interaction and fast dewetting phenomena between the printing ink and the soft polymeric printing plate which are presently not well understood. Due to the different web tensions in a flexographic printing machine, the elastic, polymer-based film to be printed is stretched differently in each printing nip. The dynamic wetting behavior varies and is particularly difficult to predict with water-based inks. Due to the increasing flow-induced pressure and shear forces in the printing nip at elevated velocities the deformation of the printing plate gains increasing effect on the microscopic viscous flow in the µm-sized ink layer between printing plate and substrate in the moment of ink splitting [21]. Specifically, the ink meniscus in the printing nip between liquid and soft solid phase is unstable and highly dynamic, causing textures and defects in the printed products. The elasto-capillary interaction between liquid and soft solid phase apparently plays a major role.

Our primary research objectives are as follows:

1. Direct observation of the fluid flow in a small portion of liquid located in the nip between a rotating cylinder (with elastic surface) and a planar substrate moving with the cylinder without slip. We would like to observe the local printing plate deformation in correlation to the fluid finger formation, and determine the quantitative relation between fluid and meniscus motion versus elastic plate compression, and to find out whether there is direct plate-to-substrate contact in the nip.
2. Same for a hard cylinder and a soft substrate. In this case it is planned to measure the substrate deformation in presence of the fluid flow in the nip, specifically in the vicinity of the wetting borders. This could be achieved by optical interferometry.
3. Fluid flows in the nip using periodic chessboard-patterned plates, with small lattice size of 0.1 to 1 mm. This is for Fast-Fourier-Transform-supplemented, pattern correlated video analysis, and more suited for comparison with FEM-simulated flow patterns (see below).
4. Understanding of the effect of different types of elasticity: compressible versus incompressible elastic materials, the role of viscoelasticity and viscoelastic relaxation.

Our research in this project could take advantage from numerical studies and simulations on the fluid flow, the meniscus dynamics and the elastic behavior of the surfaces. We therefore plan to cooperate with Dr. Kummer, Fluid Dynamics (FDY, group Prof. Oberlack), Technische Universität Darmstadt. An important aim of numerical simulation is to obtain insight into quantities (e.g. the elastic stress in the nip, the fluid flow profiles and pressure distribution) which we cannot observe directly. Moreover, the interaction of the fluid flow with textured elastic surfaces could be studied in advance of respective experiments. This could show the principal feasibility of elastic printing plates that autonomously switch flows of printing fluid or intruding air by their ability to adapt their shape, and to open or close pores between the protruding elements by fluid shear and pressure.

As the mechanical forces in the printing nip, particularly at large velocities (1…5 m/s), are large we shall restrict to mechanically robust elastic materials such as photopolymer resins or laser-ablated rubber-based elastomers as are widely used in industrial flexographic printing units.

2.3 Work programme incl. proposed research methods

The research on this project is subdivided into a number of work packages. The sequence given here does not imply that the work packages will be treated one after another. Rather, we prefer to start with each WP as early as possible. A large part of the technical work will be delegated to Bachelor and Master theses and to laboratory assistant students: construction, ordering parts and printing plates, programming, video recording and evaluation. The PhD student working on this project will mainly be concerned with the scientific tasks and with the exchange with the CRC 1194 and SPP projects, and with the supervision of the contributions from the students. In a later phase the results will be presented on conferences and published in peer-reviewed journals.

WP1: Design of the experimental setup for observation of the meniscus between a rotating cylinder and a planar substrate.
The setup will be based on the laboratory gravure printing machine GT+W superproofer. The device is already in use for high-speed video studies on fluid splitting in the gravure printing process (rigid surfaces) as presently performed in our CRC 1194 research project. A well-proven solution for the required shuttle concept, including an optical deflection system, has already been designed, and is in operation [E10]. For the present research project, we plan to construct a number of modified versions which are appropriate for the different kind of substrate materials, essentially for pieces of plastic foil or polymer blanket, and for PDMS layers which will be directly casted and cured on the shuttle, in different thicknesses.
The shuttle is also required to comply with further measurement equipment:

- direct laser ablation chamber for an optional structuring of the surface (e.g. cutting out a chessboard pattern),
- profilometric surface characterization in the confocal microscope
- contact angle measurements,
- direct integration in the stress-strain measurement system at our lab for characterization of elastic moduli

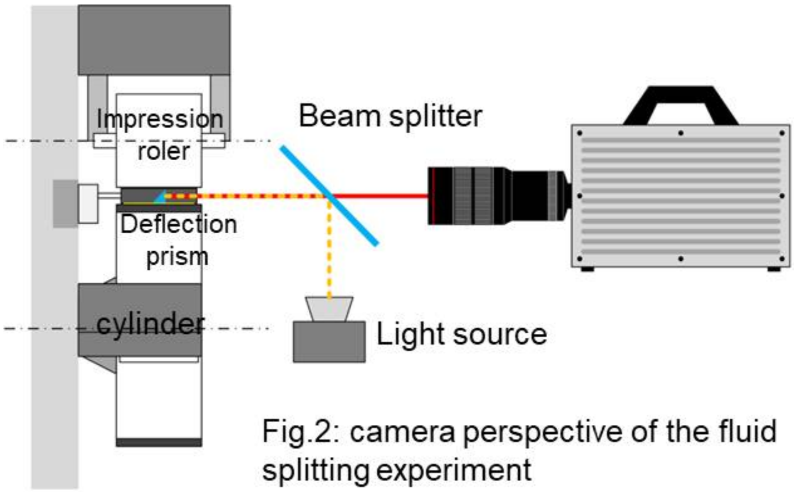

Fig. 3: Optical perspective of the video observation of the nip in the printing unit.

Fig. 4. Gravure-/Flexo- lab printing platform GT+W superproofer, with substrate shuttle and camera system.

Fig. 5: Substrate shuttle system with integrated defection prism for nip observation in a printing press, in vertical perspective (view onto the printing plate).

These shuttles will be used for the fluid transfer experiments in combination with hard as well as soft printing cylinders. The cylinder surfaces are designed as sleeves, i.e. thin metal or plastic tires which can be mounted on the base cylinder. These sleeves do not only serve as the counter-surface, but also for the injection of the studied fluid. For this purpose, the sleeves are furnished with small arrays of gravure cells. By their gravure volume these gravure cell arrays will dose a specific amount of fluid into the nip. The position of the arrays on the sleeve will be adjusted in such a way that the liquid is dosed into the nip just at the beginning of the experiment when the high-speed video record is started. Precise positioning and synchronization are essential for the success of such experiments and can be achieved with our equipment with an accuracy of 10 µm up to rotation/linear motion velocities of 5 m/s. As we intend to perform systematic experiments with a considerable number of varying parameters (velocity, fluid type and volume, substrate material etc.) a deliberate design of shuttle and printing plates is essential for steady and efficient progress of the later printing experiments.

WP 2: Optical, mechanical and fluid dynamical characterization of the materials used.

- Measuring the elastic and viscoelastic moduli of the soft printing substrate and of casted PDMS samples by strain-stress measurements (Zwick-Roell, static parameters), and by time-resolved mechanical response measurements by oscillatory mode viscosimetry (Malvern Kinexus). For comparison of the experiments with FEM simulations (cooperation with Dr. Kummer, Fluid Dynamics (FDY, group Prof. Oberlack) we require Young's modulus and the compressibility of the printing plate.
- Fluid viscosity and surface tension (although this is known for most liquids used)
- Contact angle measurements (retracting and preceding) on the elastic plate materials used.
- Optical refraction measurements (if needed)

WP 3: Synchronization of the experimental setup geometry, the printing plate and the fluid parameters with numerical simulation.

A primary objective of the proposed research project is to furnish the experimental findings, i.e. the video records, with a set of model equations which describe the coupled dynamics of the hydrodynamic (Newtonian) fluid flow in the printing liquid, of the elastic (or viscoelastic) substrate, and of the liquid air interface at the incoming and outgoing meniscus. Considering the capabilities of our experimental setup we are particularly interested in the following questions:

1. The shape and movement of the wetting border of the menisci on both sides of the nip, and the general structure of the fluid flow profile, specifically under steady motion (i.e. at constant v_p and in absence of any moving surface texture), and the formation of the viscous finger instability. We consider the suggested scaling laws mentioned in the section on the state of the art as a primary milestone as they are easy to check both in the experiment and by numerical study.
2. The formation of the viscous fingering instability on the outgoing nip side. The instability can easily be observed in our experiments, and be compared with numerical simulations. One of the main aspects here is a critical test of the proposed scaling of the finger width and length, as well as the width of the wetted area in the nip as a function of printing velocity and of substrate elasticity. Our preliminary model [E8] predicts a scaling behavior of several other physical parameters, e.g. the mechanical stress at the liquid-solid interfaces and the pressure amplitude in the nip, which are difficult to determine by experiment. A simulation of the model equation could well help to resolve these questions.
3. The elastic deformation of the substrate in the nip and at the wetting border lines. An interesting observation which is often claimed (though not proven) by flexographic printing industry is that printing fluid and the elastic surface form a self-regulated dynamical system which always drifts to a state where direct mechanical contact between the solid surfaces is avoided, and that even major perturbations or an inappropriate choice of printing parameters will be compensated to some extent. Although we are confident to obtain experimental evidence on these questions a simulation could shed additional light on the fluid dynamical details.
4. From some raw estimates on the pressure profile in the printing nip it seems plausible that cavitation could occur in the nip, a technically important point that we shall consider

in our experiments. Although we are aware that it is challenging to predict cavitation in a numerical study, a simulation could give evidence of any pressure peaks that may occur in the nip.

WP 4: Substrate shuttle and cylinder design for imaging color reflectometry (ICR) or laser-based interferometry in the nip.

In order to obtain time-resolved images of the thickness profile of the liquid layer between printing plate and substrate we shall use optical interference in the liquid film. This required to use materials for printing plate, fluid and substrate surface with a sufficiently distinct refractive index. The imaging color reflectometry (ICR) method [E9] will be useful in case that the refractive index of the soft substrate layer and the liquid is larger than ~0.2, and that the liquid film is enclosed between the very smooth surface of the printing cylinder and the soft substrate. In contrast to the measurement concept in WP1 where a highly reflective chromium surface is preferred, a black, non-reflective cylinder surface is required for the ICR and other interferometric techniques. Such a cylinder could be manufactured from Cr_2O_3 ceramics as is common industrial standard for anilox rollers in flexographic printing presses [E1,E2]. For liquid film thicknesses smaller than 5 µm the only moderately monochromic and coherent light from LED sources is adequate generate interference patterns, whereas interference effects with other transparent interfaces are avoided. This is our preferred experimental setup as the image is insensitive to any kind of mechanical vibration which will inevitably occur in a rapidly operating printing setup. The hard cylinder surface will also serve as the reference manifold for the determination of the distortion of the substrate surface. I.e. the measurement will simultaneously yield liquid layer thickness and the substrate deformation, and the respective temporal and lateral gradients.

WP 5: Systematic experimental exploration of the fluid flow under different condition.

The fluid transfer experiments will be performed varying materials and process parameters in such a way that all of the predominant dependencies are covered. These parameters are:

- viscosities (ethanol, diethylene glycol, glycerol) (1 … 500 mPas)
- printing velocity (0…5 m/s)
- Variation of the liquid quantities offered to the nip (by respective gravures on the hard surfaces). Typically, an individual gravure printing plate manufactured for this purpose will provide space for 5 to 10 independent gravure cell arrays for dosing.
- substrate materials (layer thickness, incompressible elastomers and compressible foam-type materials)
- Initial position of the elastic substrate versus the rigid cylinder surface.

WP 6: Evaluation of the video records and model definition.

We expect to obtain large amounts of high speed video material from the experiment. Evaluation of these videos, the identification of the menisci, of optical interference patterns will be done by existing Matlab algorithms (pattern recognition). The algorithms have to be readjusted with respect to length and time scales. The aim here is to reconstruct the shape of the interface between the printing fluid and the substrate, and to obtain a thickness profile of the liquid layer.

Beyond the liquid layer in the nip we are also interested in the thickness of possible prewetting layers or liquid residuals before and after the menisci.

In collaboration with Prof. Gambarian-Roisman, Technical Thermodynamics (TTD, group Prof. Stephan), TU Darmstadt, we shall also develop an analytical model. This model shall comprise a thin elastic layer the fluid flow shall be approximated in lubrication theory (as in [E2]), which is in direct mechanical contact with a rigid layer on one, and the elastic layer on the other interface. The new aspect is that we want to integrate the forces at the fluid menisci at the rims of the layer. Specifically, we want to model the squeeze flow of the liquid in relation to the deformation of the elastic layer by capillary forces, an aspect that has not been considered in [E2]. From this model, as well as from the numerical studies of Dr. Kummer, Fluid Dynamics (FDY, group Prof. Oberlack), we expect a better understanding of the apparent self-regulating abilities of the flexographic process. Industrial practice of flexography shows that the fluid transfer of this technique between printing plate and substrate is remarkably stable with respect to perturbations of the liquid layer, and to uncertain initial conditions of the printing process.

Time plan of the work packages:

WP	2019	2020				2021				2022		
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
1	X	X										
2		X	X	X								
3	X	X			X	X			X	X		
4			X	X	X	X						
5					X	X	X	X				
6							X	X	X	X	X	X

2.4 Data handling

The applicant disposes of a backup infrastructure for the internal archiving of scientific data. The data which are created in the experiment, namely the large quantities of video data, are saved at several server which are located at different places. The TU Darmstadt follows the policy to make research data available for the public on a long-term standard for this purpose, not only raw data but also meta data are collected and stored in order to make later reconstruction of results of research project possible.

As a participant of the CRC 1194 in the project Z-INF contributes, together with the computing center of the TU Darmstadt and the University- and federal library to the development of a concept for long-term usability and accessibility of research data. These concepts will be implemented into the information management facilities of the TU Darmstadt. With the end of 2018 a long-term archive system “TUdata” will be available at the TU Darmstadt.

2.5 Other information

2.5.1. Scientific integration and supervision of the PhD position applied for:

The PhD student who shall work on the proposed project will participate in the annual meetings of the SPP 2171. Collaboration with other projects within the SPP is planned as well, e.g. with

Dr. Kummer, Fluid Dynamics (FDY, group Prof. Oberlack) and Prof. Gambarian-Roisman, Technical Thermodynamics (TTD, group Prof. Stephan) at the TU Darmstadt.

Moreover, the PhD student will become an associated member of the CRC 1194 “Interaction of wetting and transport phenomena” at the TU Darmstadt. As an associated member he/she will be invited to the various meetings and colloquia, and share the scientific exchange between the CRC members.

2.6 Descriptions of proposed investigations involving experiments on humans, human materials or animals as well as dual use research of concern

Within the planed research project no experiments or studies will be performed on human beings or on materials taken from there.

No experiments with animals will be performed within the proposed research project.

2.7 Information on scientific and financial involvement of international cooperation partners

none

2.8 Information on scientific cooperation within SPP

We have made a cooperation appointment with Dr. Kummer, Fluid Dynamics (FDY, group Prof. Oberlack), TU Darmstadt, who intend a specific FEM simulation study on our fluid dynamics / wetting problem. And we have made a cooperation appointment with Prof. Gambarian-Roisman, Technical Thermodynamics (TTD, group Prof. Stephan), TU Darmstadt, for the development of an analytical model under consideration of lubrication theory.

3 Bibliography

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4 Requested modules/funds

4.1 Basic Module

4.1.1 Funding for Staff

- One position for a PhD student (N.N., M.Sc., TVTU-E13, 100 %) for 3 years (~198,000 €)
  Remark: PhD positions in mechanical engineering commonly are 100 % positions in salary group TVTU-E13 (TU Darmstadt salary group structure, equivalent to former BAT-II). The PhD positions are usually for a period of three years. The reason is that the M.Sc. degree in mechanical engineering, differently from physics or chemistry degrees, is the standard entry grade of engineers to full permanent positions in industry.
- Laboratory assistant position for a B.Sc. student (N.N., 20 hrs. per month) for 3 years (~8,280 €)

4.1.2 Direct Project Costs

Item	Cost
Flexographic printing plates (diameter: 20 cm, width: 10 cm) according to the customized layouts.	5.000,- €
Optical components for fluid imaging via printing shuttle	2.000,- €
30 x construction parts, each approx. 300 € for printing shuttles	9.000,- €
Adaptive optically transparent cylinder for mounting in the printing stage	2.000,- €
Total:	**18.000,- €**

4.1.2.1 Equipment up to Euro 10,000, Software and Consumables

none

4.1.2.2 Travel Expenses

Conferences within the EU: 2 (2,000 €),
Conferences outside the EU: 2 (4,000 €),
SPP project meetings and workshops within Germany: 6 (2 p.a.): (1,500 €)

4.1.2.3 Visiting Researchers (excluding Mercator Fellows)

none

4.1.2.4 Expenses for Laboratory Animals

none

4.1.2.5 Other Costs

none

4.1.2.6 Project-related publication expenses

Publishing costs for articles (3) in open access journals (~ 3,000 €)

4.1.3 Instrumentation

4.1.3.1 Equipment exceeding Euro 10,000

none

4.1.3.2 Major Instrumentation exceeding Euro 50,000

none

4.2 Module Temporary Position for Principle Investigator

none

4.3 Module Replacement Funding

none

4.4 Module Temporary Clinician Substitute

none

4.5 Module Mercator Fellows

none

4.6 Module Workshop Funding

none

4.7 Module Public Relations Funding

none

5 Project requirements

5.1 Employment status information

Dörsam, Edgar, university professor W3

5.2 First-time proposal data

none

5.3 Composition of the project group

Dr. rer. nat. Hans Martin Sauer, head of research group, permanent position
Julian Schäfer, M.Sc., PhD. student, CRC 1194 position
Christina Bodenstein, M.Sc., PhD. student, position funded by Federal Ministry of Research and Education
Thorsten Bitsch, M.Sc., PhD. student, position funded by Federal Ministry of Research and Education
Felix Braig, M.Sc., PhD. student, position funded by Federal Ministry of Research and Education
Tobias Hartwig, M.Sc., PhD. student, position funded by Federal Ministry of Research and Education

5.4 Cooperation with other researchers

5.4.1 Researchers with whom you have agreed to cooperate on this project

Dr. Florian Kummer, Fluid Dynamics (FDY, group Prof. Oberlack), Department of Mechanical Engineering, TU Darmstadt

Apl. Prof. Dr. T. Gambarian-Roisman, Technical Thermodynamics (TTD, group Prof. Stephan), Department of Mechanical Engineering, TU Darmstadt

5.4.2 Researchers with whom you have collaborated scientifically within the past three years

Prof. Dr. Cameron Tropea (TU Darmstadt, FB Mechanical Engineering, SLA)
Apl. Prof. Dr. Ilia V. Roisman (TU Darmstadt, FB Mechanical Engineering, SLA)
Prof. Dr. Steffen Hardt (TU Darmstadt, FB Mechanical Engineering, FG Nano- and Microfluidics)
Prof. Dr. Uli Lemmer (KIT, LTI)
Prof. Dr.-Ing. Dr. h. c. Wilhelm Schabel (KIT, TFT)
Prof. Dr. Annemarie Pucci (Uni Heidelberg, KIP)
Prof. Dr. Wolfram Jaegermann (TU Darmstadt, Surface Science)
Prof. Dr.-Ing. Wolfgang Kowalsky (TU Braunschweig, Electrical Engineering)
Prof. Dr. Uwe Bunz (Uni Heidelberg, OCI)
Prof. Dr. Harald Kolmar (TU Darmstadt, FB Chemie, FG General Biochemistry)
Prof. Dr. Markus Biesalski (TU Darmstadt, FB Chemistry, MAP)
Prof. Dr. Michael Reggelin (TU Darmstadt, FB Chemistry, AK Reggelin)
Prof. Dr. Kurt Kremer (Max Planck Institut für Polymerforschung Mainz, Polymer Theory)
Prof. Dr. Hans-Jürgen Butt (Max Planck Institut für Polymerforschung Mainz, POI)
Dr. Günter K. Auernhammer (Leibniz Institut für Polymerforschung Dresden)
Prof. Dr. Klaus Meerholz (Universität zu Köln, Institut für physikalische Chemie)
Prof. i. R. Dr. Andreas Roosen (Friedrich-Alexander-Universität Erlangen-Nürnberg, Material Science)

5.5 Scientific equipment

Experimental studies will be done in the climatized lab (23 °C, 50 % r.h., DIN 50014)

Measuring techniques:

- High speed video camera Photron FASTCAM SA4
- Optical lab for time resolved measurements and imaging (colorimetry, imaging color reflectometry, laser interferometry, shadowgraphy) with dark room, for detection of dynamical nm-/µm-range thickness changes in liquid layers
- Optical surface profilometer (confocal, white light, interferometric) Sensofar PLu Neox, for large-aperture confocal microscopy, which is required for mapping steep surface edges, e.g. the flanks of µm-/mm-scale surface textures created by gravure or laser-ablation
- Tactile surface profilometer Bruker XT
- Rheometer Malvern Kinexus lab+ (viscosity vs. temperature, shear rate, oscillatory measurement of viscoelastic moduli G', G'' of printing plate materials.)
- Contact angle / surface tension measurement system Krüss DSA100
- Buble pressure tensiometer Krüss BP100 (time-dependent surface tension in tenside solutions)
- Zwick-Roell shear-stress measurement system (measuring elastic moduli)

Printing equipment (as far as possibly useful for this project):

- Flexo lab printer FLP-21 (suited for A4-size shuttle-based printing)
- Prüfbau FT150 flexo and gravure lab printer for 6“ glass substrates and wafers
- Kammann screen printer K15Q SL (6“ format, suitable for optical shuttles)
- GT+W Superproofer (Shuttle based flexo-/gravure printer for printing sleeve technology, experimental platform for our CRC project)
- Flexo printability tester IGT F1
- Gravure printability tester IGT G1-5

- RK Printing Proofer 628
- KBA Metronic IR+fiber laser engraving systems F-9020 and K-1030 SHS (for printing plate texturing)
- Clean room for printing, available for the printing equipment mentioned above (for minimizing atmospheric particle contamination of surfaces and liquid films, as printing plates, substrates, and shuttles are beyond a size that could be handled in a glove box).

5.6 Project-relevant cooperation with commercial enterprises

none

5.7 Project-relevant participation in commercial enterprises

none

6 Additional information

none