

Prediction of gravure printed patterns using fluid splitting regime maps

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Short abstract

Gravure printing is a well-established, high-quality printing technology that often relies on the experience of the machine operator. A deeper understanding of the underlying fluid dynamics is crucial, particularly for emerging applications like biomedical printing and printed electronics. Using the publicly available HYPA-p image dataset, which comprises extensive experimental data from two gravure printing campaigns, we derive several regime maps of fluid splitting in gravure printing. These maps, a common tool in fluid mechanics but novel to gravure printing, correlate tonal value and printing velocity with the observed fluid splitting regime (point splitting, lamella splitting or transition regime). Our results demonstrate the influence of raster frequency, ink viscosity, machine type, ink type, substrate, and doctor blade angle on the resulting patterns. These regime maps provide a predictive tool for optimizing printing trials, conserving expert knowledge, and exploring unconventional process parameters for gravure printing. Future work will focus on leveraging the HYPA-p dataset even more by generating and analyzing all 152 possible regime maps.

Keywords: rotogravure, pattern formation, fluid splitting, regime maps

1. Introduction and background

Gravure printing is a well-established, high-quality printing technology, which is, e.g., used for periodicals, catalogues or packaging (Kipphan 2001). Due to the high costs for printing plate fabrication, this printing technique is especially well suited for long print runs (Johansson, Lundberg and Ryberg 2011). In daily printing practice, trained machine operators usually know from their experience which printing parameters to choose for a high-quality printing result. Hereby, the fluid dynamic processes behind the printing process often remain unknown since they are not directly relevant for this task. However, a comprehensive understanding of fluid dynamic processes during gravure printing is key for operating a printing machine in unusual process windows, for printing with unknown inks or substrates, for new applications like printed electronics or biomedical printing, or with a different definition of print quality.

Hydrodynamic pattern formation phenomena like viscous fingering (also known as ribbing) may occur during ink splitting and might act as an unwanted printing defect. According to Brumm et al. (2021), which extend the 2-class-definition from Hübner (1991), three types of ink splitting can occur in gravure printing: point splitting, lamella splitting, and the transition regime between both classes. In graphical printing, point splitting is usually favored, which produces a raster pattern of single dots. In functional printing and coating, closed homogeneous layers of ink are usually favored, which can be achieved in the lamella splitting regime. However, this regime also comes with viscous fingering instabilities (Saffman and Taylor 1958), which lead to finger-like patterns, i.e., unwanted inhomogeneities, in the printed layer. Recently, viscous fingering patterns have been used for the fabrication of biomimetic networks (Brumm et al. 2022a). A printing press is usually not operated in the process window of the transition regime, but this regime opens possibilities for new or enhanced applications for gravure printing. Fig. 1 shows examples for printed patterns of different fluid splitting classes.

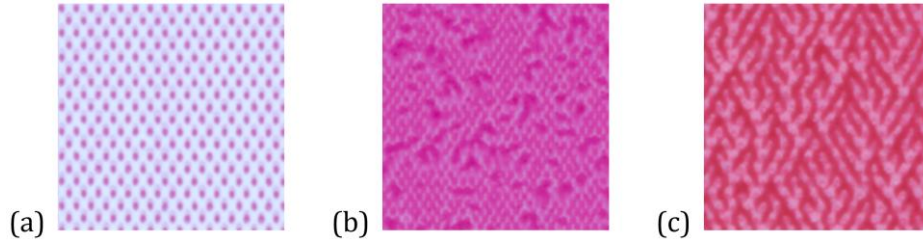


Figure 1: Examples for gravure printed patterns. (a) A dot pattern originates from the fluid splitting regime of point splitting, (b) dots are starting to transform to finger patterns within the transition regime, and (c) the complete image area is filled with finger patterns in the regime of lamella splitting. The size of each image is 260 x 260 pixels (2.75 x 2.75 mm). The images are part of the HYPA-p dataset (Rothmann-Brumm 2023a).

The aim of this work, which is part of the dissertation by Rothmann-Brumm (2024), is the creation of fluid splitting regime maps based on experimental data. Regime maps are a common tool in fluid mechanics for the characterization of fluid flow regimes (Shin and Kim 2022) but are novel to the field of gravure printing. The derived regime maps shall be used for the prediction of gravure printed patterns at a certain process window for future printing trials. Such a prediction is especially important when aiming at a certain fluid splitting regime and without having much experience with the used inks and substrates. Regime maps also enable the conservation of experience from trained printing personnel.

2. Materials and methods

The regime maps are based on digital images of gravure printed patterns (see chap. 2.1). These patterns need to be classified to assign each image to a certain fluid splitting regime (see chap. 2.2.). The classified images then serve for the creation of regime maps (see chap. 2.3).

2.1 Image data set

The publicly available HYPA-p image dataset (Rothmann-Brumm 2023a) is used as a basis for the creation of fluid splitting regime maps for gravure printing. HYPA-p comprises digitized printed patterns from two printing campaigns, one at Hochschule der Medien, Stuttgart, on a Bobst Rotomec MW 60-600/250 gravure web press, and the other one at Technical University of Darmstadt, Institute of Printing Science and Technology (IDD), on a Gallus RCS 330-HD modular web press with an installed gravure printing unit. The varied parameters of both campaigns are ink viscosity, ink type, substrate type, printing velocity, doctor blade angle, tonal value and raster frequency of the electromechanically engraved printing form, electrostatic assist (ESA) and type of printing machine.

To be able to compare the printing results of the two different printing presses, particular care was taken during the production of the printing forms. Both printing forms were manufactured using the same “job ticket” for the engraving machine. The job ticket defines all parameters necessary for electromechanical engraving, including the printing layout, the raster frequencies, the raster angle, the cell sizes, the tonal values, and the gradation curves. Only the widths and circumferences of the printing forms differ due to the requirements of the printing presses. The cylinders for the Bobst and the Gallus machine have a width of 700 mm and 370 mm, respectively, and a circumference of 700 mm and 457.20 mm, respectively. We therefore assume that the cell volumes for both printing forms are nearly identical, apart from manufacturing tolerances.

The printing experiments are named with identification numbers, e.g., B3-01 or G1-01. B stands for the Bobst machine and G for the Gallus machine. The printing campaign in Stuttgart is described in Brumm et al. (2022b). A description of the campaign in Darmstadt and further details can be found in Rothmann-Brumm (2024).

2.2 Pattern classification

Three percent of the 890,880 images of the HYPA-p dataset were manually classified by a human observer into three classes of fluid splitting, namely point splitting, lamella splitting, and transition regime, according to the approach as presented in Brumm et al. (2021) and Rothmann-Brumm and Dörsam (2023). All other images were classified using deep learning models, i.e., convolutional neural networks, which were trained on the results of the human classification (Rothmann-Brumm 2023b). Finally, the manually classified images were re-classified using the trained deep learning models to ensure consistency within the classification.

2.3 Creation of regime maps

The regime maps are created based on classified images of gravure printed patterns (Rothmann-Brumm and Dörsam 2023) and using MATLAB-code from Rothmann-Brumm (2023c). Each regime map shows the location of the point splitting regime ①, the transition regime ②, and the lamella splitting regime ③. The x- and y-axis of the regime maps show tonal value in percent and printing velocity in m/min, respectively. From the HYPA-p dataset, 152 regime maps can be derived in total. We present only a selected number of regime maps within this work.

3. Results and discussion

In this chapter we present the influence of raster frequency, ink viscosity and machine type, ink type, substrate, and doctor blade angle on the appearance of the fluid splitting regime maps. We present pairs of regime maps, which are based on printing experiments where only the mentioned parameters differ, and all other printing parameters are the same to ensure comparability.

3.1 Influence of raster frequency

Fig. 2 shows two regime maps from printing experiments with identification number B3-01 from the HYPA-p dataset with different raster frequencies of the printing form: 60 lines/cm (Fig. 2a) and 100 lines/cm (Fig. 2b). Both regime maps show a similar trend of the location of the regime borders. With increasing tonal value, which correlates with the transferred ink volume, the printed patterns transition from point splitting ① over the transition regime ② to lamella splitting ③. This means that at low tonal values, dot patterns are created, and at high tonal values, finger patterns or homogeneous layers of ink are printed. With increasing printing velocities, the regime borders of the transition regime increase towards higher tonal values. This means that at higher printing velocities we rather have dot patterns instead of finger patterns. The shape of the transition regime looks similar for both raster frequencies but is broader for the raster frequency of 100 lines/cm (Fig. 2b). A broader transition regime is undesirable for applications requiring precise control of the printing pattern, but advantageous for exploring novel applications within this regime.

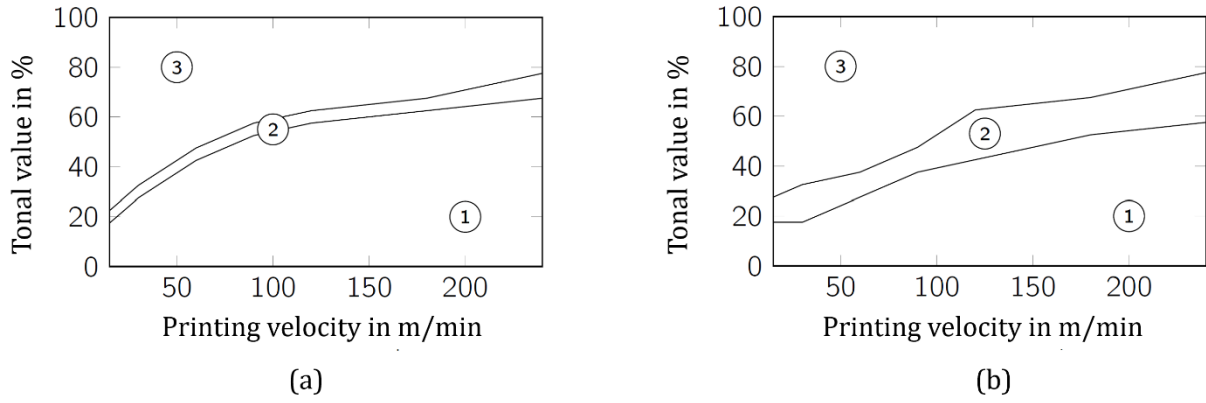


Figure 2: Regime maps from experiment B3-01 for different raster frequencies (a) 60 lines/cm and (b) 100 lines/cm. ① - Point splitting ② - Transition regime ③ - Lamella splitting. Adapted from Rothmann-Brumm (2024).

3.2 Influence of ink viscosity and machine type

In Fig. 3, we show four regime maps combined in two diagrams. Fig. 3a shows two combined regime maps for the two printing machines from Bobst and Gallus (see chap. 2.1) for a printing ink with higher viscosity; Fig. 3b shows the results for a printing ink with lower viscosity. The higher viscous ink has an efflux time of 82 s in a 4 mm ISO flow cup according to DIN EN ISO 2431 and a shear-thinning behavior with a shear viscosity in the range of 11.85 Pas to 0.05 Pas at 20 °C for shear rates of 0.1 s⁻¹ and 5000 s⁻¹, respectively. The lower viscous ink has an efflux time of 17 s, measured in the same flow cup, and a shear-thinning behavior with a shear viscosity in the range of 0.06 Pas to 0.01 Pas at 20 °C for shear rates of 0.1 s⁻¹ and 5000 s⁻¹, respectively. The lower viscous ink is a diluted version of the higher viscous ink. The experiments on the Bobst machine range from 15 to 240 m/min and on the Gallus machine from 5 m/min to 120 m/min. The transition regime borders for Bobst and Gallus only slightly differ in the overlapping printing velocity range from 15 to 120 m/min. This implies that pattern formation phenomena follow universal rules even on different types of printing machines. Regarding the experiments with higher and lower viscosity inks, see Fig. 3a and Fig. 3b, respectively, we have large deviations. The transition regime is shifted towards lower tonal values for the lower viscous ink. This implies that lower viscous inks are better suited for achieving homogeneous layers in the lamella splitting regime. However, this regime is susceptible to viscous fingering instabilities leading to surface inhomogeneities. Besides, the transition regime is broader for lower viscous inks.

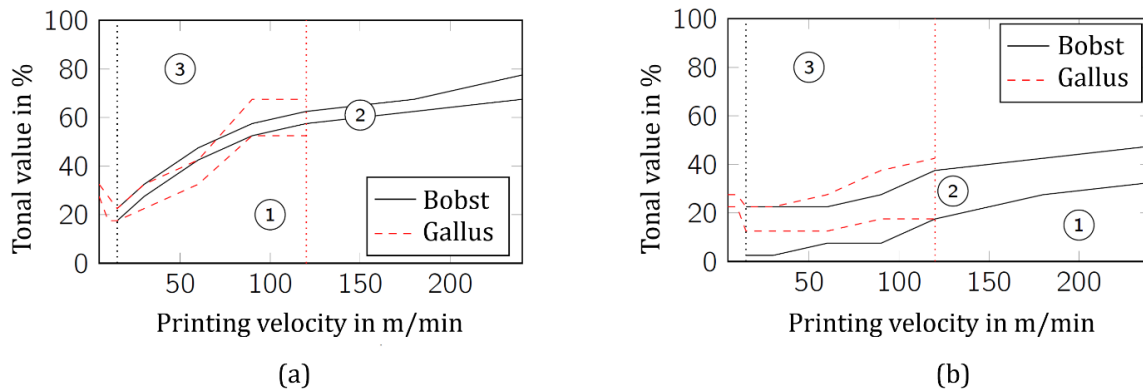


Figure 3: Combined regime maps (2 in 1) for different machine types and different ink viscosities. (a) Higher viscosity ink from experiments B3-01 (Bobst machine) and G1-01 (Gallus machine) and (b) lower viscosity ink from experiments B3-05 and G1-02. ① - Point splitting ② - Transition regime ③ - Lamella splitting. Adapted from Rothmann-Brumm (2024).

3.3 Influence of ink type

Fig. 4 shows two regime maps for different ink types, one solvent-based ink (Fig. 4a) and one water-based ink (Fig. 4b).

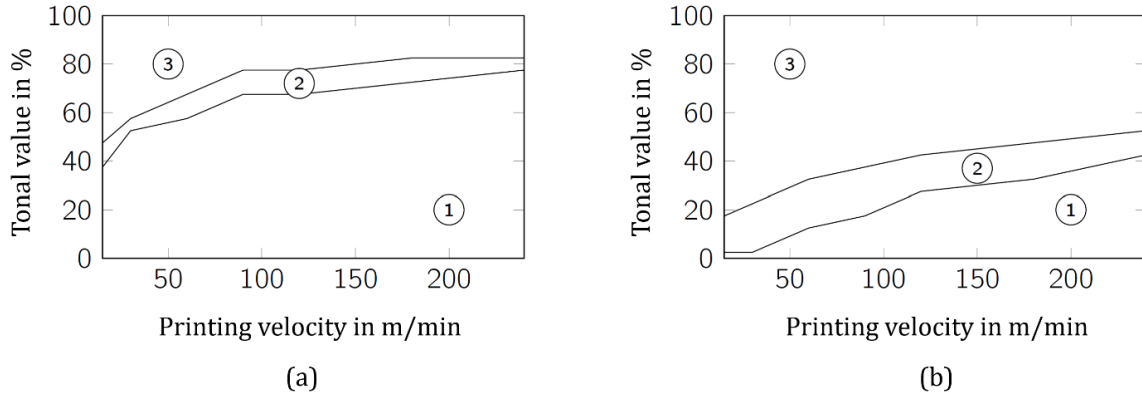


Figure 4: Regime maps for different ink types. (a) Experiment B2-02 with solvent-based ink and (b) experiment B3-02 with water-based ink. ① - Point splitting ② - Transition regime ③ - Lamella splitting. Adapted from Rothmann-Brumm (2024).

The transition regime is clearly shifted to lower tonal values for the water-based ink. This means that the regime map for the solvent-based ink is dominated by the point splitting regime whereas the regime map for the water-based ink is dominated by the lamella splitting regime, which aims at producing homogeneous layers of printed ink but also comes with finger patterns due to viscous fingering.

3.4 Influence of substrate

The influence of the substrate on the regime maps is depicted in Fig. 5. The regime map for a supercalendered paper is presented in Fig. 5a and the regime map for a one-side coated paper is shown in Fig. 5b. The regime borders of the transition regime are only slightly different, indicating that the type of paper substrate does not heavily influence the fluid dynamics of the ink splitting process.

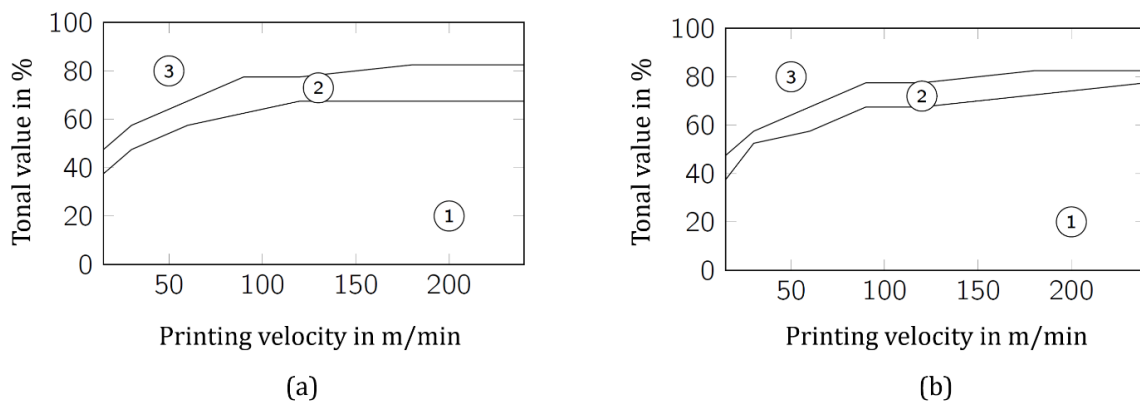


Figure 5: Regime maps for different substrates. (a) Experiment B2-01 with supercalendered paper and (b) experiment B2-01 with one-side coated paper. ① - Point splitting ② - Transition regime ③ - Lamella splitting. Adapted from Rothmann-Brumm (2024).

3.5 Influence of doctor blade angle

Fig. 6 indicates that the doctor blade angle does not have a strong impact on the fluid splitting regime map. The regime maps for a doctor blade angle of 60° and 48° are shown in Fig. 6a and Fig. 6b, respectively.

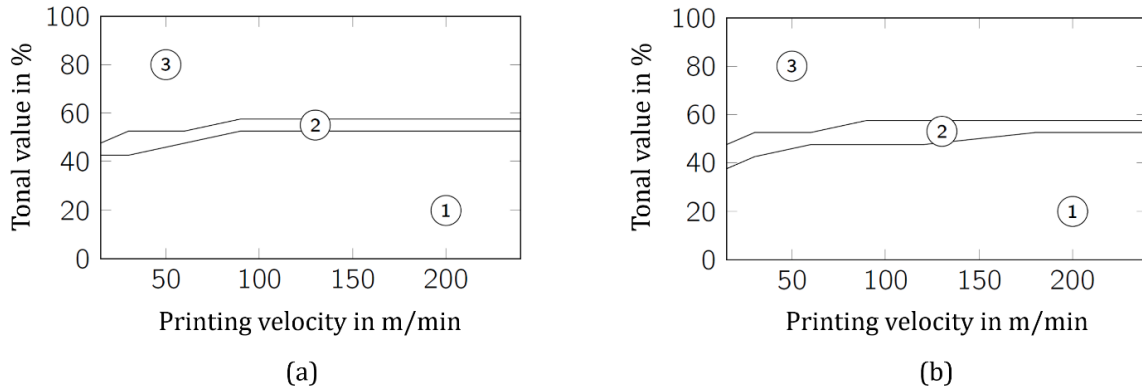


Figure 6: Regime maps for different doctor blade angles. (a) Experiment B1-04 with 60° doctor blade angle and (b) experiment B1-05 with 48° doctor blade angle. ① - Point splitting ② - Transition regime ③ - Lamella splitting. Adapted from Rothmann-Brumm (2024).

At higher amounts of transferred ink, i.e., at higher tonal values, the ink splitting class shifts from the point splitting regime over the transition regime to the lamella splitting regime. Although the doctor blade angle influences the filling level of the gravure cells, it seems not to have a major impact on the transferred amount of ink, which in turn influences the fluid splitting class of the printed patterns.

4. Conclusions and outlook

In this work, we presented 12 fluid splitting regime maps for gravure printing based on experimental data from the HYPA-p dataset. The regime maps reveal that printing velocity and tonal value have a strong impact on fluid splitting. We used pairwise comparison to investigate the influence of raster frequency, ink viscosity and machine type, ink type, substrate, and doctor blade angle on the regime maps. We found that ink viscosity and ink type have the strongest impact. Our derived regime maps can be used for the prediction of printed patterns in future printing campaigns. The next stage of research will be dedicated to the systematic exploration of the HYPA-p dataset by generating and analyzing all 152 possible regime maps. The regime maps contribute to a deeper understanding of pattern formation phenomena in gravure printing. This work demonstrates the broader applicability of regime mapping as a powerful tool for understanding and optimizing fluid dynamics in various printing technologies.

Acknowledgements

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