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Process Development for a High-Throughput Fine Line Metallization Approach Based on Dispensing Technology

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Abstract

In order to enhance prosperous dispensing technology towards an industrial application, besides a continuous process development, especially throughput rate has to be increased. In this study, paste rheology of two different dispensing pastes was transferred to CFD-simulation (CFD: Computational Fluid Dynamics) to investigate different nozzle geometries and print head designs. In the following, a single nozzle dispensing setup was used to verify simulative values by comparing them with those obtained from experimental investigations. Consequently, the single nozzle process was scaled to a parallel application, where a homogeneous pressure and flow distribution within the print head turned out to be crucial to achieve a homogeneous mass flow at all nozzles. In various iteration steps, the influence of fabrication tolerances especially concerning the nozzle geometry was isolated and print head designs were optimized based on CFD towards maximum process stability. Based on these results, a novel 10 nozzle fine line dispensing unit was designed and fabricated. Finally, successful cell production with resulting finger widths of less than 35 µm could be demonstrated using the novel prototype.

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Keywords:metallization, paste rheology, CFD-simulation, dispensing, crystalline silicon solar cells

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1. Introduction

The dispensing technology, as described by Chen et al. [1] and Specht et al. [2], offers a non-impact, high-throughput, single-step metallization process, significantly reducing finger width and thus shading losses. Dispensing pastes are derived from screen printing paste development and resulting finger geometries can be varied in a wide range by adapting paste rheology as described in previous studies [3, 4]. As opposed to screen printing approaches, finger homogeneity significantly increases while mesh marks do not occur at all. Lohmüller et al. [5] presented a record cell efficiency of 20.6 % on 125 x 125mm² FZ p-type material using dispensing technology on MWT-PERC (Metal Wrap Through – Passivated Emitter and Rear Cell) solar cells, featuring a selective emitter structure. In the meantime, finger widths were gradually reduced from a minimum of 65 µm in 2010 to around 43 µm in 2012 [3].

In order to compete with industrially established metallization processes, throughput rates have to be increased which requires a parallel dispensing of multiple fingers. Various approaches concerning this topic have been reported in the past [6, 7]. Chen et al. [1] introduced a parallel dispensing unit incorporating several n-scrypt smartpumps [8] in parallel, each feeding two or three nozzles, respectively. With this approach, contact lines of only 50 µm width were reached at traverse speeds of up to 500 mms^{-1} [9]. However, the amount of necessary contact fingers on the front side increases with decreasing line width since sufficient grid conductivity has to be provided. Thus, solutions have to be found that enable a flexible fabrication of one nozzle per contact finger with a pitch between two nozzles of down to 1.5 mm.

This paper reports on the progress in a present research project focusing on the advancement of the dispensing technology towards an industrial application using a parallel dispensing unit.

2. Experimental

In this study, paste rheology of two different dispensing pastes was transferred to CFD-simulation to support the development of multi-nozzle printing units.

As already stated in previous studies [3, 4], dispensing pastes are Non-Newtonian fluids containing a high fraction of solid particles, thus leading to a pronounced yield stress phenomenon, including a typical plug flow behavior in laminar pipe flows [10] apparent in a dispensing nozzle. A model describing this typical plastic behavior of metal pastes was introduced by Herschel and Bulkley [11] in 1926.

$$\tau(\dot{\gamma}) = \tau_y + c\dot{\gamma}^n \quad (1)$$

It describes the relation between shear stress τ and shear strain rate $\dot{\gamma}$ with specific parameters for yield stress τ_y, consistency c and power law index n, respectively. Characteristic values for yield stress τ_y of both pastes could be determined using an *Anton Paar MCR 502* rotational rheometer in stress controlled mode, equipped with a parallel plate configuration (D = 25mm). Reproducible yield stress values for high viscous printing pastes were obtained by increasing shear stress τ gradually until paste begins to yield, as described in detail by Mezger [12].

Maximum process shear rates in dispensing $\dot{\gamma}_w$ can be obtained applying the Weissenberg-Rabinowitsch equation for Non-Newtonian capillary flows [13].

$$\dot{\gamma}_w(Q) = \frac{8Q}{\pi D^3}\left(3 + \frac{1}{n}\right) \quad (2)$$

With an industrial process speed of around $v = 200mms^{-1}$, a cross sectional area of the desired contact finger of A_{Finger} = 1000µm² results in a volume flow of Q = 0.2 µls^{-1} per nozzle. Assuming a nozzle diameter of D = 60µm, shear strain rates of $\dot{\gamma}_w = 11.000\ s^{-1}$ are reached at the nozzle walls.

Due to a limited applicability of rotational rheometers to these high shear strain rates, flow curves were recorded using a capillary viscosimeter of type *Goettfert Rheograph 6000*. The influence of entrance pressure drops during capillary flow were minimized by choosing a suitable capillary with a very high ratio of length to diameter (L/D = 20 mm/0.5 mm) as proposed by Macosko [13].

In the following, rheological parameters as well as paste density measurements using a *Byk-Gardner 50ml* pycnometer were implemented into *Ansys 13* forming a paste model with respect to typical Non-Newtonian shear flow behavior and yield stress. Furthermore, a 3D model of the single nozzle dispensing geometry was imported from a commercial CAD program including cartridge and dispensing nozzle. After verification of simulative results, several nozzle layouts were compared regarding pressure distribution and flow patterns and finally transferred to multi nozzle print head designs.

3. Results

3.1. Rheological Investigations and CFD-model

In order to simulate Non-Newtonian flow behavior of incorporated Ag-pastes, shear rheological characteristics of two different pastes were recorded. Paste A has similar flow behavior to a commercial screen printing paste. As described in previous studies [3, 4], aspect ratios (height : width) of around $AR = 0.44$ are reached, with parasitic paste spreading still apparent after dispensing. Alternatively, Paste B has a significantly higher stiffness. Due to its increased yield stress (Fig.1), paste spreading can be abandoned completely and aspect ratios of resulting contact geometries build up to $AR = 0.86$. Subsequently, high shear rate flow measurements were conducted by means of capillary viscosimetry (Fig.2) in order to obtain remaining fit parameters of the Herschel-Bulkley equation (1) around the working point of the dispensing process.

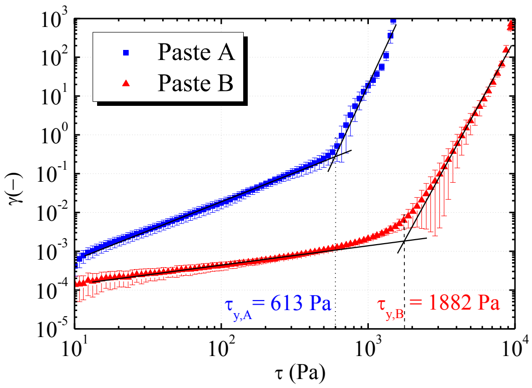

Fig.1. Determination of characteristic yield stress τ_y of both dispensing pastes using the two tangent-method, as proposed by Mezger [12].

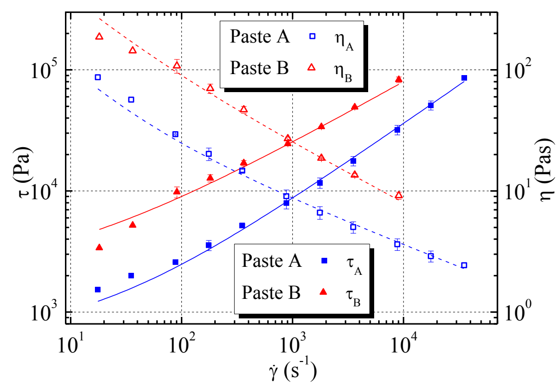

Fig.2. Weissenberg-Rabinowitsch corrected high shear rate flow curve, recorded by means of capillary viscosimetry equipped with a L/D = 20mm/0.5 mm measuring capillary.

As expected, Paste B shows also significantly higher values for shear viscosity $\eta(\dot{\gamma})$ which can be seen comparing the two values of the consistency index c with one another. All fitting parameters according to Herschel-Bulkley are summarized in Table 1 and were used together with density measurements to set up a CFD paste model in the following. Please note that all rheological parameters of printing pastes were measured at standard test conditions (T = 20°C) and may vary due to different environmental and storage conditions as well as aging effects.

Table 1
Herschel Bulkley parameters obtained from rational and capillary rheometry.

Paste	Yield stress τ_y (Pa)	Consistency c (Pa·s^n)	Power law index n (-)
A	*613*	*98*	*0.64*
B	*1882*	*650*	*0.52*

3.2. Experimental Verification

In a first step, the implemented paste model was verified using a simple time pressure dispensing setup, similar to the system applied in previous studies. For this reason, a first simulation was set up calculating pressure data as a function of applied flow rate Q using a flow-geometry obtained from original CAD-data of the dispensing system. These calculated values were then compared with flow measurements (Fig.3) during experimentation. In order to overcome hysteresis during start and stop caused by compressible air in the cartridge, mass flow rates were determined for two time intervals and subtracted afterwards. Furthermore, deviations within the mass flow measurements were minimized by repeating this procedure five times, respectively, for every step increase in dispensing pressure.

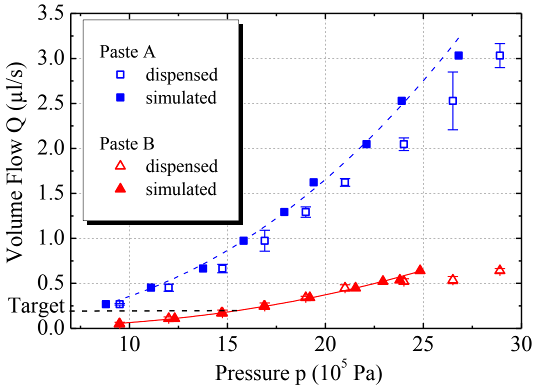

Fig.3. Verification of CFD simulation for two different dispensing pastes. Simulative results are in good accordance with experimental measurements around the target volume flow.

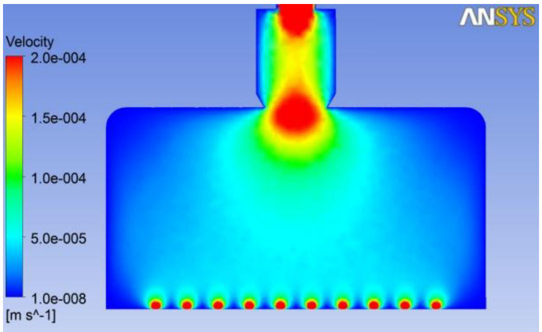

Fig.4. Velocity profile of a parallel dispensing print head. Similar flow distributions at the entrance of each nozzle ensure a homogenoues paste flow during dispensing.

Data from both pastes were in good accordance with simulative results in the low pressure region around the target volume flow of $Q = 0.2$ µls^{-1}. Furthermore, the different shear rheology of the two pastes is clearly visible. Comparing both pastes, the dispensing pressure increases with increasing values of consistency and yield stress, which is in good accordance to the applied Navier-Stokes equations [13] during simulation. A larger deviation of simulated results from those experimentally obtained might be subject to an extensional thickening behavior of these pastes due to converging flow regimes in the entrance of the nozzle as well as in the cone and will be further investigated in the future.

3.3. Simulation of Multi-Nozzle Print Heads

After investigating several nozzle types using this CFD-model concerning flow rate and pressure distribution, hardware design was expanded towards a multi nozzle application (Fig.4).

Here, investigations were focusing on a homogeneous paste flow distribution within the print head with as little system pressure drop as possible. In the following, multi-nozzle print head designs were tested and optimized regarding their robustness concerning fabrication tolerances of the nozzle geometries. Consequently, hardware experiments using a parallel 4 nozzle containing print head already led to a deviation in finger width of less than 3 % which is tolerable for a stable process without line interruptions. Especially the paste supply channels towards the nozzles turned out to have a major impact on a homogenous paste distribution. An optimal design including short supply channels and thus a small system pressure drop was finally found and the fabrication of a 10 nozzle containing second prototype was initiated. With a nozzle pitch of only 1.5 mm, it is designed to be scalable for later industrial applications with up to 100 nozzles per printing unit.

3.4. Fine Line Printing and Cell Results

In parallel to hardware development based on CFD-simulations, process optimization of the existing single nozzle approach was enhanced towards finest grid resolutions featuring a further reduction of optical shading on the cell and certainly Ag-paste consumption. Here, dispensing paste B through nozzles of just 50 µm in diameter led to record finger widths below 35 µm at aspect ratios of around 0.86 which was confirmed by different characterization tools. Solar cells on 156x156mm² Cz Si p-type material dispensed with this setup reached a typical efficiency increase of around 0.3 % abs. compared to screen printed reference samples.

Based on these experiences, the novel 10 nozzle containing dispensing unit was launched and after several test runs, a batch of solar cells of the same material was processed (Fig.5). Featuring similar contact geometries and consequently a homogeneous paste distribution between the 10 nozzles, a successful transfer of the simulated print-head and nozzle design could be demonstrated. An advanced nozzle geometry compared to the single nozzle approach allowed for a significant reduction of operating pressure by a factor of 10. Last but not least new record finger widths clearly below 30µm (Fig.6) were obtained using the novel print head.

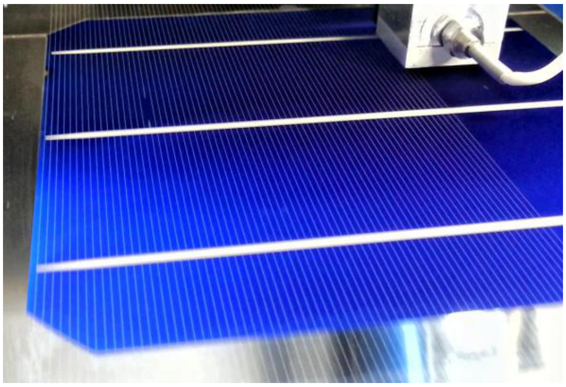

Fig.5. Parallel 10-nozzle fine line dispensing unit during cell fabrication. Homogeneous line widths below 35µm were achieved during first printing tests.

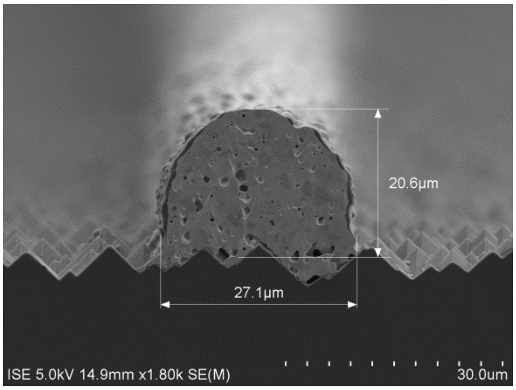

Fig.6. SEM picture of a fine line contact finger dispensed on Cz-Si material using the novel 10-nozzle print-head.

Future research has to be put into process stability as well as a precise control of line start and stop at each nozzle. Both aspects will be of great relevance on the road to an industrial application of this fine line metallization approach.

4. Conclusions

In order to enhance a time efficient and quick development of industrial applicable multi-nozzle dispensing print heads, a CFD-model was successfully implemented precisely modeling shear rheology of metal pastes used in PV printing technology. For this reason, characteristic values for yield stress were determined using a stress controlled rotational rheometer. Capillary viscosimeter experiments were conducted in order to account for high process shear strain rates. Verified by experimental data using two different metal pastes, flow patterns and pressure distributions of various nozzle geometries were analyzed using CFD-simulation. Afterwards, hardware development of this dispensing technology was enhanced towards an industrial multi-nozzle design focusing on a homogeneous flow distribution to all nozzles. Several iteration steps led to a robust design of a 10 nozzle print head. In the meantime, homogeneously dispensed finger widths on cell level were pushed below 35 µm, further reducing optical shading on solar cells compared to other single-step, thick-film metallization approaches. Finally, this dispensing process was successfully transferred to the multi nozzle approach reaching record finger widths of 27 µm.

5. Acknowledgements

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6. References

[1] Chen, X., K. Church, and X. Yang. *High speed non-contact printing for solar cell front side metallization*. in *Proceedings of the 35th IEEE Photovoltaic Specialists Conference*. 2010. Hawaii.

[2] Specht, J., et al. *High aspect ratio front contacts by single step dispensing of metal pastes*. in *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition*. 2010. Valencia, Spain.

[3] Pospischil, M., et al., *Correlations between Finger Geometry and Dispensing Paste Rheology*, in *27th European Photovoltaic Solar Energy Conference and Exhibition*. 2012: Frankfurt, Germany. p. 1773-76.

[4] Pospischil, M., et al. *Investigations of thick-film-paste rheology for dispensing applications*. in *Proceedings of the 1st International Conference on Silicon Photovoltaics*. 2011. Freiburg, Germany: Elsevier Energy Procedia.

[5] Lohmüller, E., et al., *20% efficient passivated large-area metal wrap through solar cells on boron-doped cz silicon.* IEEE ELECTRON DEVICE LETTERS, 2011. **32**(12): p. 1719-21.

[6] Hanoka, J.I. and S.E. Danielson, *Method for Forming Contacts*. 1992, Mobil Solar Energy Corporation: U.S.

[7] Fork, D.K.L.A., CA, US), Zimmermann, Thomas S. (Jena, DE), *Apparatus for forming a plurality of high-aspect ratio gridline structures*. 2012, SolarWorld Innovations GmbH (Freiberg, DE): United States.

[8] Church, K.H., et al., *Dispensing patterns including lines and dots at high speeds*. 2010, nScrypt, Inc. Orlando, FL: US.

[9] Chen, X., et al. *Improved front side metallization for silicon solar cells by direct printing*. in *Proceedings of the 37th IEEE Photovoltaic Specialists Conference*. 2011. Seattle, Washington, USA.

[10] Abdelhakim Benslimane, Karim Bekkour, and P. Francois, *Effect of addition of Carboxymethylcellulose (CMC) on the rheology and flow properties of bentonite suspensions.* Applied Rheology, 2013. **23**(1): p. 13475 (10 pages).

[11] Herschel, W.H. and R. Bulkley, *Konsistenzmessungen von Gummi-Benzollösungen.* 1926: p. 291-300.

[12] Mezger, T.G., *Das Rheologie Handbuch: für Anwender von Rotations- und Oszillations-Rheometern*. 2 ed. 2006, Hannover: Vincentz Network GmbH & Co. KG.

[13] Macosko, C.W., *Rheology: principles, measurements, and applications*. 1994: VCH.