Evaluation of printability of screen- and pad printing inks via high-viscosity piezo inkjet technology

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Abstract

Inkjet printing is not only interesting for graphical applications but also offers advantages for functional applications such as printed electronics, selective gluing, and medical uses. However, in these applications, the focus lies on the desired properties of the final print. In the case of dentures, for example, this may be a certain toughness, while for printed electronic structures, it is the ability to conduct electricity.

Currently, these applications are addressed by other printing or additive manufacturing techniques such as vat photopolymerization or screen printing. While these techniques offer a wide parameter range for materials, there are applications that require greater flexibility and individualization during processing or a multimaterial printing approach.

One printing technique that offers a high level of individualization, flexibility, and multimaterial capability is inkjet-based digital printing. It enables rapid on-demand production, requires no printing form, and is contactless. One disadvantage of inkjet printing, however, is its strong limitation in terms of jettable materials. The maximum viscosity for typical industrial piezo inkjet printheads is around 25 mPa·s. Recently, however, a novel printhead technology developed by Quantica GmbH has been introduced, which can jet fluids with viscosities of up to 250 mPa·s. This opens the possibility for a whole new range of functional fluids that could potentially be processed via inkjet.

However, the high particle loads and rheological behavior of functional materials are not yet well researched from an inkjet printing perspective. In this study, a systematic method to characterize these fluids is presented. This work presents the first steps toward identifying suitable characterization methods and potential materials to systematically evaluate the correlation between ink properties and waveform parameters.

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Introduction and background

Inkjet has undergone several transformations since its introduction in 1950. While originally being focused on graphic applications and increasing the resolution of prints advancements in the 1970s also introduced a more efficient inkjet process through shifting to drop on demand (DOD) technology. Here a droplet is only produced when needed, contrary to the former continuous inkjet techniques (CIJ) where a stream of droplets is deflected to yield an image. This DOD process was then commercialized by several brands in 1980 and laid the foundation of digital printing as known today [1–3].

Recently inkjet has undergone a shift from being used solely for graphical applications to also gaining relevancy for functional printing. Since for functional prints the focus of the printed material is to fulfill its purpose in the final part the rheological properties might not be suitable anymore for conventional inkjet printheads. Recently manufacturers such as Quantica have been working on developing printheads that can fulfill these new requirements [4, 5].

Conventionally materials made for inkjet printing were in a viscosity range below 25 mPa·s and exhibited mostly Newtonian behavior [6]. For functional materials this is often not the case. To gauge whether an ink is printable or not the most commonly used metric is the Ohnesorge number or the Z-number. These dimensionless numbers are derived from the Weber and Reynolds number which describe the relationship between the inertial force, surface tension and viscous force respectively.

Equation 1

$$We = \frac{\rho \cdot v^2 \cdot d}{\sigma}$$

Equation 2

$$Re = \frac{\rho \cdot v \cdot d}{\eta}$$

Equation 3

$$Z = \frac{1}{Oh} = \frac{\sqrt{\rho \cdot \sigma \cdot d}}{\eta}$$

Equations 1 and 2 describe the Weber and Reynolds numbers [1]. The Z-number, which is the inverse of the Ohnesorge number is often used to describe printability. In literature $1<Z<10$ or $0.1<Oh<1$ indicate that an ink is printable [7]. Proposed by Derby is a graph of We over Re to determine the jetability of a fluid, that also takes into account the different combinations of these two values that can lead to certain Z-numbers. It displays five distinct regions of jetting behaviour: A printable region in the middle, where stable jetting is possible. Then not enough energy for a drop formation and the fluid being too viscous and on the other hand zones where either splashing or excessive satellite formation are an issue [1, 7].

One key factor in the analysis of these dimensionless numbers is that all of them assume that the fluid exhibits Newtonian behaviour. As already stated, this is not the case for a lot of functional materials due to a high particle loading or high concentrations of polymer or long polymer chains in the material to yield certain properties in the final functional print. This already limits the use of these descriptors.

Additionally, these numbers are researched in relation to conventional piezo inkjet printheads, which operate on an acoustic principle. New printhead technology such as the NovoJet by Quantica GmbH technically are also driven by a piezoelectric actuation but the displacement of the material is not actuated through acoustic waves but a piston that is moved through the piezo [4, 5].

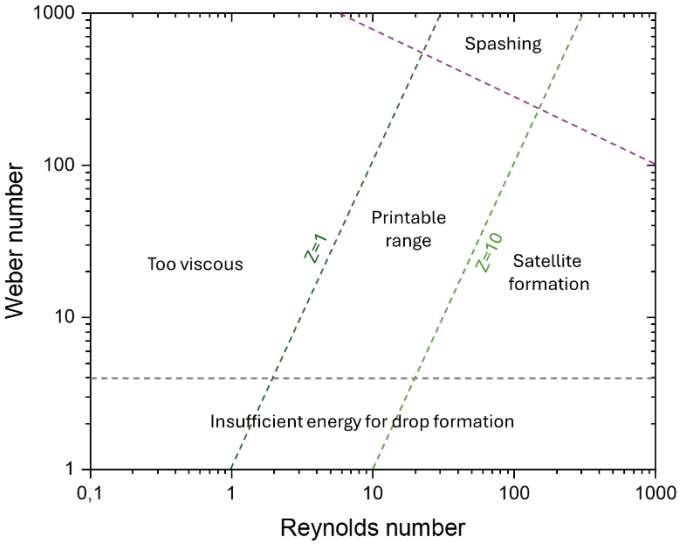


Figure 1: Graph of Weber number over Reynolds number with description of jetting regions after Derby, 2015 [7]

This makes for a different driving principle that is also limiting the use of dimensionless numbers as a strategy to assess printability. This work aims to first assess a baseline of printability of high viscous materials with the Quantica NovoJet printhead and then propose alternative measures to predict printability with functional materials.

Materials and methods

For this study, the printhead that is considered is the Quantica NovoJet with a viscosity window of 1-250 mPas [5]. As the setup for dropwatching the printhead was attached to a fluidic system by Inkatronic (Inkatronic Labtank) to ensure a

steady recirculating flow through the printhead. Dropwatching images were captured with a camera by camera (Droptical UltiStrobe). The whole setup is shown in Figure 2.

The functional material that is used are two dental resins conventionally used for vat photopolymerization. They were obtained in the standard particle-loaded version as well as without particles or fillers. As test inks Polyethylene glycol M_w 400 (PEG400) and glycerin were obtained from Sigma Aldrich.

The presented rheological assessment conducted with shear rheology measurements carried out with an Anton Paar MCR302 rheometer. A cone plate setup was used with a diameter of 40 mm and an angle of 0.3 °. The shear rate ramp was from 100 to 55000 1/s with logarithmic spacing of measurement points. The temperature for measurement was 70 °C for the dental resins and 30 °C for the PEG400 and glycerin mixtures.

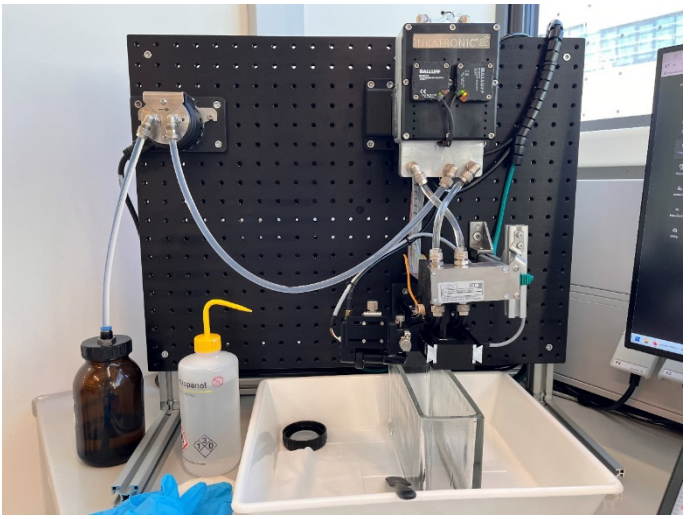


Figure 2: Dropwatching setup consisting of Inktronic Labtank fluidic system, Quantica NovoJet printhead and Droptical UltiStrobe camera

Results and discussion

Firstly, the rheological properties of the dental resin and is polymer base without particles were assessed.

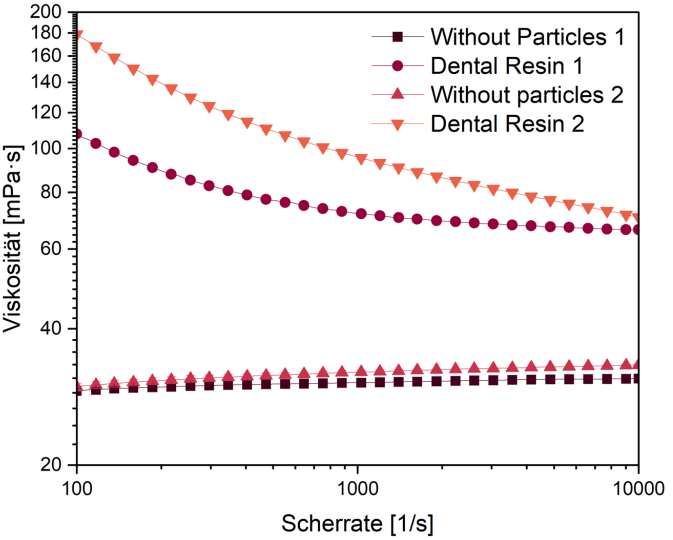


Figure 3: Shear rate sweep of two dental resins with and without particles at 70 °C

Figure 3 shows the rheological behaviour of two dental resins with and without particles over a shear rate sweep. Due to the high particle content, the commercial versions of the resins are highly shear thinning. But at the measurement temperature of 70 °C they seem to generally be in the viscosity range of the Quantica NovoJet printhead. As a comparison the polymeric base of the resins shows Newtonian behaviour and was initially intended to be a possible ink to first assess the properties of the printhead without using particles.

Due to the issue of needing to heat the material to achieve a potentially printable viscosity the polymeric base was not chosen as the initial testing material for the printhead. Instead, different mixtures of polyethylene glycol (PEG400) and glycerin with water as a solvent were rheologically characterized.

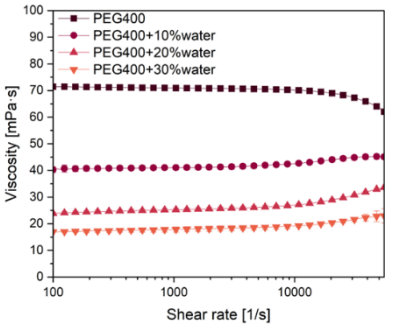


Figure 4: Shear rate sweep of different mixtures of PEG400 and water at 30 °C

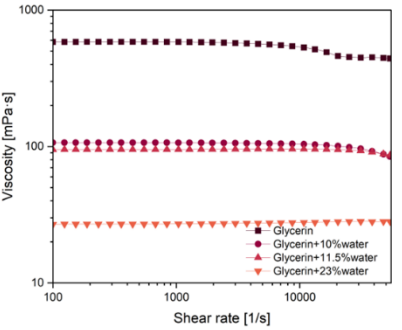


Figure 5: Shear rate sweep of different mixtures of glycerin and water at 30 °C

In Figure 4 and Figure 5, the different mixtures of PEG400 and glycerin show mostly Newtonian behaviour except for some shifting of viscosity towards very high shear rates. While glycerin can also yield a Newtonian test ink around 100 mPas it was not selected as a first candidate for jetting since its highly hygroscopic [8] and as seen in Figure 5 the viscosity changes drastically even with small amounts of water. Therefore, the water retention of glycerin could be a stability issue during jetting, as viscosity should stay consistent even with longer circulation times in the system.

PEG400 on the other hand has a viscosity of roughly 70 mPas without added water. This puts it right into the range of the printhead and uncertainties through the thinning process are also not relevant. Therefore, undiluted PEG400 was selected for initial jetting trials with the system. PEG 400 has a Z number of 0.7 at that temperature, which also is just outside the predicted printable range according to Figure 1.

In following jetting trials with the Quantica NovoJet and PEG400 stable droplets were achieved with an amplitude of 80 V, pulse length of 26 µs and 1000 Hz jetting frequency. The droplets can be seen in Figure 6 stitched together by the Droptical dropwatching software to observe a full ejection and flight phase. The jetting exhibits the key phases of inkjet drop formation: the actuation of the fluid from the nozzle, the formation of a ligament with thinning of the neck, the detachment from the nozzle as the ligament breaks off and finally absorption of the tail into the main droplet and flight phase [9, 10]. So contrary to the predictions by the dimensionless numbers the jetting of PEG400 was possible with the Quantica NovoJet printhead, confirming the fact that the numbers are not valid for this novel printhead technology.

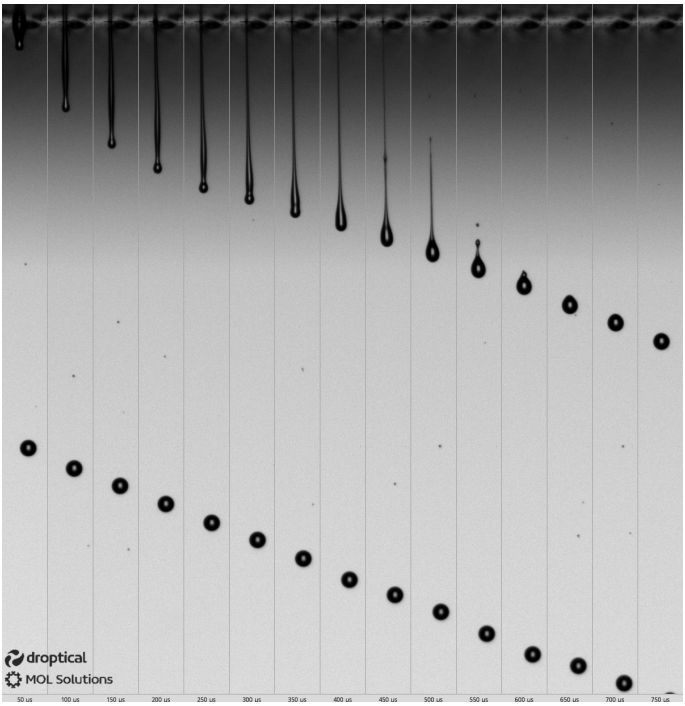


Figure 6: Jetting of PEG400 with Quantica NovoJet printhead

As an alternative to the gauging of printability through dimensionless numbers a comparative approach is suggested in this work. This is going to be validated and carried out in future studies. To avoid lengthy dropwatching trials with mostly expensive, toxic and hard to clean functional materials it is proposed to use a set of test fluids that can be used instead. The workflow of this approach is outlined in Figure 7. First the properties of several functional materials are assessed, such as resins or screenprinting inks. Based on these rheological profiles a set of test ink is formulated and adjusted to mirror the functional materials properties. The final step is the validation through dropwatching of both the functional materials and the test inks to find correlations and possible overlapping printing strategies. The goal is to give a systematic approach to characterize printheads for functional materials and do the dropwatching with cheaper and less toxic test inks that can be easily prepared by everyone. Then a functional material only has to be assessed rheologically, and the waveform of a similar test ink is applied as a starting point, hopefully significantly reducing the time needed to develop a set of jetting parameters.

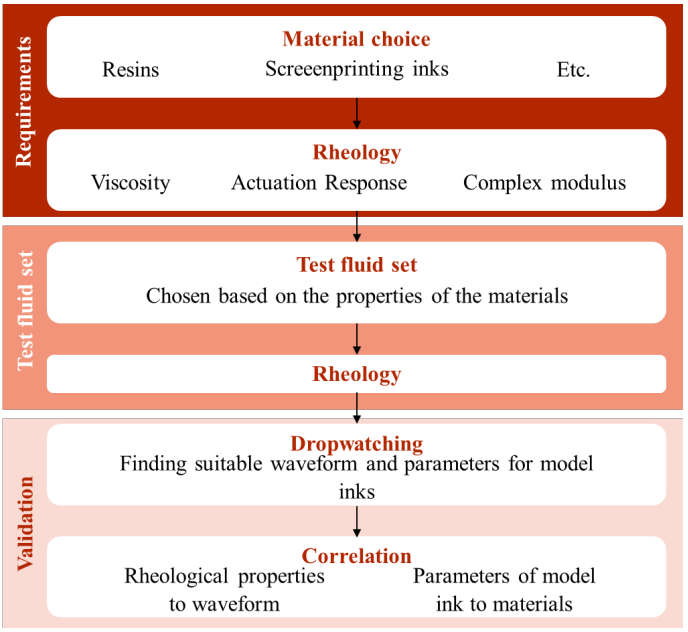


Figure 7:Workflow describing the replacement of functional materials with test fluids to develop jetting strategies

Conclusions

Even though inkjet has been around for several decades there are still new advancements and new technologies being developed. One of them being high viscosity inkjet for functional applications. As established the common descriptors for classic inkjet do not apply to gauge jetability of materials. On one hand because novel printhead technology, such as the Quantica NovoJet works on a different actuation principle, which enables it to jet fluids with higher viscosities than typical acoustic models. On the other hand, the dimensionless numbers work under the premise that the jetted fluid is Newtonian, which might be the case for classic inkjet fluid but is not true for a lot of functional materials. Therefor different means must be explored.

The first approach to assessing the possibilities of the printhead were dental resins and their respective polymer bases. The base exhibits Newtonian behaviour which would be desired for initial trials, however the need to still heat the polymer base up to 70 °C was established as a limiting factor, since it introduces another variable that needs to be managed.

After comparing several mixtures of PEG400 and glycerin with water the ultimate decision was to use pure PEG400 as a test ink, since it is just outside the jetable

range according to the Z-number. In this work it was shown that PEG400 was still jettable, further showing that new descriptors to assess jetability are needed apart from the dimensionless numbers.

One solution proposed in this work is a comparative approach that aims to link the jetting behavior of test inks to the jetability of functional materials. This should help reduce time and expensive material used for dropwatching experiments. Future steps here would be to widen the range of test inks to not only include PEG400 as a Newtonian ink, but also other viscosities of Newtonian ink as well as polymer solution for non-Newtonian behaviour and particle loaded inks to most accurately model real functional materials. The validation of this comparative workflow will be the topic of future studies.

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