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Screening : fundamental studies on the extrusion of stickies through slots

François JULIEN SAINT AMAND, Grzegorz WOJCIECHOWSKI, Dariusz ASENDRYCH, Michel FAVRE-MARINET, Rachid RAHOUADJ, Salaheddine SKALI-LAMI

Abstract

A cooperative research programme has been launched in the frame of a European project aiming at optimising the removal of stickies in deinking lines, especially by slot screening. Soft PSA particles being the most difficult stickies to remove as they can be extruded through slots, basic research work was focused on understanding the extrusion mechanisms. A single slot screening device was used at CTP to visualise the extrusion of cylindrical PSA particles. Numerical simulation of the extrusion of viscoelastic particles was performed at LEGI and special test equipment was developed at LEMTA to determine the dynamic behaviour of the adhesive material.

Water-based acrylic adhesives revealed to be much weaker than hot-melt rubber adhesives, especially at high temperature after alkaline soaking, and required lower pressure and less time to be extruded through the slot. Gentle screening

conditions with low pressure during the positive pressure pulse as well as reduced temperature and pH should thus minimise stickies extrusion as expected. Both experimental and numerical simulation results led to the same conclusions about the effects of key screening parameters. Linear relations were observed between the normalised particle diameter and the extrusion pressure and time. Particles 2 or 3 times larger than the slot width were effectively extruded at typical extrusion pressures observed in screens, but the time required to pass the slot was up to two orders of magnitude higher than the duration of the positive pressure pulse, which suggests that particle extrusion should take place step by step over several revolutions of the rotor.

The tests performed to compare milled slots with sharp inlet edges to wedge wire slots with higher inlet radius, showed less particle extrusion with the milled slots, as expected. Further investigations are however required to

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conclude, as the behaviour of adhesive particles during the reverse pulse should also be taken into account in multi-step extrusion mechanisms. Future research should include the analysis of the reverse extrusion of adhesive particles through slots with complete characterisation of the rheological properties of the adhesive material at the high strain rates observed in the extrusion process.

Introduction

Adhesives and glues entering the papermaking cycle with the recovered papers lead to numerous stickies problems including deposits on the paper machine, optical defects in the paper and printing problems caused by adhesive spots. Despite progress in recycling technology and the efforts engaged to develop environmentally benign adhesive products, stickies problems are far from being solved. PSA stickies from pressure sensitive adhesives (labels, tapes, envelopes, etc.) are the main concern in the field of deinking while hot-melt glues (container sealing, book bindings, etc.) contribute strongly to the paper machine deposit problems in the field of packaging. The research presented in this paper was performed in the frame of a European project "ScreenClean" [1], which aims at improving the removal of primary PSA stickies at the different deinking process steps, with special focus on pressure screening.

Screening is clearly the most effective technology to remove primary stickies (solid particles introduced with the raw material and showing an adhesive effect under standard test conditions) especially the "macro-stickies" fraction. Indeed, macro-stickies do not refer to particles in the visible size range, but to the particles retained by laboratory screening with typically 0.10 mm slots for deinking pulps, according to widely accepted standard test methods

[2-4]. By contrast, "micro-stickies", which are defined as the fraction of primary stickies passing the lab screen, are much more difficult to remove by screening. Large micro-stickies particles produce visible dots in the paper sheet as they are generally covered with inks, while micro-stickies are mainly responsible for paper machine deposits [5-6]. Secondary stickies (tacky particles produced in mill circuits by physico-chemical processes involving dissolved and colloidal stickies) are normally not removed by screening. Screening is currently performed in deinking mills with slots down to 0.10 or 0.12 mm for respectively wood-free (MOW) and wood-containing (ONP/OMG) deinking pulp [7-9]. Typically, fine screening systems in European DIP lines are operated with 0.15 mm wedge wire slots in the low consistency range [10]. The specific behaviour of stickies in screens is due to their ability to be extruded through the slots by the pressure generated by the rotor and the pulp flow, as a consequence of the visco-elastic properties of the adhesive material. Soft deformable stickies particles which can be extruded through slots should be considered as "probability" contaminants (normally particles with at least one dimension smaller than the slot width) rather than "barrier" contaminants (normally particles with all dimensions larger than the slot width). The behaviour of such particles in pressure screens can be characterised, on average, by a particle passage ratio, which is defined by the ratio of the downstream to the upstream particle concentration in a screen cylinder section, according to the probability screening theory [11-16]. Particle passage ratios should be determined for particles in different size and shape classes to predict correctly the performance of industrial screening systems.

Basic studies were carried out over the last decade at several research institutes, as reviewed in [16], to develop the understanding of the screening process at the scales of

both pulp “macro-flow” conditions around the rotor and unsteady “micro-flow” conditions and particle separation phenomena at the surface of the screen plate and through the slots. Investigations at CTP in this field were first performed with relevant probability contaminants, i.e. flat-shaped particles (0.5 mm² films) and long-shaped particles (shives) with lower thickness than the slot width. A major conclusion about these studies [16-17] was that all the parameters which improved the passage of the fibres through the slots, i.e. increasing slot width and the effective normalised slot velocity, also increased the passage of the tested probability contaminants. Increasing the passing velocity as calculated from the accept flow rate, reducing the slot friction factor with wedge wire design and increasing the intensity and duration of the positive pressure pulse created by the rotor were assumed to increase the effective slot velocity during the screening phase and thus to increase the probability for particles to be captured in the fluid exit layer and then to pass the slot. The effective normalised slot velocity was an extended definition of the normalised slot velocity [18], i.e. the ratio of the effective slot velocity to the tangential velocity at surface of the screen cylinder. Increasing the thickness of the exit fluid layer taken from the flow at the top of the profiles and turning into the slot (see figure 13) was assumed to enhance its ability to drive particles towards the slot inlet. CFD simulation showed that this fluid layer thickness was roughly proportional to the normalised slot velocity and to the slot width [19]. The effects observed when changing rotor velocity were attributed to changes induced by the tangential fluid velocity in the exit layer thickness [16-17]. Practically, probability screening efficiency, i.e. the selectivity of the separation between fibres and thin contaminants showed to be very difficult to improve by changing slot velocity and design or rotor velocity and design, at given profile design. Clear improvement of the screening efficiency was only achieved by reducing the height of the profiles, from 1.2 to 0.6 mm, which was attributed to particle contacts with the inclined profile walls assumed to reject more efficiently large and stiff contaminants compared to flexible fibres [17].

Indeed, the hydrodynamic screening mechanisms revealed through the investigations with thin flat and long-shaped particles should also apply to stickies at least until the particle has reached the slot inlet. Then the extrusion process should become decisive. Recent research was reported about experimental studies on the passage of acrylic PSA particles through a fine slot in a single slot laboratory device using vacuum to extrude the particle through the slot [20-21]. The particle passage probability was shown to increase as temperature and pressure drop increased and as the particle width, thickness or area decreased. Particle size and shape were controlled by changing the pulping conditions which produced mainly string-like particles.

Slight changes in particle size and shape were observed after the extrusion of the particles through the slot.

The research work reported in this paper is devoted to basic studies about the extrusion of PSA particles through slots and the influence of the most relevant parameters. The first part deals with experimental results obtained at CTP with a single slot laboratory device equipped with a high-speed camera to visualise the extrusion process. The numerical simulation work performed at LEGI [22] is briefly reported in the second part. The third part about stickies rheological properties describes shortly the new method developed at LEMTA to determine the dynamic behaviour of the adhesive material at high strain rate.

Experimental study of stickies extrusion

The objective in this study was essentially to develop a better understanding of the stickies extrusion process through visualisation, in connexion with the numerical simulation work already engaged at LEGI in the frame of the ScreenClean project.

Experimental Set Up

The single slot channel screen (figure 1) was designed to simulate the flow conditions observed at the surface of screen plates and through the slots during the positive pressure pulse and to change and control easily slot width and design. The height of the transparent channel was 10 mm and the width 15 mm. The syringe shown in figure 1 was not used in the test procedure described later. It was intended to introduce stickies particles at the right level to drive them toward the slot inlet.



Figure 1. Single slot channel screen with camera.

A high-speed CCD camera (Sony XC-HR300) was used at 100 or 200 i/s to visualise the particles in transmitted light, using continuous light source behind the transparent channel. The resolution was 2 or 8 μm depending on the magnification of the optics (x1 or x4). Visualisation was limited to the extrusion of stickies through the slot, as a conse-

quence of the shape of the PSA particles and procedure used for the tests.

Adhesive Particles and Test Procedure

PSA stickies particles observed in mills have various size and shape, depending on the adhesive type and pulping conditions. Figure 2 shows handsheets with acrylic and SBR adhesives, which were obtained by re-pulping self adhesive labels previously covered with toner inks, in a low-consistency lab pulper with standard deinking chemistry. The acrylic labels gave more flat-shaped particles than the SBR labels, which was attributed to the higher trend of the less hydrophilic rubber based adhesive film to stick onto itself and form thick rolled up particles in the pulper. Laboratory screening tests with 0.08 mm slots showed low screening efficiency of about 50% with the acrylic adhesive (the total area of micro-stickies passing the slots and measured on handsheets as specks $> 0.01 \text{ mm}^2$ was about half of the stickies area in the feed pulp) compared to 90% efficiency obtained with the thicker and larger SBR adhesive particles [4].

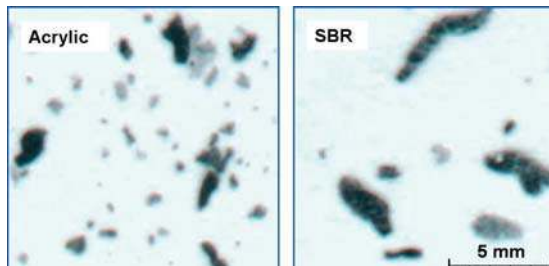


Figure 2. Handsheets of re-pulped adhesive labels.

Long-shaped particles were considered as the most relevant to study the extrusion of mill PSA stickies. Indeed, flat-shaped stickies with lower thickness than the slot width (down to 20 or 30 μm , the thickness of wet adhesive films) are not relevant while spherical particles are typically found after dispersing, especially kneading, i.e. in the second deinking loop after fine screening.

Consequently it was decided to use the cylinder as the model particle shape in the extrusion studies. Special rolls of adhesive films between two silicone release papers were used to manufacture cylindrical adhesive particles of different diameters (figure 3). Two commercial adhesives from Avery Dennison Jackstädt were tested:

- a water-based acrylic adhesive (ref E115)
- a hot-melt based rubber adhesive (ref D170)

These products were taken as reference adhesives in the ScreenClean project [4] as they represent respectively the most common type of adhesive used for label application in Europe and a growing market share among the other types of adhesives. The adhesive cylinders were measured and tested after soaking about one hour, which is particu-

larly important with the acrylic adhesive which showed to absorb about 50% water.

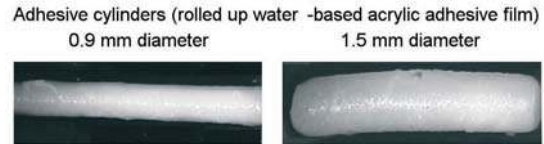


Figure 3. Adhesive particles manufactured for the tests.

The cylindrical shape of the adhesives did not allow to introduce them in the channel with the syringe (figures 1). The following procedure shown in figure 4 was adopted:

- the adhesive cylinder was introduced in the device through the valve V2 while a very low flow rate was maintained in the channel until the cylinder reached the slot inlet and was properly aligned with the slot,
- the valves V2 and V4 were closed, the flow rate in the channel was increased with the pump after opening V3 and the pressure was set to the desired value with a sufficient flow rate through the channel,
- the valve V4 was then opened rapidly ($< 0.5 \text{ s}$) to set the pressure on the adhesive particle.

This procedure was established in order to control, as far as possible, the pressure during the extrusion process, since the flow rate through V3 was much larger than through the open slot area, about half of the slot being covered by the adhesive cylinder.

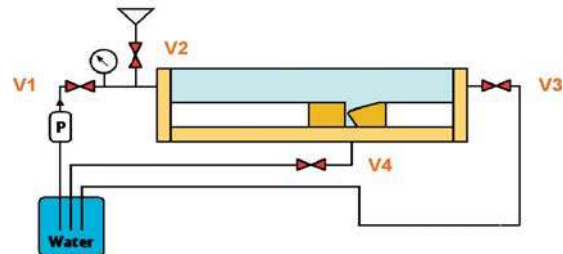


Figure 4. Adhesive extrusion test procedure.

Most of the tests were performed only to determine the pressure required to extrude the particle as a function of adhesive and slot characteristics. Images were recorded under certain conditions to analyse deformation of the particles and to determine the extrusion time. Some tests were also performed at extrusion pressures far above the usual range of positive pressure pulses observed in screens, i.e. typically 20 to 100 kPa.

Effect of Adhesive Material Parameters

A first test series was performed with 0.5 mm slots with “wedge wire like design” to study the adhesive material

parameters. New slots with more accurate design were used later to study the effects of slot design parameters. Figure 5 shows the pressure required to extrude the adhesive particle versus the normalised particle size defined as the ratio (d/w) of the cylinder diameter to the slot width, for the two reference adhesives at room temperature (22°C) and at typical temperature in deinking circuits (50°C). The extrusion pressure was significantly lower with the acrylic adhesive (E115) than with the hot-melt rubber adhesive (D170) at both temperatures, which suggests that the acrylic adhesive material is softer and that acrylic stickies should be more difficult to screen as larger particles are extruded through the slots for a given pressure. Increasing the temperature reduced the extrusion pressure, especially with the acrylic adhesive, which suggests higher softening of the adhesive material.

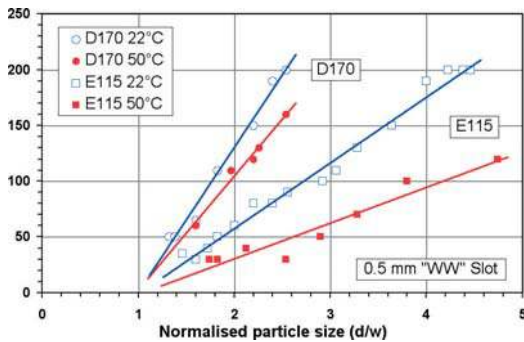


Figure 5. Effects of adhesive material and temperature.

It is interesting to note that the extrusion pressure is roughly proportional to the particle “oversize” ($d-w$) though the extrusion phenomena is probably strongly non-linear. The results in figure 5 indicate that acrylic adhesive particles with 2 to 3 times larger diameter than the slot width were extruded through the slots in the temperature and extrusion pressure range of mill screening systems.

Extrusion tests were performed after soaking the adhesive particles in cold and hot water at pH 10, in order to investigate the effect of caustic soda added to the pulper in deinking mills. The results in figure 6 show a large decrease of the extrusion pressure when the acrylic adhesive particles were soaked at room temperature with caustic soda. At high temperature the decrease of the extrusion pressure was lower as soaking pH was increased. These results suggest that the penetration of water and/or the dissolution of adhesive components, assumed to be responsible for softening the adhesive particle, required higher pH at low temperature.

Soaking caustic soda produced the opposite effect with the hot-melt rubber adhesive, as a significant increase of the extrusion pressure, by about 50%, was observed as soaking

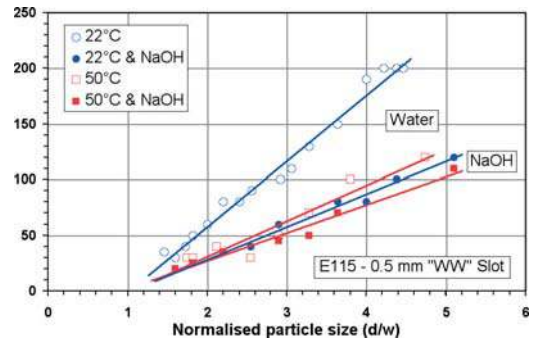


Figure 6. Effect of alkaline soaking of acrylic adhesive.

pH was increased (pH 10) at both temperatures (22 and 50°C).

Effect of Slot Design Parameters

Milled and wedge wire screen plates were compared to investigate the effect of slot inlet design which was supposed to influence significantly the extrusion process. Metal blocs shown in figure 7 were manufactured at scales 1 and 5 to improve the accuracy of the slot inlet radius. The dimensions in table 1 were defined on the basis of 0.10 mm slots and chosen to cover the variations observed with commercial screen plates. Slot print measurements were performed on various screen plates of CTP’ experimental screen [17] including Microvortex (Kadant Lamort) and Macroflow (AFT) designs.

Slot type	Slot scale	w (mm)	r (mm)	b (mm)	l (mm)	h (mm)
MS	1	0.10	0.05	0.10	0.8	1
WW	1	0.10	0.20	-	-	1
MS	5	0.50	0.25	0.50	4.0	5
WW	5	0.50	1.00	-	-	5

Table 1 - Slot dimensions according to figure 7.

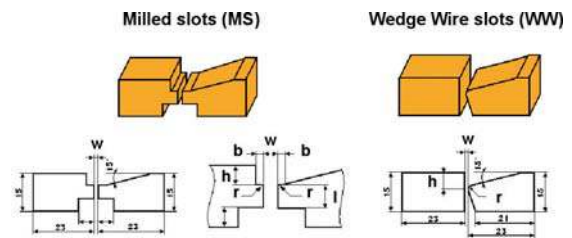


Figure 7. Design and dimensions of the tested slots.

The stickies extrusion tests were first performed with the slots at scale 5 in order to improve the accuracy of the size and shape of the adhesive cylinders. The results in figure 8, which were obtained at 47°C after soaking the adhesives in tap water, confirmed the higher extrusion ability of the acrylic adhesive. The extrusion of both types of adhesive

particles is clearly increased with the wedge wire slot compared to the milled slot, as expected when looking at the shape of the slot inlet section. In short, the particle is submitted to lower stresses when extruded through one round edge with slightly converging profile walls (165° angle with the wedge wire profile in figure 7) than through two sharp edges (4 times lower radius with the milled compared to the wedge wire slot) with slot inlet location on a flat profile bottom.

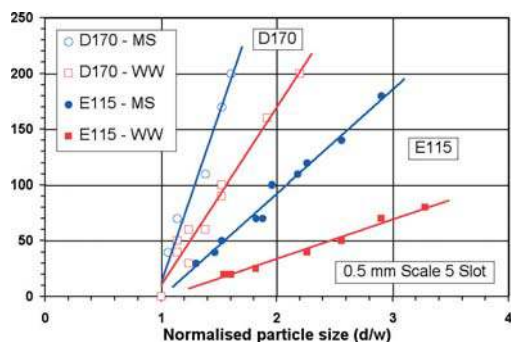


Figure 8. Effect of slot design on extrusion pressure.

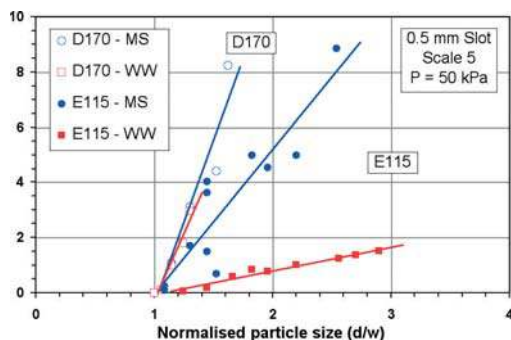


Figure 9. Effect of slot design on extrusion time.

The time needed for the adhesive particles to pass completely the slot has been recorded under the same test conditions as in figure 8, except for the pressure which was 50 kPa for all the tests. The results in figure 9 showed a much higher extrusion time with the milled slot compared to the wedge wire slot, but only with the acrylic adhesive. The higher trend of the hot-melt rubber adhesive to stick at the slot walls was responsible for the very high extrusion time measured with wedge wire design. In fact, the extrusion time is over-estimated as it was recorded when the whole adhesive cylinder had passed the slot, after detachment of all the cylinder parts stuck on the slot outlet wall, as illustrated in figure 12. The sharp inlet edges and the higher length of the milled slot are responsible for the longer extrusion time observed with the acrylic adhesive. Indeed, the most important conclusion about the results in figure 9 is that the extrusion time is about two order of

magnitude higher than the duration of the screening phase, i.e. a few seconds compared to typically 20 ms, which gives new insight in the stickies extrusion mechanisms in pressure screens. This means that adhesive particles with significantly larger thickness than the slot width cannot pass the slot during one positive pressure pulse and that the passage of such particles through the slots takes most probably place over several rotor revolutions in a multi-step extrusion process. One should however keep in mind that the experimental procedure does not take the inertia of the particle approaching the slot into account, which means that extrusion times in figure 9 are over-estimated compared to the real situation, especially at low extrusion time.

Scale effects should also be kept in mind when analysing the results obtained with slots at scale 5, especially the results in figure 9, since equal extrusion time with slots at scale 1 would correspond to a decrease of the average strain rate by a factor 5, at given normalised particle size. The extrusion time should then in fact be lower with slots at scale 1 since the elasticity modulus of adhesive materials decreases as the strain rate is decreased. The extrusion times should then however still be about one order of magnitude higher than the duration of the positive pressure pulse, and suggest multi-step extrusion mechanisms of large PSA stickies in pressure screens.

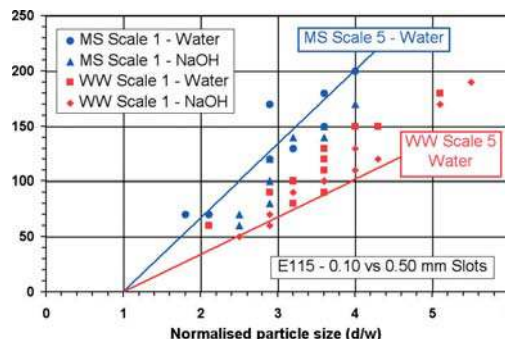


Figure 10. Scale effect on extrusion pressure.

Some tests were performed with the slots at scale 1 to evaluate extrusion pressure at mill relevant conditions, i.e. at 47°C and with acrylic adhesives after neutral and alkaline soaking. The results shown in figure 10 were less accurate, as expected, but gave similar pressure values and led to the same conclusions regarding the influence of slot design and alkaline soaking of the adhesive, though the effects were lower.

The pictures in figures 11 and 12 illustrate the extrusion of acrylic adhesive cylinders through the milled and wedge wire slots at scale 5. The ends of the cylinders passed the slot first, especially with the small cylinders. One can

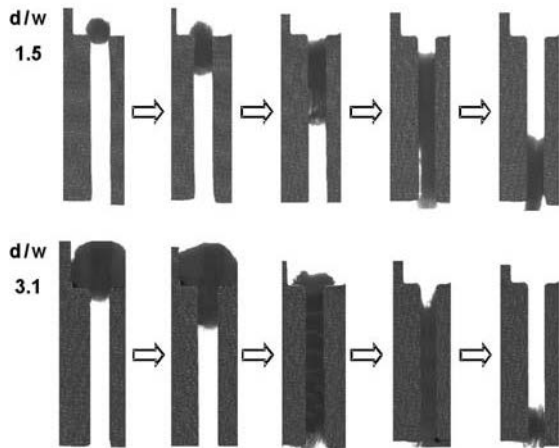


Figure 11. Stickies extrusion through milled slots.

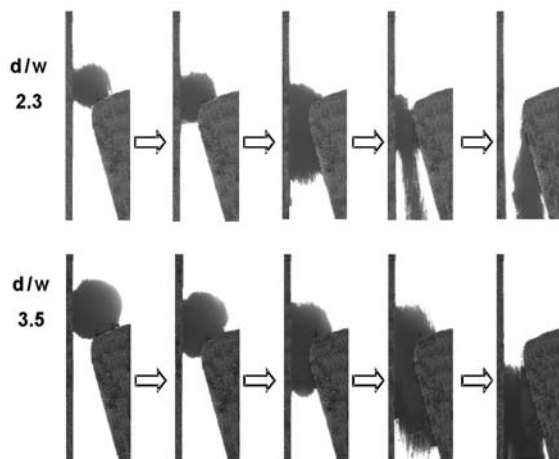


Figure 12. Stickies extrusion through WW slots.

observe with the wedge wire slots that parts of the adhesive particle still stick at the wall, generally at the right side, when the particle has passed the slot.

Numerical simulation of particle extrusion

Application of CFD simulation to screening started at LEGI in the frame of a thesis prepared in cooperation with CTP and Kadant Lamort [19,23-25] and was continued in the frame of the ScreenClean project [22].

Screen Plate Flow Simulation

The numerical simulation of the extrusion of stickies through slots first requires the simulation of the flow conditions at the screen plate in order to establish the

pressure exerted on a particle at the slot inlet. The velocity at which the particle approaches the slot is also an important parameter when taking particle inertia into account. Figure 13 shows a 2D CFD simulation of typical flow pattern at the screen plate during the screening phase, where the exit layer was coloured in blue [19,23].

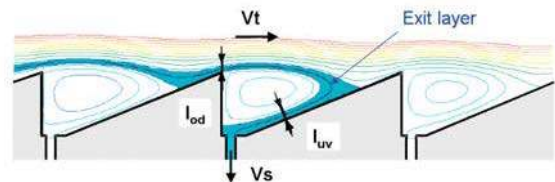


Figure 13. CFD simulation of screen plate flow [23].

Further 2D CFD simulations were performed with the commercial code FLUENT (version 5.4) to characterise the micro-flow at the slot inlet in a large range of tangential velocities ($V_t = 5$ to 20 m/s) and slot velocities ($V_s = 1$ to 10 m/s). Figure 14 shows the thickness of the exit layer over the detachment point at the top of the profile (L_{od}) and under the vortex (L_{uv}) as a function of the normalised slot velocity (V_s/V_t) for 0.10 mm slots. Particles were then introduced at the slot inlet in the simulations, which were performed in 3D with both spherical and cylindrical particles. Figure 15 shows the flow pattern in the central section of a cylinder placed at the inlet of a milled slot.

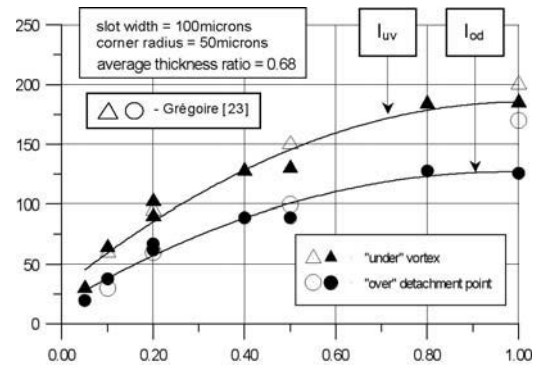


Figure 14. CFD simulation of the exit layer thickness in the case of milled slots.

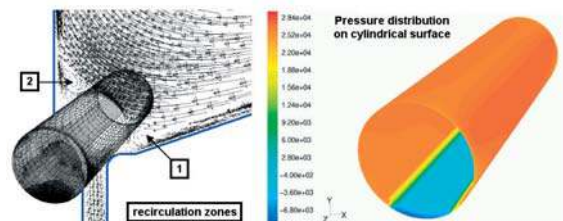


Figure 15. CFD simulation of the flow pattern and of the pressure exerted on a cylinder at the slot inlet.

The pressure distribution at the surface of cylinder revealed two zones with roughly constant pressure, a high pressure area (in red) at the feed side and a low pressure area (in blue) at the accept side of the slot (figure 15 right). The “extrusion pressure” can then be approximated, in such a case, as the pressure difference between these two areas.

Simulation of Particle Extrusion

The results in figure 15 led to strong simplification of the simulation of the extrusion of cylindrical particles, as the simulation could be treated in 2 dimensions, though it is believed that three-dimensional effects could occur during the deformation of soft particle. The rheological properties of the adhesive material as well as the friction factor between the particle and the slot wall are required as input data for the simulation.

The simulations of the particle deformation were done with the commercial code ANSYS (version 5.7) and with the use of a viscoelastic constitutive model where the material properties are represented by the elementary Maxwell model :

$$\sigma / \eta + \dot{\sigma} / G = \dot{\epsilon} \quad \frac{\sigma}{\lambda} + \dot{\sigma} = G \dot{\epsilon}$$

where σ is the stress, ϵ the strain (dot over symbol denotes time differentiation) G the shear (elastic) modulus, η the viscosity and $\lambda = \eta/G$ the relaxation time (the ability of the material to relax stresses).

The deformation of a cylindrical viscoelastic particle placed at the inlet of milled and wedge wire slots is shown in figure 16 at the initial time (deformation caused by elasticity only) and in figure 17 after 20s under a pressure of 10 kPa. The extrusion is slower with the milled slot because of the concentration of deformation and stress in the particle at the contact edges compared to the wedge wire slot where particle deformation is more uniform.

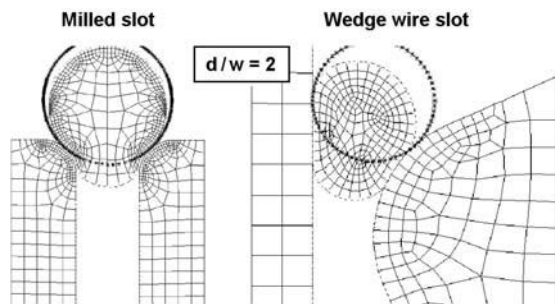


Figure 16. Particle extrusion at $p = 10 \text{ kPa}$, $t = 0$.

The simulations were done with a set of rheological properties ($G = 70 \text{ kPa}$, $G^\infty = G/10$ and $\lambda = 1 \text{ s}$) taken from

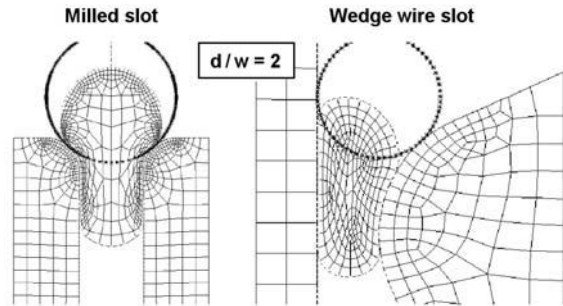


Figure 17. Particle extrusion at $p = 10 \text{ kPa}$, $t = 20 \text{ s}$.

average preliminary test results, since more relevant data were not available. Friction was included later. The simulation results were however consistent with experimental results and allowed to determine the effects of the screening parameters. Both visualisation (fig. 12) and numerical simulation (fig. 17) indicated elastic expansion in the divergent outlet section of the wedge wire slot. The following parameters turned out to increase particle extrusion:

- high screening pressure,
- particle “softness” (small elastic/shear moduli),
- short shear relaxation (more viscous behaviour),
- wedge wire compared to milled slots,
- slot inlet edge roundness (higher radius),
- reduced friction, smooth profile surfaces.

It should also be mentioned that the simulations gave about linear relations between the particle oversize ($d-w$) and the extrusion pressure or time [22] as observed experimentally (fig. 6, 8, 9, 10).

Dynamic behaviour of adhesive material

The analysis of possible single step extrusion of adhesives through slots shows that both strain and strain rate would be very high with particles much larger than the slots, if the particle effectively passes the slot during the screening phase. With integral calculation of the average strain at high deformation ($\epsilon = \ln d_0/d = \ln d_0/w$) and for a particle squeezed by a factor 3 in 10 ms, the strain rate ($\epsilon/\partial t$) would be of the order of 10^2 s^{-1} . Results about the dynamic moduli, G' and G'' , of adhesive products have been reported but the measurements were performed in dry state at much lower strain rate [26].

The analysis of the dynamic behaviour of adhesives, was subcontracted, in the frame of the ScreenClean project to provide input for the numerical simulation, to LEMTA where expertise was available in this field as well as for the analysis of friction factors with soft materials [27]. The test equipment at LEMTA had however to be adapted to the

very soft adhesive materials to be tested. In the mean time preliminary low-speed elongation tests were done at CTP to provide some input for the simulation.

Low-speed elongation tests

Preliminary tests were performed with paper testing equipment at elongation velocities up to 1 m/min, which gave a maximum strain rate of 0.4 s⁻¹ in the narrow part of the adhesive test samples (40 mm length, 15 mm width and 2 mm thickness). The dimensions of the test samples were not exactly those defined for standard rubber testing procedure because of the difficulties encountered in preparing samples with very tacky material (figure 18).

Adhesive sheets were produced from the two reference adhesive raw materials, cut in water and tested after soaking. Both adhesives recovered almost their initial length in a few minutes after elongation by a factor 10. Figure 18 shows pictures of an adhesive sample back to its initial position after a first elongation and submitted to a second elongation.

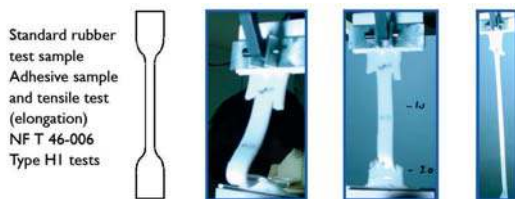


Figure 18. Low-speed adhesive elongation tests.

The typical stress strain relations are shown in figure 19. Both adhesives showed a first elastic part followed by a drop of the modulus with lower strength at the second elongation, especially with the hot-melt rubber product. The first pass elastic modulus was about one order of magnitude higher with the hot-melt rubber than with the acrylic adhesive, which gave $G \approx 20$ kPa at 1 m/min after soaking in hot water. The elastic modulus showed to increase with increasing elongation velocity and to decrease with increasing temperature.

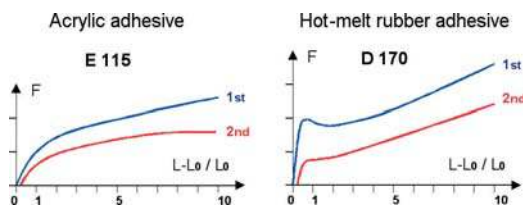


Figure 19. Typical elongation stress strain curves.

High-speed compression tests

The experimental equipment and method illustrated in figure 20 were developed to record stress strain relations applied on adhesive materials at high strain rates:

- a cylindrical adhesive sample (18 mm diameter and 28 mm height) is placed on a bottom plate equipped with a load sensor;
- a weight is dropped from different heights on the top plate above the adhesive sample,
- the compression of the adhesive sample is measured with a laser recording the height of the bottom plate.

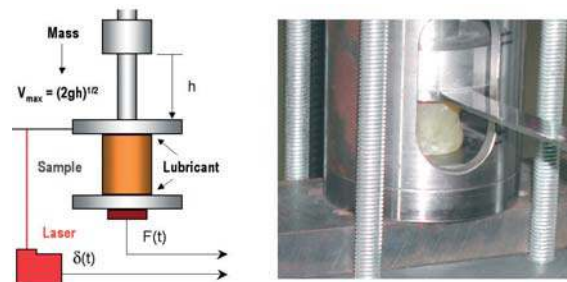


Figure 20. High-speed adhesive compression tests.

The initial strain rate are controlled by the drop height (0.15 to 0.9 m, e.g. 0.8 m gives a drop velocity of 4 m/s and an initial strain rate of 150 s⁻¹) and the stress level by the weight. The samples are covered with talcum to allow adhesive material to slip between the plates and avoid barrelling of the cylinder during the compression. The recorded data (figure 21) are converted into stresses of Cauchy and true axial strains

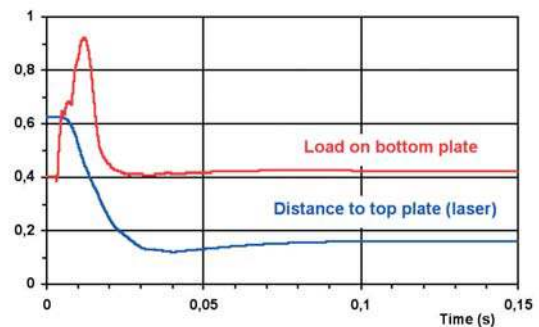


Figure 21. Dynamic test: recorded load and compression.

The dynamic compression test is distinguished from the usual quasi-static tensile test by the fact that the strain rate drastically decreases during compression, towards zero at the end of the tests. The residual stress due to the weight at the end of the test is considerably lower than the one due to the high deceleration of the weight at the impact. The strain level reached with adhesive material can be rela-

tively significant, up to 1. Figure 22 shows a typical example of stress strain curve obtained with the dynamic compression test, at non-constant strain rate.

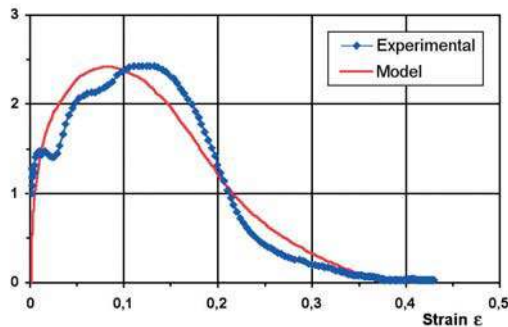


Figure 22. Typical compression test results and model.

In principle, a large number of tests should be performed to determine, as a function of the strain rate, the stress strain relations, which are required for the simulation of particle extrusion. The development of a model describing the dynamic behaviour of viscoelastic material will enable to determine these relations from the experimental data. The theoretical curve plotted in figure 22 represents the estimated result obtained from a viscoelastic model with two relaxation times. Different relaxations times generally refer to the components of the generalised Maxwell model where infinite viscosity of one component gives the solid behaviour. The new theoretical model under development is based on the thermodynamics of irreversible processes produced by the stresses and strains applied to the polymers [28-30]. Indeed, polymer chains exhibit the highest disorder, i.e. maximum entropy, at steady relaxed state, while stresses tend to stabilise. The complex behaviour of adhesive material depends on the relaxation times spectrum which is related to the micro-structural reorganisations observed at different scales.

Conclusion

The experimental and numerical simulation studies of the extrusion of PSA particles through slots led to clear and consistent results about the effects of key screening parameters. Some aspects which have not yet been taken into account should however be discussed before to conclude about the optimisation of stickies screening.

Discussion

Both the numerical simulation and the lab screening tests were limited to the screening phase with the adhesive particle initially at rest at the slot inlet. The reverse flow phase

and particle inertia should also be taken into account to further investigate stickies extrusion in pressure screens. The average slot or passing velocity V_p in pressure screens is controlled by the accept flow rate, while the effective slot velocity during the screening phase depends on the pressure pulse. CFD simulations revealed high slot velocity fluctuations (for example +5 to -20 m/s with a foil rotor and wedge wire slots) since the effect of fluid inertia on time lag and slot velocity fluctuation was relatively low [23,24]. The average effective slot velocity during the screening phase $V_s^{(+)}$ can also be evaluated by simple flow rate balance ($t^{(+)} V_s^{(+)} - t^{(-)} V_s^{(-)} = t V_p$) assuming constant slot velocity over the duration of both positive and negative pressure pulses $t^{(+)}$ and $t^{(-)}$. Increasing for example the duration of the negative pressure pulse from 10 to 20 % of the whole pulse duration t would then give $V_s^{(+)} = 2.8$ to 5 m/s for $V_s^{(-)} = 15$ m/s and a typical passing velocity $V_p = 1$ m/s. The flow velocity in the exit layer under the vortex would then be roughly equal to $V_s^{(+)}$ according to figure 13 for a tangential flow velocity $V_t = 10$ to 15 m/s.

Under these conditions the inertia of the particle approaching the slot inlet at the same velocity as the fluid in the exit layer cannot be neglected. Particle inertia should reduce or delay particle extrusion in the case of milled slots located in the middle of flat bottom profiles (with large b value in table 1) as the particle might pass along the slot inlet. By contrast the inclined wall of the convergent inlet of wedge wire slots should increase particle extrusion as a result of the inertia of the particle turning smoothly into the slot, as illustrated in figure 23. Assuming a constant deceleration of the particle over a distance equal to particle radius, which gives $\gamma = V^2 / d$, and inertial forces applied on a section equal to the particle diameter, the “equivalent pressure” is given by $P = (\pi/4) \rho V^2$, for a cylindrical particle. Such additional “inertial extrusion pressure” (e.g. 20 kPa for $V_s^{(+)} = 5$ m/s) should have similar effect than the hydraulic extrusion pressure, which is generally higher (typically 50 kPa) but with resulting pressure limited to the particle section between the contact lines with the slot inlet (see figures 16 and 17).

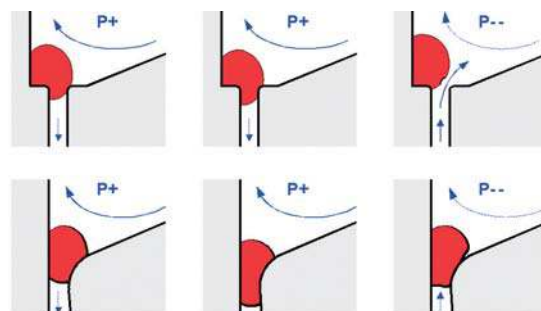


Figure 23. Possible particle extrusion mechanisms.

The behaviour of partly extruded adhesive particles during the reverse pulse should also play an important role in a multi-step stickies extrusion process, since the duration of the reverse pulse is extremely short, down to 2 ms with foil rotors. This means that the detachment of the adhesive particle from the slot wall could strongly retain the particle as long as water has not penetrated in the surface between the adhesive and the slot wall, assuming that time and pressure were sufficient to expel the water from the contact surface during the positive pressure pulse. The viscous component of the adhesive material might help to detach the particle during the reverse pulse if relaxation time is much longer time than the reverse pulse. Figure 23 illustrates possible “reverse extrusion” mechanisms of cylindrical adhesive particles. With the milled slot, the particle should be extracted very quickly from the slot inlet assuming low penetration, but difficult to detach from the corner along the profile wall. By contrast, the extraction of the adhesive particle from the wedge wire slot should take more time, especially if the particle having passed the narrowest slot section is submitted to “reverse extrusion”. Low friction factor and high relaxation time should promote reverse extrusion. The particle should then, after detachment, be ejected very quickly back to the main flow since particle inertia can be neglected and the velocity of the reverse jet out of wedge wire slots is very high [23,24]. Unfortunately the possible extrusion mechanisms described in figure 23 do not allow to conclude easily about the most effective slot design regarding the efficiency of the reverse pulse in rejecting stickies retained at the screen plate.

Synthesis

The extrusion of viscoelastic pressure sensitive adhesive particles through slots during the screening phase in pressure screens was studied numerically and experimentally by visualisation with a single slot channel screen. Special research effort was placed on the analysis of the rheological properties of the adhesive material. The effects of screen operating, slot design and adhesive material parameters were investigated with cylindrical particles to cover typical stickies screening conditions in deinking mills.

Concerning the effects of PSA material and process parameters it was shown that :

- Water-based acrylic adhesives, which represent the major part of the PSA stickies in deinking pulps, were softer and were extruded through the slots at lower pressure than hot-melt rubber adhesives, especially after soaking as they absorbed about 50 % water.
- Increasing the temperature increased significantly particle extrusion as the adhesive became softer.

- Alkaline soaking further increased the extrusion of acrylic adhesives as the adhesive became softer, while the opposite effect was observed with the hot-melt rubber adhesives.

Consequently screening should not be performed at high temperature and pH, as acrylic adhesives are the most problematic stickies.

Concerning the effects of technological screening parameters and of geometrical particle and slot design parameters it was shown that :

- Pressure and time required to extrude cylindrical particles through slots increased linearly with particle over-size with respect to slot width (d-w).
- Particles 2 to 3 times larger than slot width were extruded at pressures in the range of typical positive pressure pulses observed in screens.
- Extrusion pressure and time were larger with milled slots compared to wedge wire slots.
- The extrusion time (a few seconds) showed to be about 2 orders of magnitude higher than the duration of the screening phase (about 20 ms).

Consequently, screens should not be operated with rotors producing high positive pressure pulses and at too high slot velocities in order to minimise stickies extrusion. However, the most important conclusion was that the extrusion of adhesive particles with significantly higher thickness than the slot width cannot take place during a single positive pressure pulse, which suggests that the extrusion process in pressure screens should take place in subsequent steps over several revolutions of the rotor.

The experimental and numerical simulation results as well as further analyses about the effects of particle inertia, showed that the extrusion of a particle reaching the slot inlet (first step or single extrusion step with small particles) should be reduced with milled compared to wedge wire screen plates, which should then be less efficient in removing stickies. However, since wedge wire screen plates might be more effective in rejecting stickies during the reverse pulse if reverse extrusion hindrance can be neglected, the advantages of milled screen plates have still to be demonstrated with respect to multi-step extrusion of large adhesive particles.

Finally it should also be kept in mind that particle extrusion is not the only micro-process step to consider in the optimisation of stickies screening since all particles do not reach the slots as they can be rejected through contacts with the profile walls.

Perspectives

The fundamental studies engaged on the extrusion of stickies through slots have clearly improved the knowledge about the physical mechanisms involved in the extrusion of soft deformable particles, but also raised a number of questions about possible multi-step particle extrusion processes.

Further analyses of adhesive rheological properties are in progress to determine more completely the dynamic behaviour of the adhesive material at high strain rates.

Experimental and numerical simulation work about the extrusion of viscoelastic particles through slots should be continued with special focus on the effects of particle inertia and on the analysis of the reverse extrusion and rejection of partly extruded adhesive particles during the negative pressure pulse.

Pilot stickies screening tests are under progress to verify the conclusions of this paper at industrial scale and to

investigate the effects of other key screening parameters, especially the influence of profile height and design on the removal efficiency of PSA stickies and on the performance of screening systems in terms of production capacity and fibre losses.

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