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HIGH QUALITY AUTOMATED HONEYCOMB POTTING WITH ACTIVE PRESSURE CONTROL

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ABSTRACT

With increasing demand and market pressure suppliers in aircraft production industry require optimized and automated processes. Especially automated honeycomb potting receives much attention in recent years. While some system integrators already offer ready to use production plants the process itself has not yet been thoroughly investigated in literature. In this paper we analyse the popular concept of velocity based dispensing and propose a new approach with closed loop control of potting pressure. In extensive experiments it has been found that the pressure is directly tied to overall process quality and its control allows for high quality, repeatability and stability in honeycomb potting.

1 INTRODUCTION

As predicted by Airbus and Boeing, the air travel market is rapidly growing and a doubling of the global commercial aircraft fleet is expected until 2037 [1,2]. Due to small batch sizes, flexible processes and individual specifications aircraft production and specifically composite structures are often produced in manual labor [3–5]. Automation is the key to achieve higher production rates and satisfy increasing quality requirements [6,7]. While much work has been done on maintenance, repair and overhaul (MRO) operations regarding primary structures made of composites, the secondary structures and hereby especially cabin components should especially focus more efficient production processes. Aircraft cabins get partially replaced regularly, with complete refurbishments in intervals up to eight years, generating an aftermarket of up to three times the volume of the OEM market [8].

Common materials in aircraft interior components are sandwich structures consisting of glass fiber prepregs (pre-impregnated with phenolic resin) as face sheets and a Nomex honeycomb core [5,8]. These panels basically fulfill the requirements for lightweight, high strength and stiffness as well as low flammability and smoke toxicity [3]. In most cases the basic panel structure need to be modified to satisfy individual requirements, such as for local reinforcement, load introduction, close-outs and milled pockets. Published design guidelines for honeycomb sandwich elements only introduce qualitative examples, and especially due to the history of manual processing the possible constructional modifications are numerous and varying between manufacturers.

As discussed in [6], most of the individual features can be manufactured with honeycomb potting which is hereby the most competitive process in regard to automated sandwich production. Therefore, automated honeycomb potting has received much attention in industry in recent years with system integrators such as Airborne offering complete production cells [9]. While available solutions cover many basic applications it is expected from industrial insight that they are not running at full potential. Apparent problems are entrapped air, potting spillage / smearing and inconsistent filling levels. With no other research work known for honeycomb potting, this paper analyzes the process and material behavior and proposes a control concept addressing the quality requirements.

2 BACKGROUND

2.1 Process description

Eschen et. al. [6] introduced a generalized process chain for sandwich production. Figure 1 illustrates the relevant sandwich components and the separate production steps during "laying" and "potting". Each of these introduce specific requirements to the process of honeycomb potting.

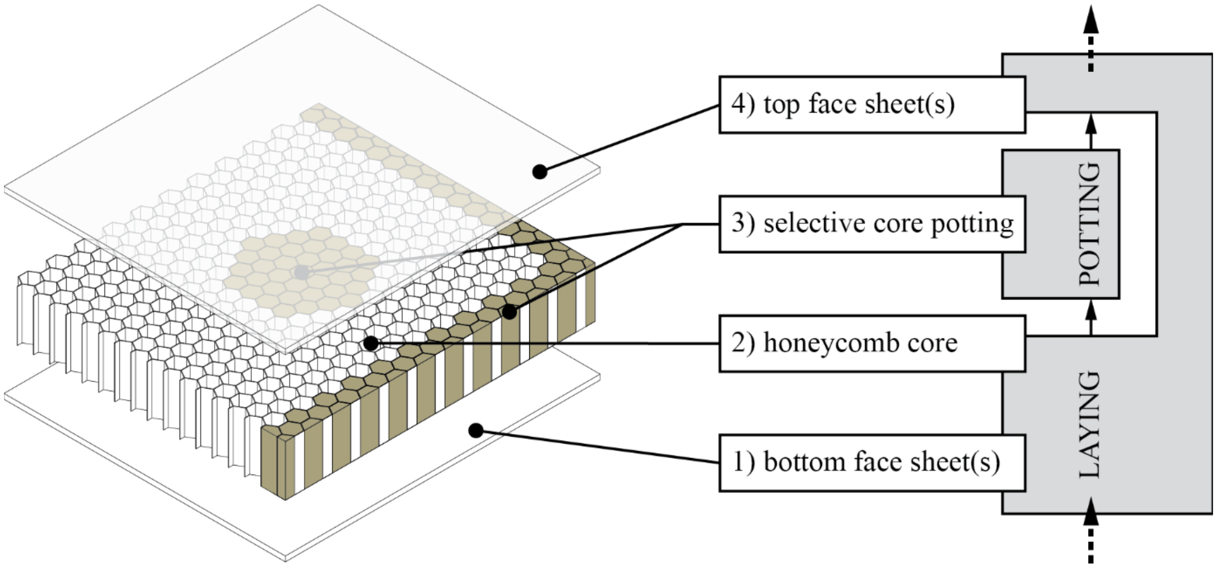

Figure 1: honeycomb potting as part of a generalized process chain

The potting itself can be achieved with different approaches. The main requirement is to completely fill each cavity at a specified area without air entrapment or damaging of core and filler material. While multiple technical approaches are feasible, an integration into already existing layup processes provides the most flexible and economical solution for smaller to mid-sized composites suppliers. Hereby the lower face sheet and the core are already laid on the workpiece carrier. The potting material is continuously dispensed through a moving nozzle at the top side of the core. To reduce smearing nozzle and core should either be at contact or with minimal gap. Figure 2 outlines the different states during the potting process.

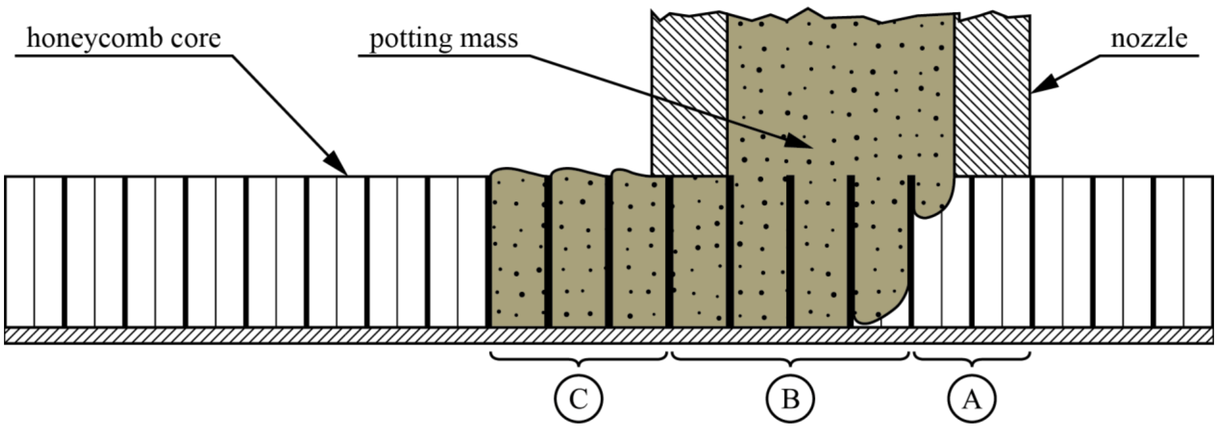

Figure 2: internal states during honeycomb potting

At the beginning of the process or with every new cell entering the area of the nozzle the potting mass can flow into the cavities with the least resistance, since the entrapped air can evacuate at the gap or contact area of nozzle and core (state *A*). As soon as material has entered over the complete cross-section of a cell (state *B*), the air can only evacuate at the contact area of core and lower face sheet. The flow resistance is hereby increased due to the tackiness of the prepreg and the higher contact force exerted by the potting mass and (depending on the setup) the nozzle. Under continued dispensing the air gets compressed and pushed out, after which the pressure builds up in the potting mass, ultimately leading to bursting cells as shown in fig. 3a. When the nozzle leaves the cells before damage occurs, pressure is released towards the top opening and the material can expand (state *C*). If the air did not completely evacuate during *B*, it is possible that potting material gets pushed out of the cell, leaving small blobs at the surface as shown in fig. 3b. Even without entrapped air, a small excess of material can appear at the top due to the compressibility of the potting mass.

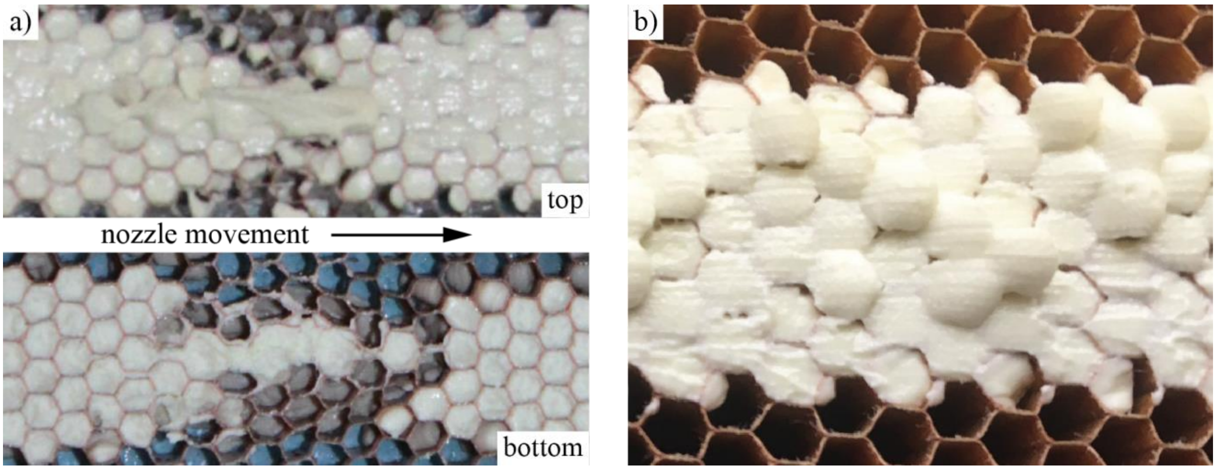

Figure 3: (a) burst honeycomb cells due to excessive potting pressure; (b) decompressed air leading to blobs of potting mass

2.2 Material properties

As already noted the common core materials are Nomex honeycomb structures. Variations with non-hexagonal patterns (such as the over-expanded cores) are used for better draping characteristics. While this work focuses on flat panels the generalized analysis is transferable to curved structures. Due to the nature of the production processes of the core sheets the cutting edges on top and bottom appear roughened and frayed (with exposed aramid fibres). Specifications usually have high tolerances in dimensions, e.g. the Airbus norm ABS5035 allows deviations of ±0.13 mm in panel height [10] at common ranges of 9-25 mm.

The prepreg has a critical role in the potting process since the entrapped air needs to evacuate at the interface to the core or through the material itself. The prepregs used as face sheets mostly consist of woven glass fibres with phenolic resin as a matrix. Within specifications such as the Airbus ABS5047 [11] prepregs can vary in percentage resin content weight, fabric type (both resulting in different ply thickness) and tackiness. The air flow through prepreg material has been thoroughly investigated for the use in out-of-autoclave curing [12]. Using the Law of Darcy the gas flow can be described as a function of a permeability factor K and a pressure gradient. It has been shown that the permeability is influenced by prepreg type and external factors such as compression of the prepreg and temperature. A high potting pressure can therefore be used to ensure sufficient air flow during evacuation, while an excessive pressure from the core on the prepreg reduces permeability and should be avoided.

Potting masses are highly viscous, thixotropic, modified epoxy resins. Common manufacturers are 3M (e.g. Scotch-Weld product line) or Cytec (e.g. BR 623P4). Additives like hollow glass spheres decrease specific gravity but increase the sensitive to shearing or high pressure. The viscosity is usually quantified by extrusion rates and in a range of 50-300 g/min according to Airbus test method AITM7-0003 [13].

2.3 Plant concept and experimental setup

The main component of the potting plant is the dispensing system. Pressure controlled systems are cost-effective solutions widely used in production of electronical components [14]. Hereby the dispensed volume is difficult to predict with non-Newtonian fluids, and even though much effort has been done in modelling the process as in [15] only positive displacement pumps can reliably control volume flow independent of rheological material properties [16,17]. For the experimental setup a progressive cavity pump (PCP) was chosen. The low shearing forces ensure low or no deterioration of the sensitive potting material while the high stiffness allow reliable dispensing of highly viscous fluids.

In preliminary studies it has been found that even small variations within specifications in the gap size between nozzle and honeycomb core can drastically increase the smearing of potting material. The gap can either be minimized by sensory inspection of actual core height and path adaption or by a force actuated tool head which controls the pressure exerted by the nozzle on the core. In this work the latter was chosen to further study the effect of different pressure levels on the probability of air entrapment.

The positioning unit needs to be selected under geometric considerations. While gantry kinematics allow processing of larger panels, industrial robots have a higher flexibility and can be utilized for other tasks such as the sandwich layup as proposed in [6]. The workpiece carrier acts as a fixture, securing the core against possible process forces or against its stiffness in case of three-dimensional parts. For common flat panels an aluminium plate with mechanical stops is sufficient.

The overall system is illustrated in fig. 4. While the control system KRC4 of the used KUKA robot would be able to also control the dispensing, the use of an external IPC increases the flexibility during development and data analysis.

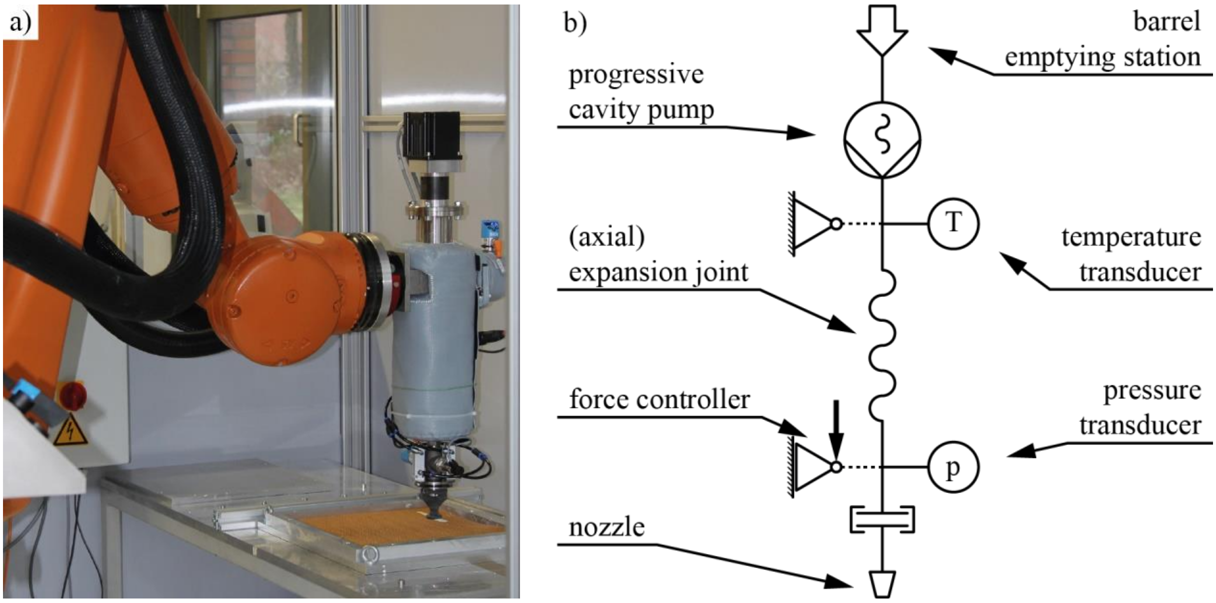

Figure 4: (a) experimental setup for honeycomb potting; (b) schematic of the potting tool

The test specimens used in this work are the widely used ABS5035-A4 Nomex honeycomb [10] with a height of 9.8 mm and 24.8 mm and ABS5035-C4 with a height of 24.5 mm as core material and one ply of ABS5047-48B prepregs [11] with tackiness level 2 as lower face sheet. For dispensing nozzle diameters of 10 mm and 15 mm were used. The test process always consists of three linear paths with overlaps of 0%, 33% and 67% in respect to nozzle diameter, e.g. as shown in figure 6.

3 POTTING CONTROL VARIANTS

3.1 Velocity Controlled Dispensing

The control task of honeycomb potting can be compared to that of adhesive or sealant application as in [16]. Hereby the volume flow is controlled so that the geometry of the dispensed bead meets quality requirements. The simplest approach is to use an open loop control with a proportionality factor between flow and velocity of the dispensing nozzle, assuming an ideally rigid behavior of the pump:

$$U \propto n \propto Q = Pv, \tag{1}$$

with volume flow Q, rotational speed of PCP n, voltage for the motor controller of the pump U, proportional gain P and the velocity of the nozzle v. For steady movement the gain equals the cross section of the bead.

In honeycomb potting the height of the cross-section of the dispensed path should always correspond to the cell height, while the ideal width depends on the number of cells covered by the nozzle and their dimensions. Therefore the width of the cross-section is dependent on the path coordinate, as illustrated in fig. 5. For sections of overlapping paths (e.g. to fill rectangular areas such as for milled pockets) the process control needs to be taken into account during path planning to generate a relative cross-sectional area as additional parameter. Additionally core specific start and stop routines are necessary to ensure complete filling. Further uncertainties arise the proportionality factor P in eq. 1, which is dependent upon cell height and nozzle diameter. With the permissible deviations in core dimensions panel thickness should be measured for each part to be potted. In conclusion it can be stated that even for a simple path the proportional gain needs to be fine-tuned.

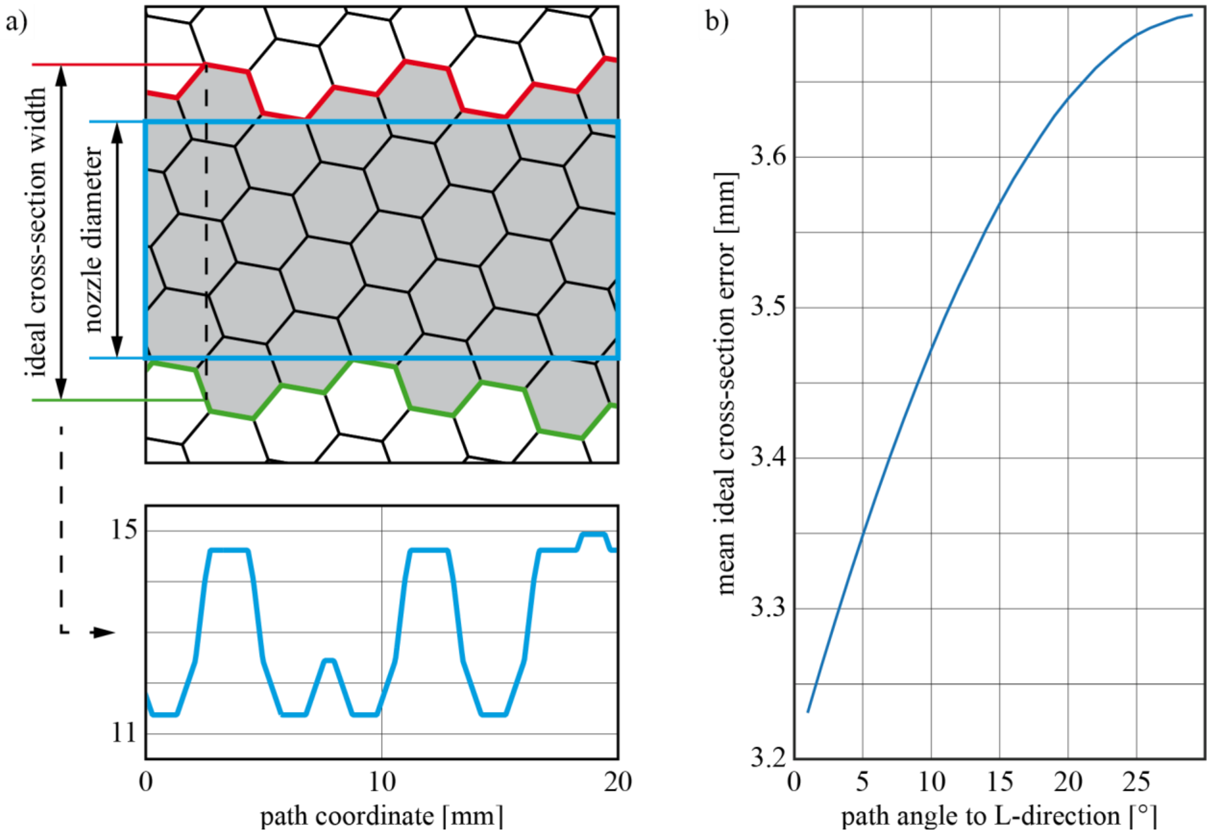

Figure 5: deviation cross-section width for ideally potted 3.2mm cells; (a) variation over path for 10 mm nozzle; (b) mean difference to nozzle diameter for different path angles

3.2 Pressure Controlled Dispensing

As already discussed the potting pressure has a relevant influence on the process outcome. Depending on the permeability and tackiness of the prepreg, a low pressure may hinder sufficient air evacuation and cause entrapment, while an elevated pressure may cause bursting of the cells or material excess due to compression during the dispensing. Leakage of the highly viscous potting mass can be prevented with a sealing nozzle design and a contact to the surface of the core or a sufficiently small gap. Therefore the dispensing can be realized with a constant pressure system.

This opens up two possible control concepts. Since the knowledge of volume flow is not necessary to achieve good process results the hardware costs can be reduced by replacing the dispenser with a set of valves. Still, the complexity of the control increases to ensure sufficient pressure at the source. Modelling of the rheological behaviour of the potting mass is hereby necessary for barrel emptying stations with piping systems of up to 5 m length. Systems with shorter flow paths and less pressure loss such as pneumatically emptied cartridges could meet the dynamic requirements without model based compensation but are only economic for small production volumes.

The approach taken in this work is to integrate a pressure sensor close to the nozzle and achieve the constant pressure system with a closed loop control of the displacement pump. The volume flow is additionally acquired via the linear relation to the motor current and used for quality control. The pressure is directly dependant on the net volume flow and a basic PI controller can be used to achieve a stable pressure level. Due to the low dynamic of the fluid system as well as the risk of instability a differential part should be omitted. Depending on the overall flow path from the pump outlet as the correcting element and the pressure transducer as measuring element the rheological behaviour and pressure losses result in a dead time. This drastically limits the dynamic of the controller, still the manually tuned PI(T_1) used in the test setup gave promising results. To increase the dynamic and stability of the control system it would be possible to either model the material behaviour or to reduce the dead time by using the nozzle velocity and hence the negative volume flow as correcting element.

4 DISCUSSION OF EXPERIMENTAL RESULTS

4.1 Validation of Potting Pressure as Quality Criteria

As underlying hypothesis of this work we stated that the potting pressure can be used to ensure complete potting of the honeycomb cells. Due to practical limitations the pressure of the potting mass is not measured at the nozzle outlet (or better, in the cell) but at a distance of about 100 mm upstream in the piping. Therefore the target values vary for each set of cell and nozzle dimensions and needed to be determined experimentally. Once defined potting results with high quality and repeatability could be achieved. As expected the target values are only dependent upon used panel components and nozzle diameter while nozzle movement (velocity and direction) and path overlap did not influence the outcome. Figure 6 and 7 show a satisfying potting result for A4-type core, 9.8 mm height with 15 mm nozzle and varying overlap. While the potting pressure is held at the target value by the closed loop controller, volume flow is reduced accordingly at different levels of overlap.

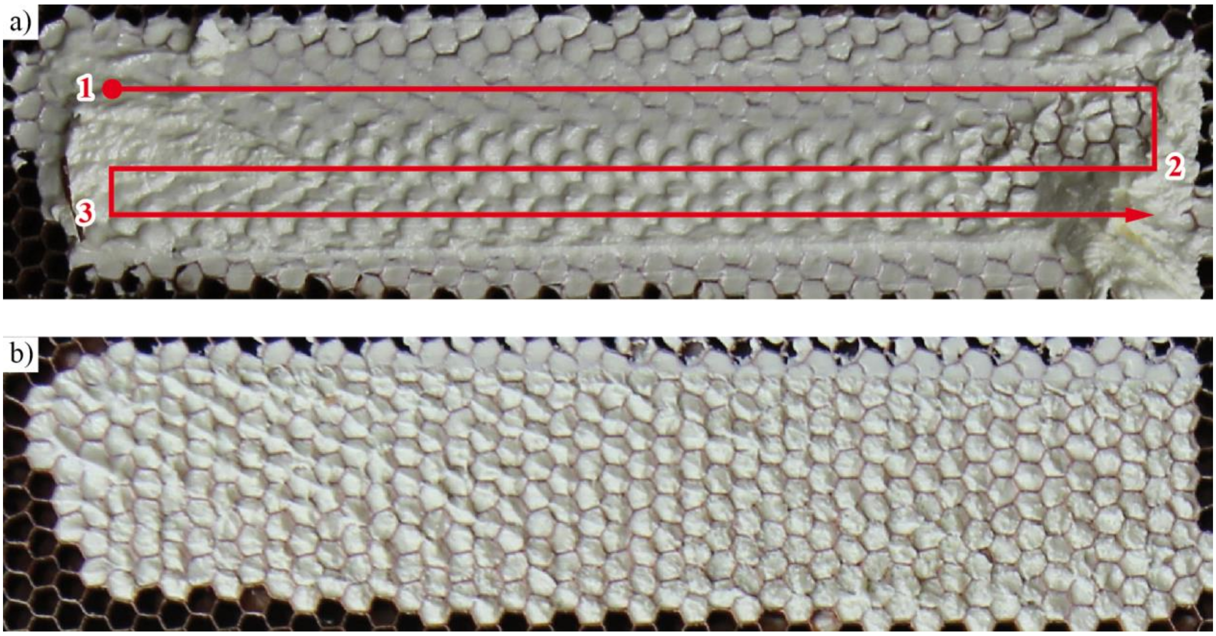

Figure 6: good potting results for A4-tpye core of 9.8 mm height with 15 mm nozzle using closed-loop control of potting pressure; (a) top view of potted core; (b) bottom view with prepreg removed

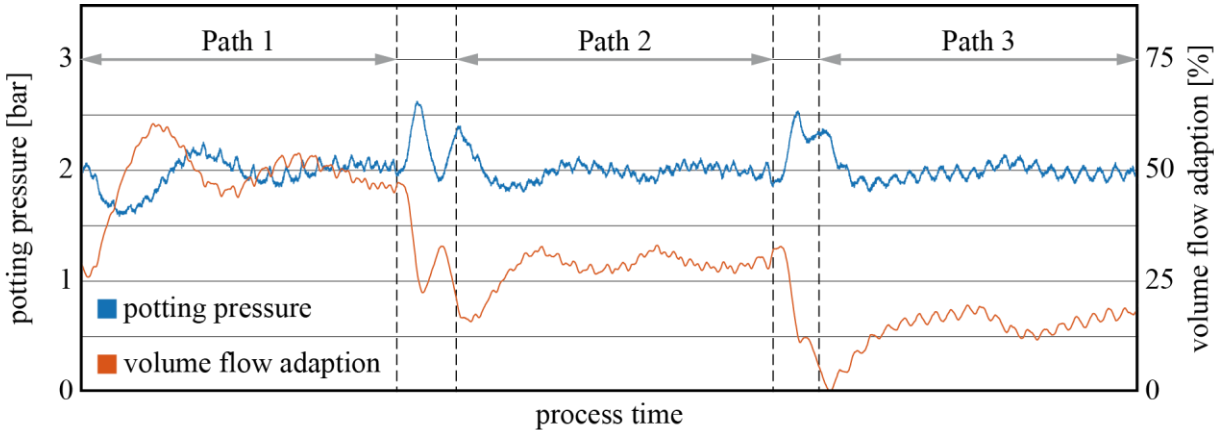

Figure 7: good potting results for A4-tpye core of 9.8 mm height with 15 mm nozzle using closed-loop control of potting pressure; potting pressure and volume flow adaption

It was observed that the process tolerates temporal variations in pressure level by about 10-20% of the target value and still generates an overall satisfying result but with increased possibility of underfilled cells at the borders. Main cause of periodic fluctuations are the changes in the cross section width (as mentioned in section 3.1). It is expected that pressure variations are compensated by compressibility of the material and the rather long flow path as long as the mean pressure corresponds to the set point.

If the mean pressure drops too low the cells are not completely filled. In case of excessive pressure different effects can be observed. Firstly, the smearing at the top of the core increases, which can be tolerated in most cases. With the use of an axial expansion joint further exceeding pressure can lead to air entrapment, since the contact forces between core and lower face sheet are also increased. This is shown in fig. 8, where poorly configured parameters of velocity based dispensing causes a steady increase in pressure level. In extreme cases the core can be destroyed as discussed in section 2.1.

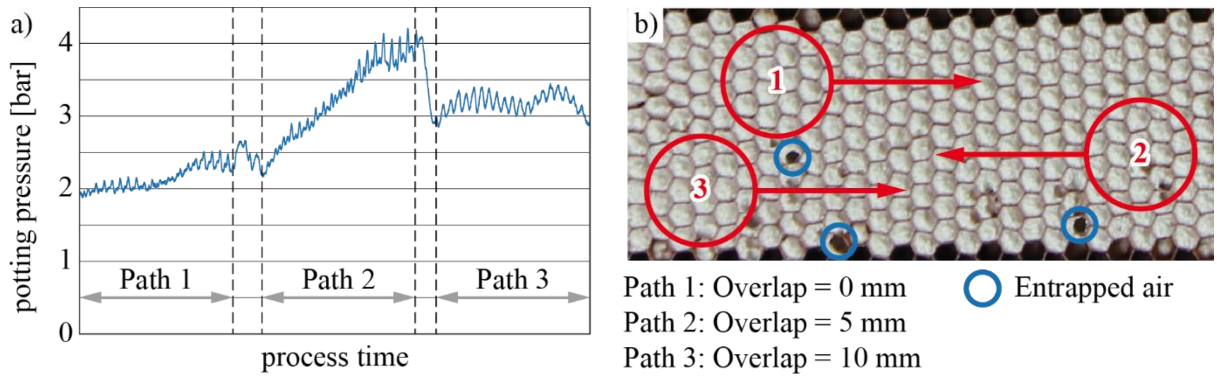

Figure 8: faulty potting results for A4-tpye core of 9.8 mm height with 15 mm nozzle using velocity based dispensing; (a) increasing potting pressure due to poor controller tuning; (b) bottom view with prepreg removed and entrapped air at excessive pressure levels

4.2 Validation of Control Concepts

Both concepts have been proven to be capable for repeatable and high quality honeycomb potting with proper parameter tuning. The closed-loop pressure control required initial determination of PI(T_1) parameters which then where used for all conducted experiments. The following selection of pressure set points required very few effort and iterations since effects are directly apparent. Fine tuning of the proportional gain of velocity based control is less intuitive since it needs to compensate for calibration errors of the dispensing pump, tolerances of nozzle diameter and cross-section deviations. Especially the latter leads in conjunction with varying path overlaps to limited usability of this control concept. For a simple path the compensation can be approximated in a first iteration by the model proposed in section 3.1. In case of overlapping paths this compensation should ideally be adapted. Otherwise pressure levels can change during the process. Additionally due to the dependency of cross-section width on position and movement direction of the nozzle in relation to the core identical potting processes can result in different pressure gradients. Both effects are illustrated in figure 9.

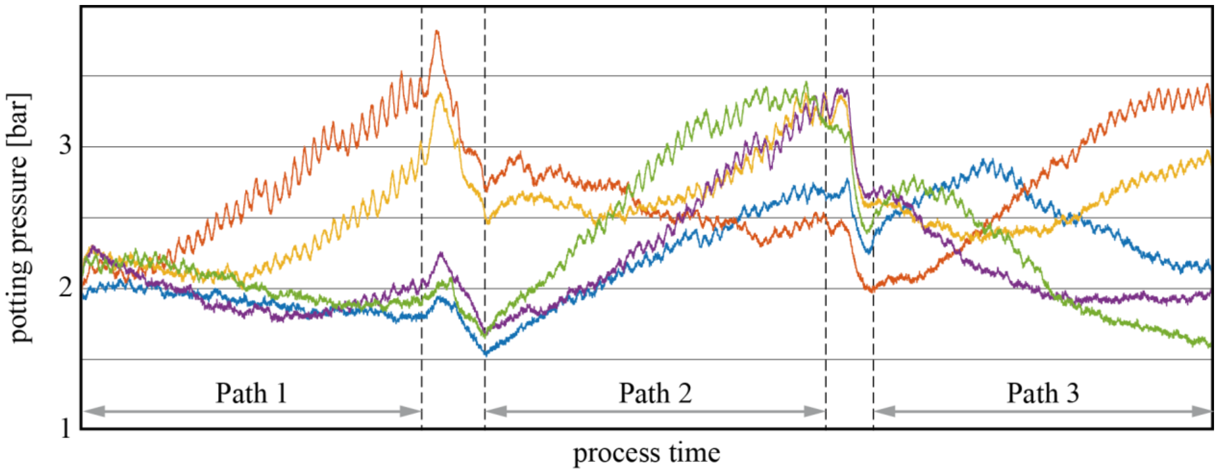

Figure 9: different pressure gradients during velocity based dispensing with identical control and path parameters due to overlap and position dependency of cross-section width

The pressure controlled dispensing delivers very promising potting results independent on path position, orientation and overlap. The only discovered limitation lies in the slow dynamic of the initially tuned PI(T_1). In case of elevated nozzle velocity the controller was not able to deliver necessary volume flows at initial sections of the paths, as illustrated in fig. 10. In future work this could be addressed by parameter sets adjusted for different velocity ranges.

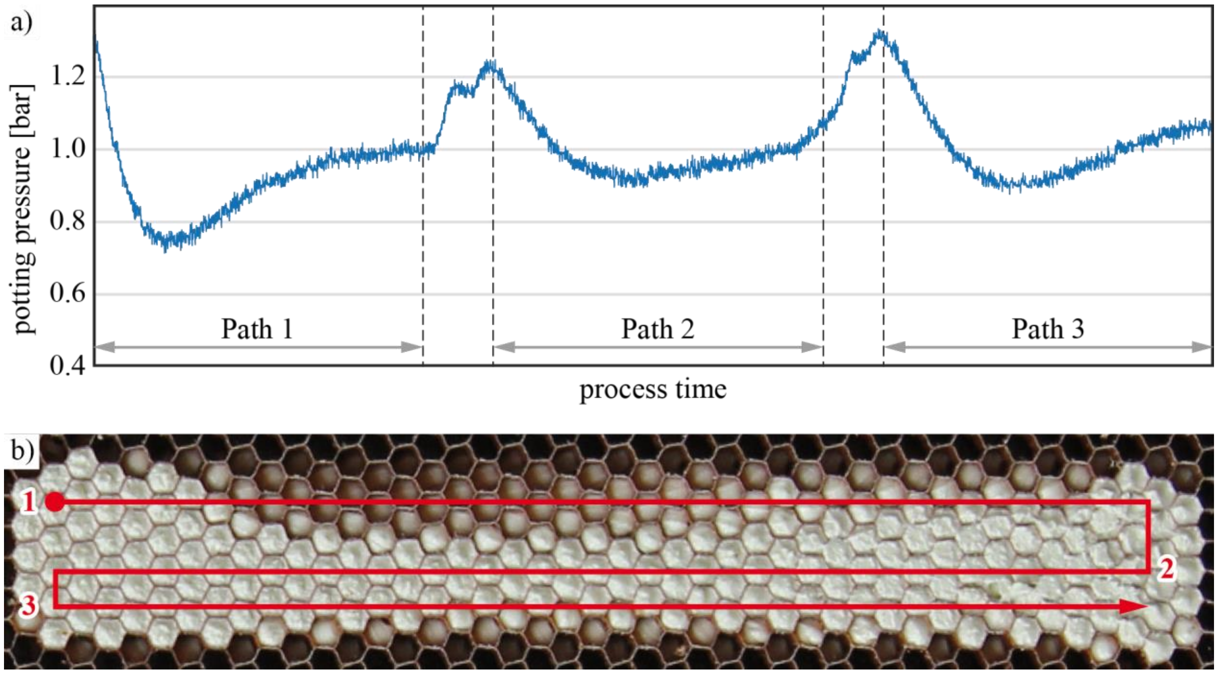

Figure 10: (a) slow pressure buildup with closed-loop control at high nozzle velocities due to limited dynamics; (b) bottom view with prepreg removed

5 CONCLUSIONS

In this paper different control concepts for automated honeycomb potting were compared. The classical approach with open-loop control of volume flow based on nozzle diameter, velocity and core dimensions is known to be used in available industrial applications and works similarly as widespread glue bead application processes. The main advantage hereby is the simple controller layout and therefore the effortless implementation in available controllers of handling devices. Limitations of velocity based dispensing for honeycomb potting lie within the counterintuitive fine tuning and problematic repeatability at overlapping paths. The necessity to know overlaps for valid process control increases complexity of path planning algorithms. Since the potting pressure has been found to be directly tied to overall process quality a closed-loop control results in high repeatability and stability to variations in core dimensions and tool velocity. With automatic adaption of volume flow even extreme overlaps can be processed. This concept decouples planning and processing algorithms and facilitates the development of optimized CAD/CAM solutions. Further work needs to address the problem of low dynamics apparent at higher velocities and optimization of the tool head with reduced flow paths and dead time. The validation of pressure based control opens up the possibility to realize honeycomb potting with pneumatic dispensing and therefore drastically reduced investment.

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