INVESTIGATION OF INFLUENCING PARAMETERS WITH RESPECT TO FILLING TIME IN VIBRATION ASSISTED RTM PROCESSES

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Keywords: *Resin Transfer Molding, vibration assistance, shear thinning, mold filling time*

1 Introduction

Industries of the transport sector count on lightweight materials in general and on Carbon Fiber Reinforced Plastics (CFRP) in particular for the reduction of CO^2 emissions and energy consumption. The high specific mechanical properties of CFRP are also of interest in other fields such as wind energy production for the manufacture of large rotor blades. Broader application of CFRP is often limited, however, by their high costs resulting from expensive raw materials as well as lengthy and labor intensive production processes. The latter are addressed by Liquid Composite Molding (LCM) processes, which offer high potentials for automated production and short cycle times.

Resin Transfer Molding processes are a specific type of LCM processes and encompass the use of stiff molds giving the opportunity of a fast production of high quality Fiber Reinforced Plastics (FRP) parts. In the RTM process, a dry fibrous preform is placed into a cavity, the mold is closed and resin is forced through the porous textile. The flow is driven by an applied pressure difference between the resin reservoir and the cavity. The infiltration process can be modeled using Darcy's law which describes a linear correlation between the resin flow velocity v within a homogeneous porous media and the applied pressure gradient ∇p: [1]

$$v = -\frac{K}{\eta}\nabla p \qquad (1)$$

The proportionality constant is the quotient of the permeability K of the fibrous preform and the dynamic viscosity η. Hence, highly permeable preforms together with low viscosity resins are advantageous for high resin velocities and thus fast infiltration and short cycle times. Along with the applied temperature and the degree of curing, the viscosity of some thermoset resins depends on the applied shear rate. Additional shear rates induced by the application of vibration assistance in LCM processes result in a reduced viscosity [2]. In addition to this, the effects of vibration assistance on the compaction behavior of the fibrous preform [5] and the void content of the resulting material [3, 4] have already been observed.

In this work, additional shear rates are induced into the liquid matrix by a vibration engine which is mounted on the RTM tool with the entire setup being supported by 4 coil springs (Fig. 1). The study presented investigates the efficiency of vibration assistance in RTM processes with respect to the mold filling time for the following process parameters: injection pressure (2 and 3 bars), mold temperature (20 to 40 °C), vibration frequency (10 and 60 Hz) and the spring rate of the coil springs. To this end, filling studies by means of channel flow experiments are performed. Furthermore, the flow behavior of the resin is characterized in a rheometer.

A reduction in mold filling time is expected for resin systems showing shear thinning behavior due to the decreased apparent viscosity which results from the created vibration motions in the injected resin. The question whether high vibration frequencies and/or amplitudes are more beneficial for an enhanced resin flow is addressed, too.

2 Mathematical description of the infiltration process in channel flow experiments

For channel flow experiments with constant inlet pressures, Darcy's law can be transferred into [6]:

$$x_f{}^2 = \frac{2Kt\Delta p}{\eta(1-\varphi)} \tag{2}$$

In Eq. 2, x_f represents the flow front position, K the permeability, t the time, Δp the pressure difference between the injection pressure p_{inj} and the flow front and φ the fiber volume content (FVC) of the compacted preform.

Under the assumption of a constant permeability K, a constant fiber volume fraction φ and a constant pressure difference Δp during the experiment Eq. 2 can be rewritten as:

$$x_f = \left(\frac{C}{\eta}t\right)^{0.5} \tag{3}$$

The constant parameters of Eq. 2 are summarized into one constant C in Eq. 3. Hence, the flow front progression over time in a channel flow experiment can be theoretically modeled by a power function with exponent 0.5. This correlation will later be used as quality criterion for the performed filling experiments.

If the permeability of the preform is known and remains constant during infiltration, then Eq. 3 can be rearranged to determine the viscosity during infiltration:

$$\eta = \frac{C}{x_f{}^2}t \tag{4}$$

2 Materials and test setup

In contrast to other studies in the literature dealing with vibration assisted LCM processes [2, 3, 4, 5, 7], the present work focuses on standard materials and processes which are currently applied in industry. A carbon weave is infiltrated with epoxy resin in a RTM process, hence, a CFRP plate is manufactured in each channel flow experiment.

2.1 Reinforcement material

A carbon 5H satin-weave, 370 g/m², manufactured by Hexcel (HexForce® G0926 D 1304 TCT) is used as fiber material. The layers are manually cut to a size of 380 x 192 mm, with the warp direction being aligned with the longer edge. Stacks of nine layers are compacted in a mold to a target thickness of 3 mm resulting in a target FVC of 63.07 %. This material is typically used in aerospace applications.

2.2 Matrix materials

The preforms are infiltrated by an epoxy resin system (EPIKOTE™ Resin MGS® RIMR 135 and EPIKURE™ Curing Agent MGS® RIMH 1366) manufactured by Momentive. The same amount of resin and hardener are mixed manually for each trial according to the mixing ratio suggested in the data sheet at room temperature, 15 minutes before the injection is started. This epoxy resin is typically used for the production of wind turbine blades. A slow curing resin system designed for curing at room temperature is chosen in order to keep the experimental procedure easy to control and the prepared samples easy to handle. In addition to this, the influence of curing reactions can almost be excluded here, making the results more robust against inevitable differences in the sample preparation and the experimental procedure, such as slightly varying room temperatures during mixing and infiltration. Consequently, an equal initial mixing viscosity is ensured throughout the experiments.

Silicon oil (Dow Corning® Xiameter PMX 200/100 cS) is chosen as the reference material for a Newtonian fluid. .

2.3 Test setup

The mold consists of a 17-mm thick steel lower platen, a 3-mm thick spacer frame and a 35-mm thick transparent polycarbonate upper platen. The fiber stacks are placed in the cavity with the aid of spacers to ensure uniform positioning of the preform in each experiment with respect to the markings on the transparent mold half, which are necessary to measure the flow front progression during infiltration. The cavity dimension in the lengthwise direction is longer than the preform, resulting in the linear inlet and outlet typical for channel flow experiments [6]. Strips of rectangular cut silicon gaskets are placed alongside the longer edge of the preform between the fiber stacks and the spacer frame to prevent race tracking effects. The linear inlet is connected to a pressure pot and the outlet to a can. The injection pressure is manually adjusted by a pressure controller and monitored by a pressure transducer.

A vibration engine (MVE 60/30M from OLI® Vibrationstechnik) is mounted on the rear side of the lower tooling platen. Since the rotational axis of the engine is oriented in the lengthwise direction of the setup, the unbalanced torque creates shaking motions perpendicular to the adjusted pressure gradient and flow of the injected resin. The mold is supported by four coil springs mounted at the edges of the lower mold so that shaking motions are induced into the setup by the engine. Since the viscosity of the epoxy resin is highly sensitive to temperature, the vibration engine is mounted to the tooling plate having a small gap of approximately 10 mm. Through this gap, the waste heat generated by the engine can be released by an installed fan combined with cooling fins which are attached to the engine. Furthermore, the temperature of the tooling is measured by a thermocouple placed on the tooling plate directly above the engine. The experimental setup is shown schematically in Fig. 1 and 2.

3 Experimental descriptions

The goal of this study is to identify influencing parameters in vibration assisted LCM processes. A closed mold process is chosen for this purpose since the compaction of the fibrous preform and thus the permeability can be assumed constant during infiltration in contrast to Resin Infusion under Flexible Tooling (RIFT) processes [8]. The injection pressure, the processing temperature, the frequency of the vibration motion and the spring rate of the coil springs supporting the entire setup are investigated as influential variables. The stiffness of the coil springs, the unbalanced mass and the frequency of the vibration engine together with the total mass of the vibrating setup determine the amplitude of the swinging motion. It must be noted here however, that the frequency of the vibration engine and the amplitude of the oscillating mold are expected to be unequal to those in the liquid matrix.

3.1 Permeability measurements

Since Eq. 4 will be used to determine the viscosity during filling, the appropriate permeability value of the preform is mandatory and must be determined in advance. For this purpose, permeability values of the compacted fiber stacks are measured in the same setup and not in a separate permeability test rig. Although the described mold is very similar to that used in the type of permeability test facility suggested in the literature [9], different results would have been likely due to differences in the deflection and thickness variations of the molds.

Silicon oil is applied to measure the unsaturated permeability value. The tests are performed at room temperature for constant injection pressures of 2 and 3 bars to account for the resulting higher mold deflections and thus the overall permeability values. The mold temperature is recorded throughout the test in order to determine the oil viscosity for the calculation of the permeability. Apart from that, the general experimental procedure of the unsaturated permeability tests is equal to the filling studies described later in section 3.3. The permeability measurements are made without applied vibrations.

3.2 Rheological measurements

The shear thinning and the Newtonian behavior of both, the epoxy resin and the silicon oil are characterized in a rheometer (MCR 302 from Anton Paar). A constant shear rate is induced across the sample by applying a cone and plate measurement system with a cone angle of 1°. The viscosity is determined for logarithmic linearly increasing shear rates between 1 and 15 000 s^{-1}. No studies could be found in literature concerning the determination of shear rates in LCM processes. The maximum shear rate range of the rheometer is therefore chosen. The shear thinning behavior of the epoxy resin is measured at 20, 30, 35 and 40 °C. To account for possible curing effects, these measurements are conducted 15, 30 and 45 minutes after mixing. According to the manufacturer’s specifications, the pot life of the epoxy is around 60 minutes at 30 °C. The Newtonian behavior of the silicon oil is verified at 25 °C. A viscosity profile between 10 and 30°C is further determined for the analysis of the permeability tests.

3.3 Filling studies

The entire setup described in section 2.3 (Fig. 1) is installed in an oven to control specific mold temperatures and exclude perturbations caused by varying room temperatures. The inlet of the mold is connected to a pressure pot outside the oven whereby the outlet of the mold is completely inside. In preliminary studies it was proven that the mold temperature dominates the resin temperature. The latter exhibits mold temperature after only a few seconds for an adjusted temperature difference between the injected resin and the mold of 35 °C. The channel flow experiment is started by opening the injection gate as soon as the pressure in the pressure pot is adjusted and after 1 hour when the whole mold is at a uniform temperature in the oven. All experiments are carried out at constant injection pressures for either 1 hour or until the flow front reaches the outlet. The flow front progression is monitored by a video camera installed above the transparent mold. The experimental setup is schematically shown in Fig. 2.

3.4 Experimental design

The basic parameters in vibration assisted RTM processes for a specific layup are considered to be injection pressure p_{inj}, mold temperature T, frequency f and stiffness of the spring coils c. Their influences on the resin flow velocity are investigated in filling studies as described in section 3.3. Since the temperature primarily influences the viscosity of the resin, effects of different temperatures are principally studied in rheological measurements performed before the filling studies (see section 3.2). Channel flow experiments at specific temperatures based on these results are performed for validation purposes of the rheological investigations and are compared to reference measurements without vibration. Possible effects of all of the other parameters are investigated in screening experiments using a two-level fractional factorial 2^{k-1} design with a resolution of III as suggested in [10] for experiments with a high number of possible factors k. The two levels of the specific factors k are listed in Tab. 1.

4 Results and discussions

4.1 Permeability measurements

The results of the permeability measurements are shown in Tab. 2 for the two different injection pressures. The permeability measured at 2 bars injection pressure is lower than the value measured at 3 bars. This meets the expectations since higher injection pressures lead to increased mold deflection and consequentially lower overall FVC [9] while lower FVC lead to higher permeability values [1]. The actual FVC is determined for each preform based on its weight and the mean values are given in the brackets of Tab. 2 together with the target values calculated for a mold with infinite stiffness and the areal weight of the applied weave according to the manufacturer’s datasheet. Mold deflection has neither been considered for calculation of the actual FVC. The differences between the target and actual FVC are around 0.5 % FVC.

4.2 Rheological measurements

The viscosity curves for the various temperatures of the manually mixed resin 30 minutes after mixing are shown in Fig. 3 together with the curve of the silicon oil representing a Newtonian fluid. The different viscosity levels are explained by the different temperatures with the lowest viscosity being measured at the highest temperature. With the exception of the curve at 40 °C, all of the curves generally exhibit shear thinning behavior at low shear rates. Each of these curves can be divided into three regions. The fluid behavior is described as shear thinning according to the literature [11] for shear rates between 1 and 100 s^{-1} and for those above 1 000 s^{-1}. The resin behaves as a Newtonian fluid at values between 100 and 1 000 s^{-1} and also at 40 °C. Consequently, the shear thinning behavior of the epoxy resin depends on the processing temperature at lower shear rates and does generally not change during curing. The latter is shown in Fig. 4, where the viscosity curves at 30 °C are exhibited at different times after mixing. The increasing viscosity levels of the curves are attributed to the ongoing curing reaction.

4.3 Filling studies

Filling studies based on the results of the rheological measurements are performed at 30 °C and 40 °C. The former temperature is chosen to investigate the influencing parameters of vibration assisted RTM processes and the latter to prove that the effect of an enhanced flow in vibration assisted LCM processes is due to the shear thinning behavior of the epoxy resin.

Fig. 5 presents the results of the filling studies. Firstly, the flow front progression is faster in the case of a higher injection pressure of 3 bars compared to the trials at 2 bars and consequently meets the expectations. As can be seen in the upper curves, one set of parameters leads to an enhanced flow for both levels of injection pressure. The stiffer coil springs are applied in both cases but at different frequencies. A frequency of 60 Hz at 2 bars injection pressure and a frequency of 10 Hz at 3 bars are seen to be most beneficial. In contrast to the static trials, no enhanced flow is measured for the trials with the weak coil springs. Although it can initially be concluded that stiffer coil springs should be chosen in vibration assisted LCM processes, a different scenario emerges when the resulting amplitudes of the swinging motions are calculated. Fig. 6 shows the vibration response of the setup for the different coil springs when the model of a simple mass oscillator is assumed. A high frequency combined with a low amplitude is most beneficial for the 2 bar injection pressure experiments, while a low frequency combined with a high amplitude is preferable at 3 bars. Consequently, the two parameters of frequency and amplitude generally influence the creation of additional shear rates in the liquid matrix and interact with the applied injection pressure. Additional experiments are needed to draw further conclusions about the significance of the detected interactions [10]. Nevertheless it can be stated, that the effectiveness of vibration assistance with respect to a faster flow front progression amounts to 25 % for the 2 bar trial and 17 % for the 3 bar trial compared to the static cases, where the times until the flow fronts touch the farthest position amount to 3500 s and 3200 s, respectively.

The experimental data fit well with the theoretical function of Eq. 3 which describes the flow front progression for experiments with constant injection pressure. This is further shown in Fig. 5 by the fitted line of the fastest trials. It therefore seems reasonable to use Eq. 4 for the determination of the apparent viscosity during mold filling. The results for the experiments with 2 bars injection pressure are shown in Fig. 8. The lowest viscosity is determined for the fastest trials and is about 20 % lower than the viscosities in the reference trials and trials without any effect of vibration assistance. These values coincide with the viscosity values measured in the rheometer at 30 °C. Conclusions about the apparent shear rates based on the rheological data cannot however be drawn due to the long duration of the filling studies and the resulting changes in viscosity due to curing. Furthermore, local mold deflections are not considered in this approach. The overall permeability value of Tab. 2 is used for the calculation of the resin viscosity according to Eq. 4.

The experiments with the biggest effect are repeated at 40 °C and compared with the static trials at the same temperature. The results are shown in Fig. 7 and indicate no enhanced flow due to vibration assistance. Consequently, the higher resin velocities of Fig. 5 can be related to the shear thinning behavior of the epoxy resin at temperatures below 40 °C as the rheological investigations suggest (compare Fig. 3).

5 Conclusions

The paper presented here proves that shear thinning epoxy resins provide the opportunity for faster mold filling by introducing additional shear rates. In this work, it is achieved by a vibration engine mounted to the mold with the entire setup being supported by coils springs. The flow behavior of the applied epoxy resin is analyzed in a rheological study. It is discovered, that the shear thinning behavior depends on temperature. Newtonian behavior at low shear rates only exists above a certain temperature of the investigated resin system. Filling studies based on these results are performed which demonstrate that both, the frequency and the amplitude of the vibration motion influence the resin flow. For constant injection pressures of 2 and 3 bars the time until the flow front touches the farthest position in the filling study is reduced by 25 and 17 %, respectively. It is further demonstrated that the faster flow front in vibration assisted LCM processes can be related to the shear thinning behavior of the resin at lower shear rates.

In the future, the determination of shear rates in LCM processes will be addressed by flow simulations. Knowledge of the natural mean shear rate during infiltration without vibration assistance is seen as essential for deciding whether additional shear rates lead to decreased viscosities based on the viscosity curves determined in the rheometer. Moreover, the discovered interactions between process parameters such as injection pressure, frequency and the amplitude of the vibration motions will further be investigated. Thereto, a stiffer mold will be designed in order to reduce the influence of mold deflections on the filling studies and process value.

Acknowledgements

The authors gratefully acknowledge the support of the Institute for Carbon Composites and the TUM Graduate School of the Technische Universität München.

Figures

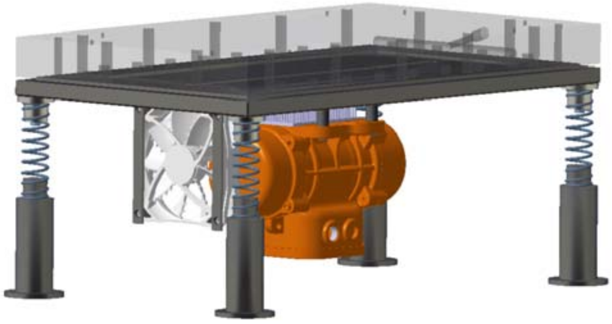

Fig. 1: Vibration assisted standalone RTM tool.

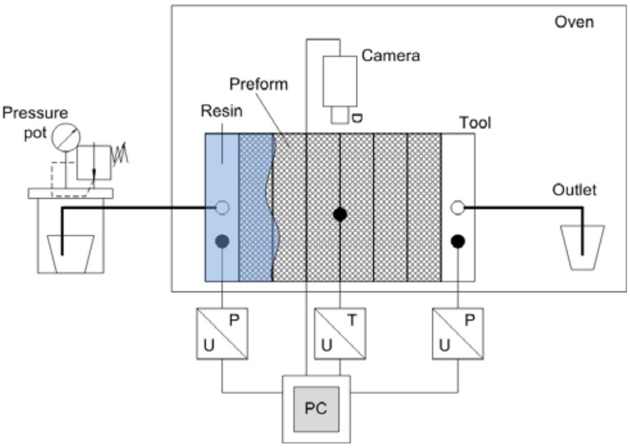

Fig. 2: Experimental setup.

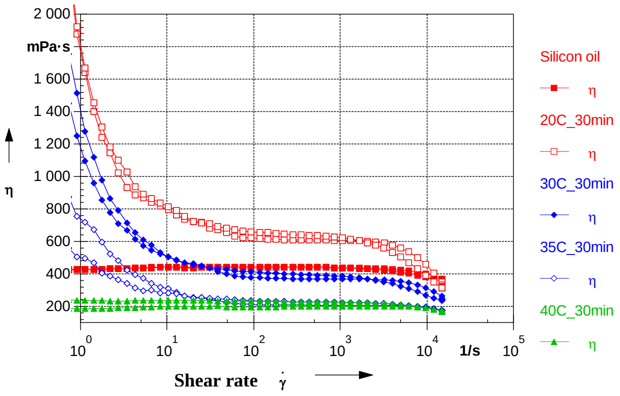

Fig. 3: Viscosity curves of the silicon oil and the investigated epoxy resin at various temperatures.

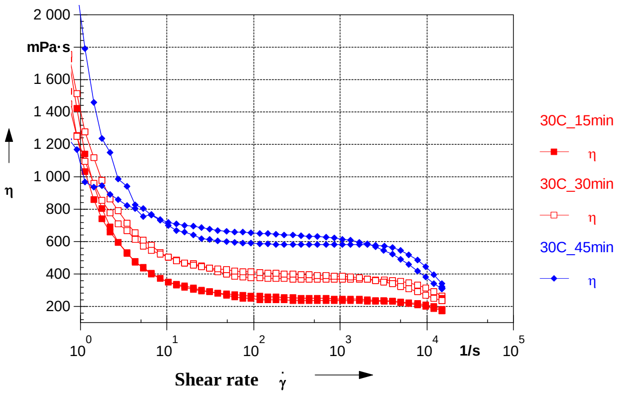

Fig. 4: Viscosity curves at different times after mixing.

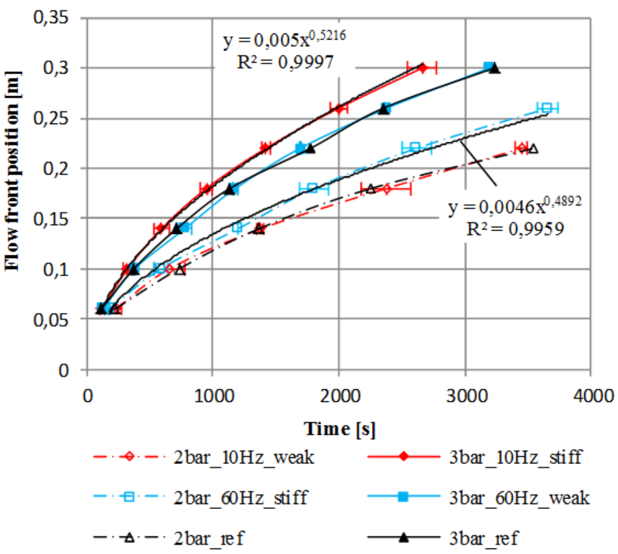

Fig. 5: Flow front progression over time at 30 °C. The error bars represent the standard deviation.

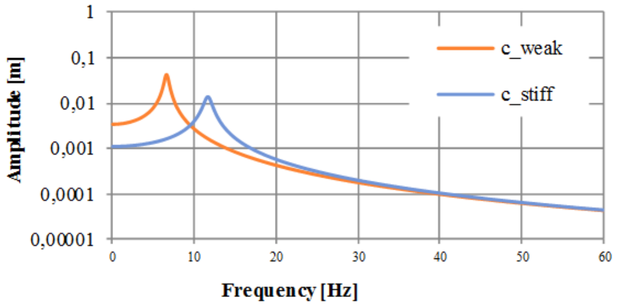

Fig. 6: Vibration response of the setup for the different coil springs.

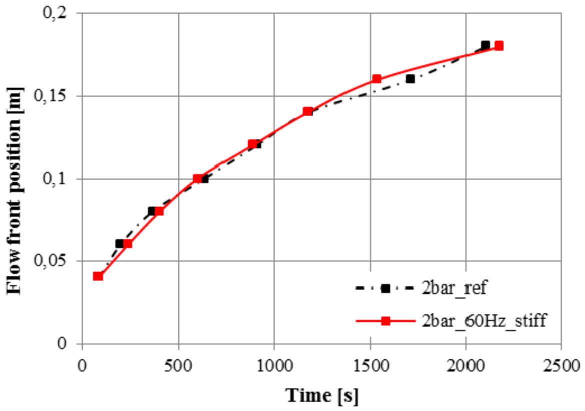

Fig. 7: Flow front progression over time at 40 °C.

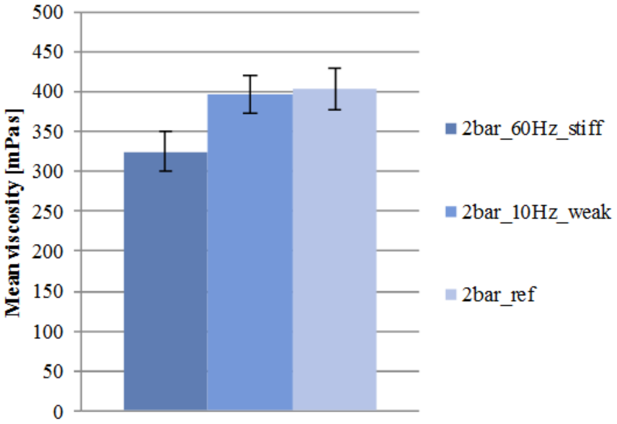

Fig. 8: Calculated mean viscosities in the filling studies with 2 bars injection pressure. The error bars represent the standard deviation.

Tables

Factors Levels	p_{inj} [bar]	f [Hz]	c [N/m]
High	3	10	230 472*
Low	2	60	74 784**

* c_{stiff}

** c_{weak}

Tab. 1: Design variables and levels.

p_{in} [bar]	*2*	*3*
K (63.07*) [m²]	5.24E-12 m² (63.60 %**)	7.73E-12 m² (63.59 %**)

* Target FVC for the given number of layers N

** Mean FVC based on the preform weight

Tab. 2: Permeability values for the two different injection pressures.

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