HIGH-SPEED CURTAIN RECOATING FOR STEREOLITHOGRAPHY

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Abstract

The University of Leuven uses a liquid curtain recoating system for resin deposition in stereolithography. This system deposits new liquid layers of photo-polymer by means of a liquid curtain travelling over the build vat. Experiments have been carried out to increase the speed of the liquid curtain while depositing a layer. Speeds up to 1.2 m/s, and accelerations up to 1 g have been tested successfully, meaning that it is possible to coat high-quality layers of 75 μm thickness with this recoating technique. However, the curtain restores too slowly after acceleration. This paper discusses possible reasons and tries to formulate adequate solutions. Possible solutions consist in controlling small pressure differences in the curtain's neighbourhood. A solution to this problem is necessary, as to make the travelling length of the curtain, and so the machine length acceptable with respect to the dimensions of the build vat.

Introduction

The process of *curtain coating* consists of pumping a coating liquid from a reservoir into a precision extrusion head, which has a narrow slot along its lower face. The liquid is extruded out of the slot, and in flowing downwards under the influence of gravity it forms a liquid sheet, also called a *liquid curtain*. The liquid curtain then hits a substrate. This substrate moves relative to the curtain, and by so doing a liquid film is coated onto it. Liquid sheets are often employed to deposit uniform liquid layers on a moving substrate as, for example, in the coating of photographic film. For more applications, the reader should consult Finnicum [4] and the references of Brown [2]. Typically, the liquid curtain is long and thin, and can be up to several metres wide. Because of their technological and theoretical interest, the flow in a liquid curtain has been extensively studied, addressing both the shape of the curtain [4, 5], and instability issues [8, 7, 2].

In our application the extrusion head is displaced, rather than the substrate. The substrate, consisting of a build vat filled with liquid photo-polymer and a partially built stereolithography part, is not moving. In order to apply a new liquid layer in the stereolithography process, the extrusion head together with the liquid curtain is moved over the build vat. As several subsequent layers are coated during the process of fabricating a part with stereolithography, we refer to this coating technique as *curtain recoating* [9, 6]. Curtain recoating is one of the fastest coating techniques, able to coat a new liquid layer for stereolithography in about two seconds. Considered the appreciable amount of layers a stereolithography product usually consists of, curtain recoating enables a substantial reduction of part build times.

Basically, a build vat with moving platform is used as depicted in figure 1. Before coating a new layer of liquid photo-polymer, the platform is lowered over a distance equal to the layer thickness. Hereafter, the coating head, and thus the liquid curtain is moved over the build vat. As a result, the liquid level in the build vat after each newly coated layer remains at constant height. A basin around the build vat collects the excess of resin and feeds it to a supply reservoir which, in turn, feeds a metering pump. In a sense, this application of curtain coating is unique with respect to all previously published studies, because of the coating head, rather than the substrate, is moving. The problem of seeking optimal operating conditions, necessary to coat layers of good quality is described in the following section. The subsequent sections discuss the experiments that have been performed in order to gain a better understanding of the curtain's dynamic behaviour, a necessary prerequisite for process improvement.

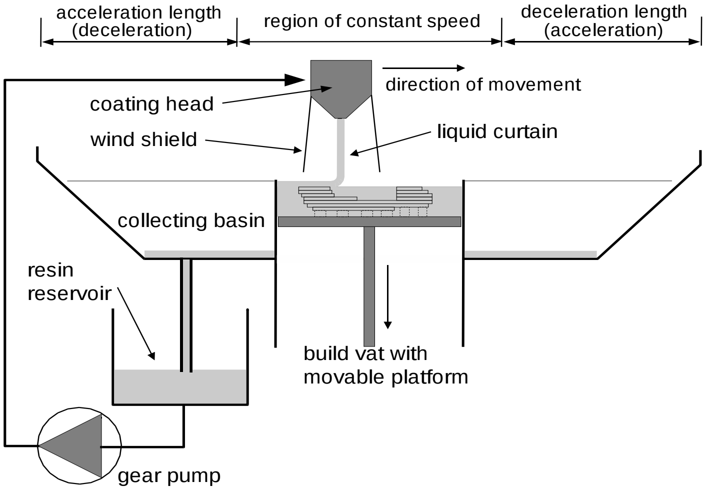

Figure 1: *Curtain recoating for stereolithography: coating of a new liquid layer*

Problem description

The thickness d of a coated liquid layer relates to the flow rate q through the extrusion head's slot per unit slot width [m^2/s], and the speed of the coating head U [m/s], according to:

$$d = \frac{q}{U}. \tag{1}$$

In order to coat a layer of uniform thickness, q must be constant along the width of the curtain, and U must remain constant while the head crosses over the build vat. There exists a minimum value for q for good operation, based on a stability issue for the liquid curtain. Below this minimal q the liquid curtain breaks and no intact liquid layers can be coated. Hence, in order to further decrease the thickness of a coated layer, U has to be increased. A typical value for q = 90 mm^2/s for our coating head, meaning that in order to coat a layer of d = 100 μm, U must be 0.9 m/s; for d = 60 μm, U = 1.5 m/s.

Actually, decreasing the layer thickness is not the primary goal of high-speed curtain recoating. The deposition of a liquid layer of good quality is a more stringent problem to be solved. If the recoating speed U is equal to the fluid velocity V in the curtain at a point where it impinges onto the substrate, then the thickness d of the coated layer will be equal to the thickness h of the curtain at its lower end. When U is smaller than V, d will be larger than h, and a kind of 'heel' will form where the curtain hits the substrate [1, 3]. Figure 2 depicts this phenomenon. Recirculating flows will develop in this heel, thereby entrapping air in tiny bubbles. These bubbles will, eventually, be trapped in the liquid layer. At present, the curtain in our machine is 125 mm long, and the velocity of the fluid at the lower end of the curtain is about 1.4 m/s [2]. The maximum achievable speed U in our machine is 0.7 m/s, meaning that the thickness of the coated layer d is about two times the curtain thickness h at its lower end. Thus, our primary goal in this research is seeking better operating conditions than the ones presently used.

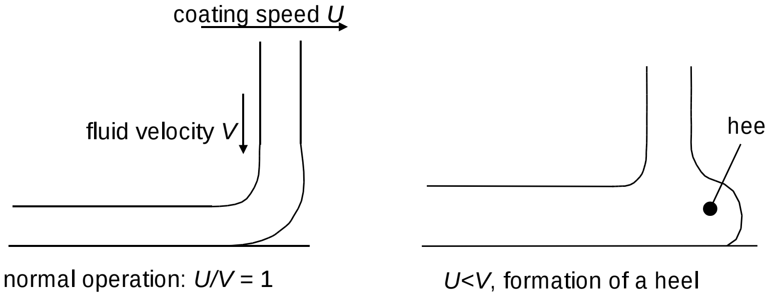

Figure 2: *Formation of a heel at the lower end of a liquid curtain when the coating speed is substantially smaller than the fluid velocity in the curtain*

In order to coat a liquid layer, the coating head has to be accelerated from rest to the desired coating speed U. Throughout this paper the distance travelled by the head during acceleration will be called the *acceleration length* (fig. 1). A section of constant speed U follows next. In the beginning of this constant speed section, the curtain has to reassess from acceleration. Subsequently, a liquid layer is coated. Finally the coating head decelerates in order to be at rest at the end of its stroke. When coating the subsequent layer, the head starts at this latter position and moves towards the former rest position, thus necessitating a symmetrical machine.

Some problems that are encountered in high-speed curtain recoating are now discussed. Firstly, the machine dimensions have to remain within reasonable proportions. It would be unacceptable to have a machine of more than 3 m long with a build vat of only 250 mm diameter. The acceleration length should thus be limited. When increasing the coating head's speed U, the *peak acceleration* should be increased, rather than the acceleration length. Secondly, inertia forces during acceleration will bend the liquid curtain backwards. Vertical rods at both lateral ends of the curtain are needed to maintain a straight curtain, as surface tension would otherwise contract it. The curtain is pinned at these rods, also called 'edge guides' (fig. 3). Thus, when bending backwards the curtain will curve also in a horizontal plane, remaining pinned at the edge guides and assuming a maximal bending in its middle. This situation is depicted in figure 4. After reaching the desired coating speed U, the curtain slowly returns to its original, planar shape. This planar shape has to be reached before beginning to coat the layer, otherwise the contact line between curtain and substrate will be curved. Since, in this case, the curtain is still in a transient state, its velocity is not equal to the constant speed U, and the thickness of the coated layer will not be uniform. A number of experiments have been performed in order to investigate the feasibility of using high-speed curtain recoating for stereolithography. The following section describes the set-up that has been used for the experiments.

Experimental set-up

A number of experiments have been performed in order to investigate the possibility of high-speed curtain recoating. In the context of curtain recoating for stereolithography, *high-speed* means coating speeds U higher than 1 m/s. The coating head was mounted on a linear drive, having a total stroke of 900 mm. This linear drive was chosen because of its ease of programming different acceleration profiles, and because of the high accelerations the drive can achieve. Degraded Somos 7100$^{\text{tm}}$ resin with a viscosity of 1.1 Pa.s @ 34$^\circ C$ was used for the experiments. The curtain was 400 mm wide and 125 mm long. Figure 3 shows the set-up. A Sony digital video camera was mounted next to the coating head, moving together with the head and slide. Video frames were recorded at a rate of 50 Hz during motion.

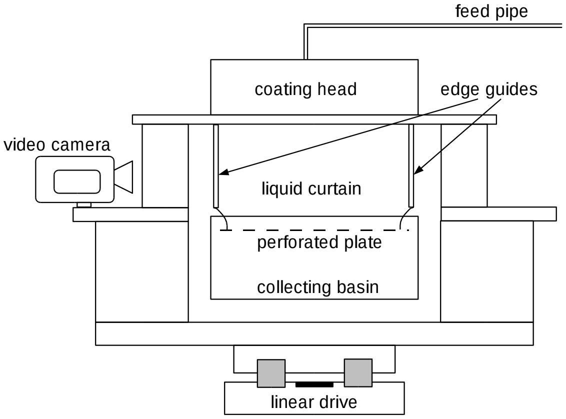

Figure 3: *Experimental set-up for the investigation of the curtain's behaviour during acceleration to high speeds of the coating head.*

Different acceleration profiles were tested, among these a 2$^{\text{nd}}$ order polynomial, having a discontinuous jerk profile at the beginning and end of the acceleration section, and a 4$^{\text{th}}$ order polynomial, having a continuous jerk profile throughout the entire trajectory of the drive. For a given acceleration length, the 2$^{\text{nd}}$ order profile gives the lowest peak acceleration. For a given peak acceleration, the 2$^{\text{nd}}$ order profile gives the shortest acceleration length. No substantial difference has been observed in the curtain's response to both mentioned profiles. This observation is also supported by the results of a simulation of the curtain's behaviour during acceleration of the coating head. As a liquid curtain possesses a very low stiffness, a shield is mounted at both sides of the coating head to protect the curtain from aerodynamic forces during motion. Figure 5 and 4 show cross-sections of a backwards bent curtain. The following section covers the performed experiments in more detail, and discusses the results.

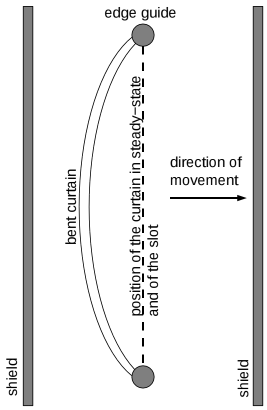

Figure 4: *Horizontal cross-section of a liquid curtain bending backwards during motion. The shields are protecting the curtain from aerodynamic influences.*

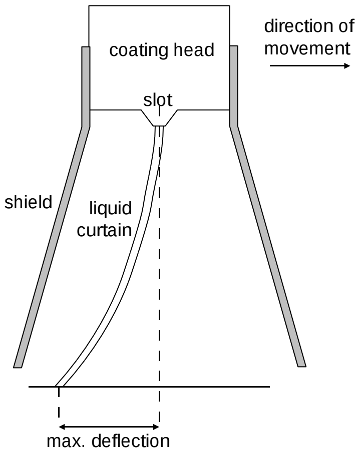

Figure 5: *Vertical cross-section of a falling liquid curtain bending backwards during motion.*

Results and discussion

A first issue in the experiments was to observe up to which maximum peak accelerations the curtain could resist without breaking. A higher peak acceleration shortens the acceleration length needed to achieve a desired speed U, thus making the machine shorter. The coating head and curtain were subjected to a peak acceleration of 1g (9.8 m/s^2), both with a 2^{nd} and 4^{th} order polynomial acceleration profile to reach a speed U of 0.9 m/s only after an acceleration length of respectively 62 mm and 77 mm for the 2^{nd} and 4^{th} order polynomial profile. During acceleration, maximum backwards bending of the curtain, as defined by figure 5, was 42 mm. No breakage of the curtain was observed. These observations show that high accelerations are no limiting factor for high-speed curtain recoating. Secondly, the feasibility of letting the curtain move at speeds higher than 1 m/s was investigated. Due to the limited stroke of the linear drive, the maximal speed tested was U = 1.2 m/s. To reach this speed, a peak acceleration of 9.0 m/s^2 was used and the acceleration length was respectively 120 mm and 150 mm for the 2^{nd} and 4^{th} order polynomial profile. No breakage of the curtain was observed, and the curtain's maximum backwards bending was 52 mm with respect to the slot's position.

However, in restoring towards its flat shape after acceleration to a speed U, the curtain takes a much longer time than would be expected. As the curtain must return to its flat shape before actual coating can start, the observations show that extra length has to be added to the travelling length of the coating head, in order to give the curtain sufficient time to reassess. It is the purpose of this paper to investigate the reasons of this unwanted slow reassessment of the curtain, and to formulate a possible solution. The behaviour of the curtain during acceleration of the coating head has been simulated. A two-dimensional model of the curtain has been used for simulation, thus assuming a curtain of infinite width. As the curtain in reality, is pinned laterally to the edge guides, it reaches its maximal bending in the middle. This pinning of the curtain at its lateral ends will undoubtedly influence the amount of bending in the middle, as the curtain is not free to deflect as a whole. Therefore, the simulation will always yield a higher deflection than experimentally observed. It is not a purpose of this paper to describe the simulation in detail. What does matter in this stage of analysis, is that the model is able to qualitatively predict the experimentally observed behaviour of the curtain.

The curtain's shape is governed by the equations of Navier-Stokes for viscous flow, suitably transformed to be used for liquid sheets. External forces acting on the curtain are: gravitation, inertial forces due to the acceleration, and aerodynamic forces induced by the air between the curtain and the two shields. The influence of viscosity and surface tension was also modelled. The aerodynamic forces, that act as a pressure difference between the curtain's front and back side, are most subject to uncertainty. The reason for this uncertainty is due to the fact that, although the shields indeed protect the moving liquid curtain from still air, an amount of air still enters the space between curtain and shield through a gap between the lower edge of the front shield and the substrate. The shields may not contact the liquid substrate. Therefore the shields are mounted such that a gap of 2 mm is left between them and the substrate. When the curtain is moving, air enters through this gap into the space between curtain and shield. The liquid curtain will subsequently have to deflect the inflowing air toward its lateral ends, where the air is free to escape. Since in this case the curtain is moving at a speed U, while the air can be considered to be at rest, the aerodynamic forces have been modelled as a stagnation pressure, acting as a pressure difference between the curtain's front and back side. The modelled stagnation pressure relates to the coating speed U according to:

$$p_s = \frac{\rho_{air} U^2}{2} \tag{2}$$

with ρ_{air} the density of air. This pressure is very low ($\approx$ 1 Pa when U = 1.2 m/s), but its influence on the curtain dynamics is nevertheless tremendous, because the bending stiffness of the curtain is also very low. According to our model, and considering a steady state, a constant pressure difference of 1 Pa between the curtain's front and back side causes the curtain to deflect by 70 mm at its lower end, measured from the slot's position. The reader should bear in mind that the length of the curtain in this case is only 125 mm.

With this in mind, and in order to qualitatively predict the experimentally observed behaviour, the reader should notice from figures 6 and 7 that during the motion at constant speed U, the curtain shows a relaxation towards its planar shape. The relaxation obviously suggests that the pressure difference across the curtain slowly vanishes. This means that the stagnation pressure in our model should be subject too to a relaxation, which was implemented as an exponential decay of the stagnation pressure. As the dynamics of the experimentally observed relaxation are not clear yet, the relaxation constant of the modelled exponential decay of the stagnation pressure is found such that a best fit between the experimental data and the model's results is achieved. A relaxation constant $\tau \approx$ 0.2 sec is found to agree best with all data, as can be seen in figures 6 and 7.

The introduction of a *stagnation* pressure is open for discussion; what is important though, is that the experimental data shows that the curtain first deflects, due to inertial and aerodynamic forces, the latter ones increasing with increasing speed U. The deflection shows afterwards a kind of relaxation. This relaxation is mainly caused by a pressure in front of the curtain, that has built up during acceleration and is now disappearing slowly. A first possible explanation for the dynamics

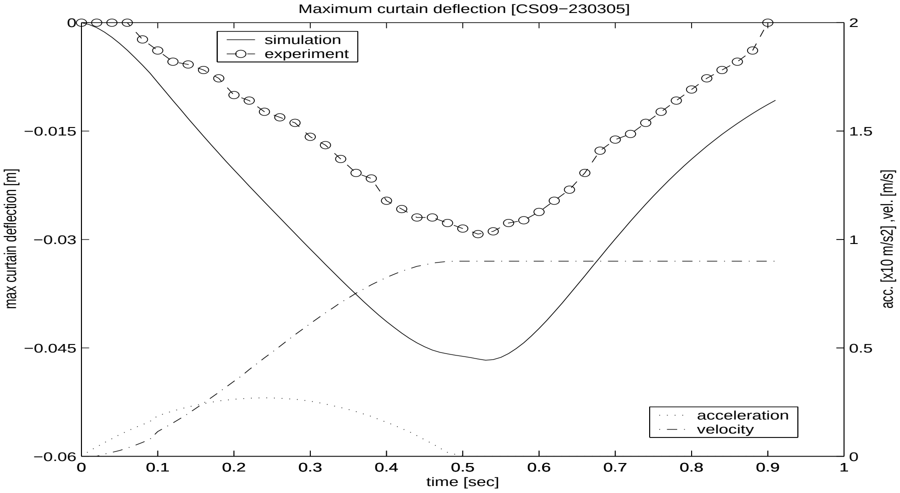

Figure 6: *Plot of the curtain's deflection measured at its lower end with respect to the slot's position. Both experimental data and simulation results are plotted; values refer to left y-axis. The applied acceleration (2nd order polynomial profile, a_{max} = 2.7 m/s^2) is plotted, together with the speed of the coating head U_{max} = 0.9 m/s (right y-axis).*

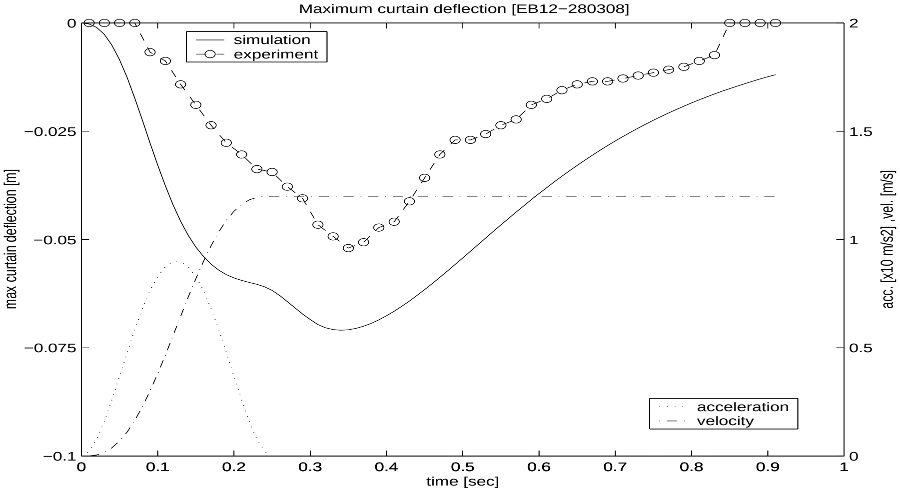

Figure 7: *Plot of the curtain's deflection measured at its lower end with respect to the slot's position. Both experimental data and simulation results are plotted; values refer to left y-axis. The applied acceleration (4th order polynomial profile, a_{max} = 9.0 m/s^2) is plotted, together with the speed of the coating head U_{max} = 1.2 m/s (right y-axis).*

of the relaxation is a rearrangement of the air flow in the space between the curtain and the air shield. Once a constant speed U has been achieved, a rearrangement of the air flow could drop the pressure in the direct vicinity of the curtain's front. A second possible explanation is a pressure building up behind the curtain, thereby balancing the pressure in front of the curtain. The dynamics of this pressure build-up could reasonably be slower than the ones accounting for the curtain's front pressure. The pressure differences occurring in this problem are very low (magnitude 1 Pa). Since pressure differences are the driving force behind flows, the flow rate of air is minimal too, thereby serving as a possible explanation for the slow relaxation. Moreover, the compressibility of air certainly affects the curtain's dynamics, because the speed of propagation of a pressure disturbance is finite in a compressible medium. The relaxation constant τ, that has been introduced in our simulation is thus a generic parameter, accounting for all physical effects that influence the observed relaxation.

A validation of these assumptions is difficult, since the pressure measurements are difficult to perform because of their small magnitude and because of the occurring accelerations that will influence the measurements. Another approach consists in visualising the streamlines of air around the curtain in a wind tunnel. Such a test would be incomplete though, due to the inability to simulate inertial forces acting on the curtain. Actually, the assumptions could be tested by experiments aiming at influencing the relaxation. If the relaxation is dependent upon a presumed pressure difference between the curtain's middle and its lateral ends, the speed of relaxation could be increased by increasing the mentioned pressure difference. A second solution could be accomplished by increasing the pressure at the back of the curtain, thereby balancing in a much faster way the stagnation pressure that has built up in front of the curtain. Anyway, it is clear that there are methods to dynamically control the curtain's deflection during acceleration. These ideas have not been implemented yet, but will be a research topic in the future. They are needed for implementing high-speed curtain recoating for stereolithography while maintaining the length of the coating head's drive, and thus the machine length within reasonable proportions.

Conclusion

This paper has discussed preliminary experiments for the implementation of high-speed curtain recoating for stereolithography. Curtain recoating is a fast technique to coat even very thin liquid layers. The terminology 'high-speed' is used in this application to refer to coating speeds higher than 1 m/s. Speeds up to 1.2 m/s and accelerations up to 1g have been tested successfully, without breakage of the curtain. A main problem to be solved is the curtain's slow returning to its flat shape after bending due to acceleration. In this respect, the curtain's dynamics have to be made faster. Possible solutions to this problem have been mentioned, all consisting in controlling small pressure differences in the curtain's neighbourhood. A solution is necessary as to make the machine length acceptable with respect to the dimensions of the build vat.

Acknowledgements

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