Design Issues for Slot-Die Coating Heads - Case Study

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Abstract. In this article, the authors briefly present the development, features, operating principles, and typical applications of slot-die technology. Slot-die technology is a coating method in which a consistent thickness, coating layer, can be applied to a receiving surface in an almost completely closed system. The technology was first used in the production of films but is now used for the application of a wide variety of coatings (e.g., plastics), from battery production, through semiconductor production, to solar cell production. It can also be used to make membrane air filters / filters, which can help to overcome today's covid epidemic. Due to the proliferation of electric cars, the production of batteries has become an increasing slice of industrial production. In this article we present in detail, in a systematic way, the information gathered during the literature search, which we used in our work. In this article we present with a case study, the problems and experiences that arose during the design and manufacture of a coating machine operating under laboratory conditions. The construction of the machine was done with the technical assistance of a joint project with an industrial partner. The laboratory machine will be suitable for sheet-to-sheet coating. The article presents strength and deformation simulations along with the experience gained during the production of the coating machine.

1. Introduction
The invention of slot-die coating technology is attributed to Albert E. Beguin, who filed his patent with the U.S. Patent Office in 1952 (US2681294A). The technology first appeared at Eastman Kodak Co. in the United States [1] as one of the technologies in film production. Nowadays, with the proliferation of electric cars, the production of high-performance batteries is becoming increasingly important. In this area too, it is important to be able to create thin layers on the surfaces of battery electrodes. Slot-die technology is an excellent way to solve this problem. More and more new investments are starting in Hungary, which are related to battery production in some way; so researching, understanding and getting to know the technology can be an advantage for our country. The basis of slot-die technology is to deliver the material, to be applied to the receiving surface (substrate), through a thin gap. The layer thickness of the thin coating can range from a few tenths of a micrometer to a few tenths of millimeter. The liquid flowing out of the gap reaches the substrate as a curtain. There is relative movement between the substrate and the gap. The movement is usually performed by the substrate, compared to where the gap is located. The substrate is very close to the gap. In the original invention, Beguin created his movement using a rotating drum. This type of technique is called a roll-to-roll technique, abbreviated R2R. If the receiving surface is a flat sheet, it is called sheet-to-sheet technique, shortly the S2S technique. It is now possible for the gap to move over the receiving surface. With slot-die technology, both types have their own applications.
Our aim is to create a coating machine with slot-die technology to support our joint project with our industrial partner. By acquiring the initial steps on a small machine, we want to produce machines for industrial production.

2. The principle of slot-die technology
Nowadays, slot-die technology is becoming more widespread, both in industrial and laboratory applications. Figure 1 shows a schematic of a slot-die tool. The names of the tool components and the parts of the coating bead formed at the application site, can also be identified from the figure.

![Figure 1. The overall design of a slot-die head](image)

- Substrate: a carrier/receiver surface, to which the coating is applied. It can be rigid or flexible.
- U: the velocity of the substrate.
- Upstream die: the upstream part of the slot-die head.
- Downstream die: the downstream part of the slot-die head.
- Upstream meniscus: the fluid profile of the upstream side.
- Downstream meniscus: the fluid profile of the downstream side.
- Coating bead: a layer of fluid applied from the slot-die head.
- Wet thickness: the thickness of the applied material when wet.
- w: the width of the gap.

The fluid flowing through the gap arrives at the receiving surface to form a consistent thickness. Changing the size of the thickness can be influenced by the values of several application parameters. Such parameters are:

- Density and viscosity of the liquid.
- The speed of the substrate.
- Flow rate of fluid flowing through the gap.
- The size of the gap.

In the case of a given combination of listed parameters, a stable liquid profile is formed on both sides of the slot-die head; in which case it is possible to apply a thin and consistent layer thickness. In his invention, Beguin [1] proposed the use of a vacuum in front of the upstream die, of the slot-die head. The vacuum helps to stabilize the fluid profile exiting the gap, by removing air adhering to the substrate surface as it moves. Applying a vacuum is only a problem during high-speed coating applications, also it is not worth applying below 2 m/s [2,3,4]. In 1976, Ruschak researched the stability of coating production and introduced the concept of the “coating window.” If the parameters are inside the “window,” the coating will be good [5]. Changes in coating preparation parameters have a major impact on the shape of the upstream and downstream meniscus. The size of the gap between the inlet and outlet.
sides of the slot-die head is created by a spacer (shim) plate. By changing the thickness of the spacer plate, it is possible to apply different thicknesses (we can influence the thickness with other parameters, but this is the main option). The following figure (Figure 2) shows a disassembled slot-die head, which also shows the names of the inner surface of the head and the fluid distribution channels.

![Figure 2. Names and design of the interior of the slot-die head (symmetrical)](image)

3. Slot-die head interior design

If we look at the products of the companies that make slot-die heads, we find that two different principles/directions have emerged in the design of the interior of the head. One direction is when the two halves of the head (upstream and downstream) have the same design (symmetrical head). The other direction is when the downstream side element of the head is a flat surface, while a chamber(s) is formed on the upstream side (asymmetric head). The symmetry or asymmetry of the lips of the head is another very complex issue, which are not discussed in this publication; but there are studies examining the effect of the shape and position of the lips to the upstream and downstream meniscus [3].

3.1. Some characteristics of asymmetric heads

Like all engineering solutions, the asymmetric-symmetrical design of slot-die heads have disadvantages and advantages.

Disadvantages:

- For such heads, two different parts have to be manufactured, which complicates production, but this effect is not significant.
- As the manifold channel passes through the upstream die element of the head, the assembled head must be closed on two sides with end caps. New parts are needed for the design.
- Usually used for wide width heads.
- The direction of the dividing plane of the head should be as horizontal as possible during installation.
- The maximum deformation of the heads due to the pressure in the interior is greater than in the case of symmetrical heads (see 4.3 for details).

Advantages:

- In asymmetrical heads, the manifold channel runs along the entire head to help clean the head.
- It is also easier to set the parameters of the machined surface in a case where the surface to be machined, can be accessible from two directions.
- Machining the inner surface of a non-ducted element is simple, a planar grinding task.
- When filling the head with liquid, any air bubbles that may form can be more easily removed from the head (horizontal placement).
3.2. Symmetrical heads

An example of a symmetrically shaped head is shown in Figure 2.

Disadvantages:

- Due to the symmetrical design of the head, it is difficult to remove air bubbles from the liquid. Often some additional elements are needed (aeration valve, adjustable head angle).
- Harder to clean because the head is impassable.

Advantages:

- Two parts of the head are identical, must be made of the same parts.
- The manifold channel does not run through the head, so no end caps are required.
- The maximum deformation of the heads due to the pressure created in the interior is smaller than in the case of asymmetric heads (6.3).

When deciding on the design of the heads, you can choose based on the properties indicated above.

4. Case Study

After the introduction, we would like to present a case study in the publication. In 2019, our institute joined a tender project. In the project, we were given the task of designing the mechanics of a non-traditional printing machine. In addition to mechanical engineers, chemists and physicists took part in the project; it was their job to experiment with the special material. At the beginning of the work, we first got acquainted with the coating technologies, from which many types have evolved (Dr. Blade, Microgravure, Slot-Die, spray coating, etc.).

4.1. Starting the planning task

The choice of application technology should always be based on the properties of the material to be applied to the substrate. In our case, the base material was PVA (polyvinyl alcohol) and PU (polyurethane), modified by chemist and physicist colleagues with various ingredients. One of the ingredients is a solid for which particle size and hardness are very important. Large grains can block fluid flow, and hard grains wear the inner surface of the slot-die head; causing the gap to change in size and the application to be uneven. Fortunately, in our case, the wet thickness of the film and the size of the solid grain should not cause this type of effect. It is important to know the solvent of the liquid, as it can be very aggressive and even explosive. Unfortunately, in our case we have this problem, as the solvent for PVA is ethanol and the solvent for PU is toluene; both of which form an explosive mixture with air (see Material Safety Data Sheet). If an explosive atmosphere can develop during the operation of a machine, in Hungary; it is regulated by the National Directorate General for Disaster Management, Ministry of the Interior (NDGDM) [9]. Furthermore, to know the drying kinetics of the materials is very advantageous, because than we really have a good choice of technology. In our case, dealing with the materials’ drying time, depends greatly on the amount of solvent, air pressure and temperature.
4.2. Spraying experiment to select coating technology
To obtain first-hand knowledge of the material to be applied and to select the appropriate application method, a spraying experiment was performed. In the experiment, PVA was applied to a PC (polycarbonate) film. Ethanol was used as the solvent. PVA was diluted for spraying (close to water density). An air-brush gun (Fine Art Fa-1800 type with 0.5mm nozzle) was used for spraying. Spraying was performed in an extraction chamber. (Figure 4). During spraying, we found that it was possible to create a coating.

![Figure 4](image_url)

Figure 4. The spraying experiment a) Arrangement, b) the material did not adhere to the PC foil, c) good coat

Features:
- 15µm thin layer can be created.
- The coating material should be warmed to at least room temperature (raw material should be stored at 5 °C if the material does not adhere to the PC surface when cold [Figure 4. part b]).
- Atomized PVA particles will appear in the air, which is another danger in addition to the solvent.
- The applied coating dries in a few minutes.

Unfortunately, we cannot provide more detailed information because the photo technology material is a secret of our industrial partner. Based on the experiment, we concluded that a closed (or nearly closed) system is required for application. This eliminates the problem of rapid drying and atomized airborne particles. This is how we got to the selection of slot-die technology, which seems to form an almost closed system, according to Figure 1. The experiment highlighted the importance of adhesion between the substrate surface and the applied material. In the absence of mutual “attraction” between the two surfaces, coating may become impossible (the applied material shrinks to droplets, Figure 4, part b marked with circles). The adhesion of the materials can be influenced by treating of the substrate. A detailed description of the applicability and mode of treatment can be found in the literature [8].

4.3. Difficulties encountered in the design and manufacture of laboratory machinery
Once the application technology has been selected, the design and selection of the elements can follow. Further research was limited to slot-die technology. In order to gain experience with slot-die heads, we set out to create a prototype. Here we took advantage of the benefits and disadvantages presented earlier. During the design, we examined the proficiency of the slot-die head elements using FEM simulations. The first version of the slot-die head was a symmetrically designed head. The FEM test result for this is shown in the following figure (Figure 5). The load was the pressure inside the interior, which was chosen to be 1 MPa, which is a small value for the slot-die heads. The fastening was made through the mounting holes. Fixation and constraints are presented on the next figure (figure 5.)
The result of the test was that the strength compliance was met, the maximum stress value was 1 MPa in the tested components (in this case, the yield strength of the aluminum alloy is 280 MPa). However, if we look at the displacement values and the direction of the displacements, we see that the situation is no longer perfect. The pressure on the inner surfaces deformed the outer part of the head. The most problematic place is the environment around the lips (circled in figure 6.). Here you can see that the outer edges of the lips turn outwards, even the inner edges turn inward. This changes the size of the width of the gap in the slot-die head and the shape of the lips.

This deformation may already affect the application. The value of the deformation is around 2 µm. And by increasing the internal pressure, this situation will only get worse. Like all results, this should be evaluated. If the gap of the tool is 200-300 µm, the displacement of 2 µm is not significant. On the other hand, if the size of the gap is only 20 µm, then a displacement of 2 µm will result in a deviation of 10 %. Optionally, part of the gap may close, or a solid component of the liquid can stick between the lips. It is recommended to choose stainless steel as the material for the slot-die head. Corrosion and consequent material loss and sizing do not have to be considered. When choosing a material, a material with high tensile strength is recommended to be able to withstand the pressure in the head (more than 1 MPa). Manufacturers recommend 15-5PH stainless steel, in H1025 heat treatment condition, then UTS above 1000 MPa. Unfortunately, high tensile strength is not a guarantee of small deformation, as it is most affected by the modulus of elasticity. This value is lower for stainless steel (1.9x105 MPa) compared to carbon steel (2.1x105 MPa) [11]. The deformation of the lips can be improved by changing the shape of the lips.
of the geometry. The outer edge of the lip, which is turned inwards. If removed, this problem is reduced (see modified head (Figure 8 and Figure 9)). The deformation of the lips affects the change in the size of the gap, which affects the thickness of the applied layer.

4.4. Comparison of symmetrical and asymmetric heads using FEM
After the first test, two types were made with the same dimensions, one with a symmetrical internal design and the other with an asymmetric design.

In both, the symmetrical and asymmetrical case, deformations due to the internal pressure (applied pressure 1 MPa) were examined. In the study, we compared two different supporting states, to look for the effect of different installation options. On the next figure (Figure 8.), the fixations and constraints of the symmetrical head configuration in two different fixation cases can be seen (back, back and bottom).

In part a) the element with the manifold channel; in part b) the element with a flat surface. If we assemble two #1 parts we get a symmetrical head. If we assemble one from part #1 and one from part #2, we get an asymmetric head.

The following two figures (Figure 9a) and b)) show the results of heads with a symmetrical interior with two different gripping states.
The maximum value of the displacement increases by 0.1 μm in case b) compared to case a). If we look at the displacement values that appear at the lips, we also see an increase there. That is, in the case of symmetrical heads, mounting on a rear surface favors better deformation conditions. The following two figures (figure 10.) show the VEM test result for an asymmetric head with two different gripping cases.

In the case of the asymmetrical head, we find a larger maximum displacement than in the case of the symmetrical heads, but it is concentrated only in the end caps and their environment. The deformation of the lips is the same order of magnitude. If we look at the test with the rear and lower fixation (Figure 9. b), we can see that the deformation of the lips is 0.1-0.2 μm, which is a very similar value to that of the symmetrical heads. Considering that there are several advantageous features in the operation of asymmetric heads, it is worth choosing them to use a strong rear and lower grip. An example of such a design is shown in Figure 11. There is still much room for the optimization of the grips and geometry to achieve significant material/mass savings; an example of which is given in [13]. A generic design can also be included in this area, as we see a similar example of material savings in generative design, using [14], [15], [16] literatures.

4.5. Surface roughness and accuracy, tolerances
The quality of the machining of the slot-die head is also a very important issue. Manufacturers of slot-die heads have developed special grinding processes [10] that can achieve up to Ra 0.02 roughness. It
is recommended to have as little surface roughness as possible, so that the bumpiness of the tool lip does not copy onto the applied layer. The flatness of the surfaces is also very important, as the velocity of the fluid flowing through the gap of the tool will only be constant at a constant volume flow. If the gap size changes, it will flow faster in the narrower parts and slower in the wider parts due to the incompressibility of the fluid. This affects the thickness of the applied layer. The more continuous and uniform the flow conditions are, the more uniform the layer is. Manufacturers target a deviation of 2-3 µm for the lips of the tool, it is recommended to approach this. After applying the liquid, the surface tension of the liquids can still smooth the surface, but in the case of a fast-drying material, there may not be enough time for it. The surface quality data described above are very strict and expensive to produce. The lips of the heads have a small surface area, and the components of the heads have a significant weight, so the lips must be protected from mechanical impact. It is advisable to use some protective/covering caps that will only be removed from the lips once the heads are in place and ready to begin application.

4.6. Assembling the two halves of the slot-die head
There are several things to look for when assembling the two main components of slot-die heads:
- the order in which the screws are tightened,
- tightening torque,
- to position the elements of the head relative to each other.

The tightening sequence should be as follows; by starting to tighten the clamping screws in the middle of the head, then moving alternately toward the edge of the slot-die head, and then moving alternately toward the lips of the slot-die head. During tightening, check the size of the gap with a feeler gauge. In our case we must realize a 250 µm gap width. For screws, it is advisable to use stainless-steel with a friction-reducing coating (e.g., Teflon). Using this method, a larger proportion of the torque applied to the screw head is used as compression, while a smaller proportion is used to overcome the friction between the running surfaces. Of course, the screw connection must be self-locking, it is worth protecting the connection against loosening. In the case of screw connections, with the repetition of the tightening-loosening cycle, the compressive force due to the tightening torque decreases with each repetition, as can be seen in [12]. We can counteract this phenomenon by stabilizing the frictional conditions. Disassembly and assembly of the heads is a common operation on coating machines, as the head must be cleaned after each shutdown or change to another material, for which disassembly is essential. Optimal tightening torque is between 12-14 Nm. Thus, the clamping between the surfaces is sufficient to seal the surfaces outside of the gap and the shim elements are not overloaded. The elements of the head must be positioned relative to each other. Therefore, orienting elements must be developed.

Figure 11. CAD model of the slot-die head examined

4.7. Design of the machine to be made
The design of the laboratory machine is basically based on BOSCH profiles. Construction from profiles is a common technology for experimental or custom-built machines and equipment. When designing
the frame structure of the machine, the goal is to keep deformations at a very low level. Any deformation in the frame of the machine has a detrimental effect on the quality of the application, so heavy-duty sections (90x45) must be used. Basically, we do not encounter large forces during the operation of the machine, in practice we have to take into account most of the loads resulting from the own weight of the elements. The designed machine is a(n) S2S system, and the substrate moves under the slot-die head. The head is mounted on a bridging (bridge) component in a naturally adjustable manner. The table connecting the substrate is connected to the frame of the machine by two parallel linear guides and 2-2 carriages per guides. In the case of overlapping elements, it must be possible to adjust (level) so that the table always passes at the same height under the head. The table connects with one fixed and three height-adjustable elements (screw thread). This ensures that the table can be leveled in two directions. The level is adjusted relative to the bridge of the slot-die head, using a hundredths of a millimeter dial gauge. Gauges should be placed so that they measure at both edges of the table. After setting the table, the slot-die head must be set relative to the table. This can be done in two ways. In one case, gaps are placed between the lips of the head and the table (e.g., with gaps of guaranteed thickness manufactured by SKF [17]). Another option is to use two gauges attached to the two edges of the slot-die head. In this case however, the accuracy of their installation is very important. Examples of both solutions are given in the literature. As long as the thickness of the layer to be applied does not need to be changed, the gap can be fixed after an adjustment. The following figure (Figure 10) shows the current state of the experimental machine.

![Image](image.jpg)

Figure 12. The S2S coating machine in a half-assembled state

5. Summary and future plans
The slot-die technology presented in the above chapters is a forward-looking coating technology. The technology seems very simple at first glance, but it can also be seen from the diversity of the literature used, that it is not at all. In the article, the authors presented the experience gained during their work in designing a slot-die head and a machine that works with it. They presented their experience in the design and construction of the experimental machine. Using simulations, the differences between symmetric and asymmetric slot-die heads were pointed out. The authors continue the work with the design and construction of the fluid delivery system, which is essential for the preparation of the coating. The results found there are summarized in a subsequent article.

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