MASTER

Concept design for reel to reel flex foil handling on a component mounting machine

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Concept design for reel to reel flex foil handling on a component mounting machine

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CONCEPT DESIGN FOR REEL TO REEL FLEX FOIL HANDLING ON A COMPONENT MOUNTING MACHINE

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CONSTRUCTIONS AND MECHANISMS

Eindhoven, 24th June 2005
Preface and acknowledgements

This report describes the concept design for a reel to reel flex foil production line, that is developed during my Master thesis project at the Technische Universiteit Eindhoven, faculty Mechanical engineering, group Constructions and Mechanisms. This project has taken place at Assembléon B.V. Veldhoven, from April 2004 until April 2005.

First, I would like to thank Assembléon who gave me the opportunity to do my Master thesis at the department Assembléon Special Products (ASP). They gave me a lot of facilities and coaching from several people. Special thanks go out to ing. Wessel Wesseling of Assembléon Special Products, he has been my coach for the past 12 months and gave me a lot of freedom in doing my work. He involved me in the complete process of starting the new production line, inclusive client visits and technical brainstorms of other parts of the production line. The design, in cooperation with Unitek Eapro, of the reflow-oven is one example.

I'm grateful to Prof.dr.ir.M.Steinbuch being my professor and giving me the opportunity to finish my master’s at the section control systems technology.

Special thank’s goes out to dr.ir.Nick Rosielle who was my coach at the TU/e, during my graduation project and my second traineeship. He, and Eef Reker, supported me, together with all students of the group constructions and mechanisms for the last one and a half year. In this group I learned the importance of the design principles. The weekly returning discussions at Monday gave the opportunity to not only focus on my own problem, but the problems of all students in the group, which was very interesting.

Finally I would like to thank Roel Bouwman from Assembléon who helped me a lot in the concept design and realization of the two experimental setups I build.

Eindhoven, 24th June 2005

Remko Wakker.
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Samenvatting

Dit rapport behandeld een nieuwe methode om het transporteren van flexibele print circuits en het plaatsen van elektrische componenten op flexibele print circuits in de componenten plaatsingsmachine (AX) van Assembléon mogelijk te maken.

Vanuit Assembléon B.V. is de opdracht gekomen om een deel uit een nieuwe fabricagelijn te ontwikkelen. Dit deel beslaat voornamelijk het gedeelte dat zich afspeelt in de plaatsingsmachine, waar met hoge nauwkeurigheid componenten op de flexibele print folie geplaatst dienen te worden.

Om een complete fabricagelijn te realiseren om flexibele print folie te voorzien van componenten waarbij aan het begin van deze lijn flexibele print folie wordt afgewikkeld, soldeerpasta wordt aangebracht, componenten worden geplaatst, soldeerpasta wordt opgesmolten, waarna de folie weer wordt opgerold is het noodzakelijk het gedrag van deze folie met bijbehorende afwijkingen te bekijken.

Als eerste wordt duidelijk gemaakt dat bepaalde flexibele print folies initieel niet vlak en recht zijn. Het is echter alleen mogelijk om componenten te plaatsen met een hoge plaatsingsnauwkeurigheid wanneer de folie vlak is en afsteund op een stijve ondergrond.

Dit afstudierwerk zal zich voornamelijk richten op flexibele print folie afhandeling in de componenten plaatsingsmachine AX, welke op drie vlakken bekeken wordt:

1. ondersteuning van folie tijdens het plaatsen van componenten
2. het vlak maken van niet-vlakke flexibele print folies
3. het transporteren van folie door de componenten plaatsingsmachine.

Een eindige elementen analyse verschaft het inzicht over hoe de folie zich gedraagt onder spanning, welke optreedt wanneer niet vlakke folies vlak getrokken worden.

Na de inventarisatie van mogelijke geometrische afwijkingen en mogelijkheden om folie te spannen zijn een aantal concepten bedacht die aan bovengenoemde punten voldoen.

De realisatie van de "rol-naar-rol" productie lijn is gebeurd in samenwerking met Hella, leverancier van elektronische toepassingen voor de automobilist industriële. Tijdens het afstuderen is een experimentele opstelling gebouwd om bepaalde delen uit de concepten te evalueren. Na het verkregen inzicht van deze experimentele opstelling is de componenten plaatsingsmachine zodanig gemodificeerd dat hierin flexibele print folie transport mogelijk is.
De moeilijkheden (uitdagingen) van flexibele print folie transport werden zichtbaar in dit 1:1 model en zijn meegenomen om de concepten te evalueren. In de behandeling van de concepten komt duidelijk naar voren hoe de bestaande AX-machine minimaal gemodificeerd kan worden voor deze toepassing.
Verder is gekeken naar een langere termijn oplossing welke het mogelijk maakt een breder scala aan flexibele print folies te verwerken.

Als laatste deel van dit afstudeerwerk worden conclusies getrokken en aanbevelingen gedaan hoe het laatste concept gerealiseerd kan worden.
Abstract

This report discusses a new method of transporting flexible printed circuits in the component mounting machine (AX) of Assembléon B.V.

The assignment from Assembléon B.V. is to design a part of a new production line. This part is mainly focussed on handling flex foil in the component mounting machine. Here, the components have to be picked and placed with a high placement accuracy.

To successfully realize a complete production line to mount the components to the flex foil, it’s important to understand the behavior of the flex foil under tension and all deviations of a flex foil.

In chapter 2 is clarified that certain flex foils are not flat and straight. It’s only possible to place components with a high accuracy if the flex foil is flat and is supported by a stiff carrier.

This master thesis will mainly focus on flex foil handling in the component mounting machine, and is subdivided in three area’s of interest:

1. support of flex foil during pick and place actions
2. flatten non-flat flex foils
3. transporting flex foil through the component mounting machine (AX)

A finite element analysis provides an insight on how flex foil acts under tension, which is needed to flatten the non-flat flex foils.

After making an inventory of all geometrical deviations of the flex foil, the concepts are discussed.

The realization of a reel to reel production line is in close co-operation with the customer Hella.

During this master thesis an experimental setup is built to evaluate several parts of the concepts. After the obtained insight of this experimental setup, it’s implemented in an AX3 machine. In this 1:1 model the difficulties of flex foil transport became visible.

In the discussion of the concepts is emphasized how a minimum modification of the AX can be done to realize flex foil transport.

Also, a long term solution is discussed which is able to handle a wider scale of flex foils.
In the last part of this thesis conclusions are made and recommendations are done how the last concept can be realized.
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX</td>
<td>Pick and place equipment of Assembléon</td>
</tr>
<tr>
<td>Buckle</td>
<td>Out of plane deformation of a flex foil without tension it (e.g. material defects)</td>
</tr>
<tr>
<td>De-reeler</td>
<td>Unwind station for coil of flex foil</td>
</tr>
<tr>
<td>FCB</td>
<td>Flexible Circuit Board</td>
</tr>
<tr>
<td>Flex foil</td>
<td>A lot of Flexible Circuits are present on the flex foil</td>
</tr>
<tr>
<td>Flex foil skew</td>
<td>Curvature of flex foil with respect to straight flex foil</td>
</tr>
<tr>
<td>FR4</td>
<td>Flame Retardant, type 4 (woven glass)</td>
</tr>
<tr>
<td>Kapton</td>
<td>Patented name for PI foils</td>
</tr>
<tr>
<td>PET</td>
<td>Polyetheentereftalaat (Polyester)</td>
</tr>
<tr>
<td>PI</td>
<td>Polymide</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>Reeler</td>
<td>Coiling station for flex foil</td>
</tr>
<tr>
<td>Reflow oven</td>
<td>Oven to solder components to flex foil</td>
</tr>
<tr>
<td>Sagging</td>
<td>Bending of flex foil due to gravity</td>
</tr>
<tr>
<td>Transportbeam</td>
<td>Mechanism in AX to transport PCB’s or FCB’s</td>
</tr>
<tr>
<td>Wrinkle</td>
<td>Out of plane deformation of a flex foil due to tension</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction to reel to reel flex foil transport

This chapter gives a short explanation of the history and development in surface mount technology. It will deal with the introduction of the variety of flexible circuits. The reason for this thesis, a reel to reel production line for flexible circuits is also discussed.

1.1 History

The inventor of the printed circuit was probably the Austrian engineer Paul Eisler (1907 - 1995) who, while working in England, designed one of these circuits about 1936 as part of a radio set.

About 1943 the Americans began to use the technology on a large scale to make rugged radios for use in World War II. After the war, in 1948, the USA released the invention for commercial use. Printed circuits did not become commonplace in consumer electronics until the mid-1950s.

Before printed circuits, point-to-point construction was used. Originally, every electronic component had wire leads, and the PCB had holes drilled for each wire of each component. The components were then soldered to the PCB. This method is called through-hole construction. This could be done automatically by passing the board over a ripple, or wave, of molten solder in a wave-soldering machine. Through-hole mounting is still useful in attaching physically-large and heavy components to the board. However, the wires and holes are wasteful. It costs money to drill the holes, and the excess length of the wires has to be cut. In the 1960s, a technique called surface mount was invented. It became widely used in the late 1980s.
1.2 Surface mount technology

Surface mount technology (SMT) is a method for constructing electronic circuits in which the components are mounted directly onto the surface of printed circuit boards (PCB’s). An SMD (Surface Mount Device) component is smaller than its leaded counterpart (because it has no leads) and has either short pins or flat contacts. The site on the PCB where the component has to be fitted has flat, usually tinned, copper pads without holes. One technique for assembly coats the pads with a thin layer of solder paste, which also acts as a temporary adhesive to hold the component in place during soldering.

Soldering, in this technique, consists of heating the circuit board and components in an oven; this drives off the flux from the solder paste and melts the remaining solder. The surface tension in the liquid solder prevents the component from sliding off while the solder is liquid. The circuit board is then cooled to solidify the solder.

1.3 Flexible circuits

One of the next development areas in surface mounting technology on printed circuit boards (PCB’s) is component placement on a flexible circuit board (FCB). These products can be found in objects as diverse as an automobile or a cellular phone. Flexible circuits can replace wiring harnesses and hard wiring or can be designed to combine several wire harnesses into one flexible circuit. (See figure 1.1)

There are many reasons for choosing flex circuitry, from interconnecting, to the demand of miniaturization within todays electronics environment. Flexible circuits offer several advantages and some of those include:

- Reduction in packaging size and weight
- Reduction in loan costs of producing flexible print circuits w.r.t. to assembling a wiring harnesses.
Chapter 1: Introduction to reel to reel flex foil transport

- Reduce assembly costs
- Dynamic flexure of circuitry requirement
- 3-Dimensional packaging scheme
- Flexible circuits can replace wiring harnesses and hard wiring or can be designed to combine several wire harnesses into one flex circuit
- Reduction in material costs: the costs of $PCB/m^2$ are triple the costs of flexible printed circuits per squared meter. $FCB/m^2$

In the production line the flexible circuit is in a two dimensional state (flat). After component placement the flexible circuit can be cut and folded to create a complex 3-dimensional state. Figure 1.2 shows two flexible circuits. The right figure shows a flexible circuit with a lot of fold lines. Appendix A shows a few examples for the use of flexible circuits.

Typically, during the production process nowadays, flex circuits are rigidized (placing a flexible circuit on a rigid stiff board) so that they appear and handle like rigid boards. The flex is usually pinned or taped onto a bare piece of rigid material. After components are placed and the circuits are reflowed (melting of solder via a typical temperature-profile), the circuit must be removed, usually by hand, and sent on its way through further assembly. There is a lot of manual handling of these flexible circuits and recycling and cleaning of the rigidizing boards.

![Figure 1.2: Flexible circuits, containing a lot of folding lines](image)

This method isn’t suitable for high volume circuit production and therefore a reel to reel application is required. A reel to reel foil line consists of a de-reeler (unwind station), screenprinter (adding solder), pick and place equipment, reflow oven and a reeler. These components are discussed in section 1.5.
1.4 Diversity of flexible circuits

There exist a wide range of flexible circuit types and designs. In addition to widespread aerospace applications, flex circuits can now be found in under-the-hood automotive control modules, laptop computers with extremely tight packaging requirements, telecommunications equipment, and cameras. Flex circuits are increasingly supplanting rigid boards. A wide range of construction materials are available to meet customer application requirements.

Single-sided flexible circuits, the simplest and easiest to manufacture, commonly consist of a layer of copper foil laminated to a layer of dielectric material. As can be seen in figure 1.3, some flex foils have pre-punched holes, these are often used for connecting switches or lamps.

Figure 1.3: Construction of flex foil
Another layer of insulating material may be laminated to the flex foil to encapsulate the conductors. For dynamic applications, single-sided circuits provide maximum flexibility. Due to the orientation of the copper patterns, the thickness of the base laminate, the thickness of the used copper pattern and the length and width of the flex foil, the stiffness of the flex foil differs with direction. To give an order of magnitude of the stiffness, figure 1.4 shows the stiffness for different widths and thicknesses (constant length of 2400mm). One time without copper patterns and one time with an extra copper pattern in length-direction of 50% of the flex foil width.

![Figure 1.4: Stiffness of flex foil](image)

1.5 Schematic layout of reel to reel flex foil production line

In this section the layout of the reel to reel flex foil production line is discussed. Figure 1.5 shows a schematic view of the production line.

Unwind station

The unwind station, or de-reeler, is the installation where coils of flex foil are installed in at the beginning of the production line.

Splice table

If a new reel of flex foil is installed in the unwind station, the beginning of that foil is connected to the end of the previous flex foil with tape on the splice table.
1.5 Schematic layout of reel to reel flex foil production line

Figure 1.5: Schematic reel to reel flex foil production line

Solder paste apply

Solder paste can be applied in several ways to the printed circuit. In this case, screen printing is used: a fine-mesh screen coated with emulsion, except the areas where solder paste is required, is placed over the printed circuit.

Figure 1.6: Solder apply with screenprinting

A squeegee is then passed across the screen to force solder paste through the areas in the emulsion and onto the solder lands on the printed circuit, after which the screen is removed.

Pick and place equipment

If the solder is applied, the next step is placing components in the solder paste in the AX. The AX places components with high speed and high accuracy on printed circuits. The AX-machine consists of a base, in which PCB’s are transported, and a number of placement robots that pick and place the components. The components are led towards the pick-position by several feeders. These feeders are stacked in feeder trolleys. (More detailed information
about the AX is given in appendix C. In this appendix the main functions of the AX are explained in order to help with understanding the discussion of the concepts in section 4.

**Soldering (reflow oven)**

After the solder paste is applied and the components are placed into the paste, the soldering process takes places in the reflow oven. High quality, low defect soldering requires identifying the optimum temperature profile for reflowing the solder paste. The heating and cooling rise rates must be compatible with the solder paste and components. The amount of time that the assembly is exposed to certain temperatures must be defined and maintained.

More detailed information of reflow soldering see appendix B.

**Inspection table**

Between the reflow oven and the windup-station the operator can inspect the results after placement and can add or replace components.

**Windup station**

At the end of the production line, the flex foil with components is coiled. While coiling the flex foil, the components can be harmed, and therefore a foam protection is inserted during coiling.

### 1.6 Limitations of handling the flex foil

It must be very clear that there exist a buffer between the screen-printer and the run-in of the pick and place machine, (see figure 1.5). This is due to different cycle-times of both machines. This buffer means that there is no pretension in the flex foil already, when it leaves the screen-printer and enters the AX-machine.

Another point is the fact that the top-side of the flex foil is full of solder, therefore no actions can be done via the top-side. The flex foil has two free zones of 5 mm, one on both edges, where no components have to placed. Also the bottom-side is available to handle, stretch or transport the flex foil.

The built-in height available in the AX-machine is 300 mm. The available height in the placement area is 6 mm. This is the distance between placement robot and flex foil support.
1.7 Concept specifications

In this section the specifications are itemized:

List of specifications

- Stiff support for flex foil during placement of components.
- Transport and index flex foil with an accuracy of about 50µm.
- Handling of different flex foil dimensions.
  Width varies from 50-500 mm.
  Thickness varies from 0.05 - 0.4 mm.
- Transport mechanism able to handle spliced flex foils.
- Transport synchronization with next machine in line.
  No "buffer" is allowed between AX and reflow oven. (because of bad solder joints due to relative motion of solder paste and the leads of components.
- Handle non-flat flex foils

List of desires

- No decrease in throughput with respect to PCB transport.
  Spacing between flex foil edge and pick-position of components minimized.
- No modification to current configuration of the AX machine.
  Transport module has to be exchangeable.
Chapter 2

Flex foil stability

This chapter deals with deviations present in a flex foil. It’s important to understand these problems for designing a reel to reel flex foil application. Causes and effects of these deviations are discussed. Two situations are distinguished: first, the deviations due to material defects, and secondly, deviations due to external influence.

Figure 2.1: Buckles in untensioned flex foil
2.1 Definitions

In this report two different terms are used for out of plane deformations of the flex foil. First, the so called buckles (definition in [Haw02]). These are the out-of-plane deformations due to material defects. The second term is wrinkling, wrinkling occurs if a flex foil is forced by external forces.

The wrinkles (due to external forces) are regions of temporary elastic buckling caused by compressive flex foil stresses. The size, wavelength and the direction of these wrinkles depend much upon the magnitude and direction of the applied loads within certain boundary conditions.

![Buckles in a flex foil](image)

**Figure 2.2:** Buckles in a flex foil

The wrinkles disappear when the loads are removed. In the pick and place area of the AX there is need for a taut state at all times (figure 2.3).

Denote the principal stresses by $\sigma_1$ and $\sigma_2$ with $\sigma_1 \geq \sigma_2$. Two states of the wrinkled flex foil, can be defined by principal stresses as follows:

**Taut state**  $\sigma_1 > 0 \cap \sigma_2 > 0$

The flex foil is tensioned in all directions

**Wrinkled state**  $\sigma_1 > 0 \cap \sigma_2 \leq 0$

Wrinkling occurs when $\sigma_2 \leq 0$, it follows the line $\sigma_1$ If the applied tension $\sigma_1$ is too high, the flex foil cannot withstand the compression tension $\sigma_2$ and forms a so called wrinkle.

To realize a taut state and remove material wrinkles (discussed in section 2.2) it’s important to apply loads within boundary conditions. If the loads and boundary conditions are applied in a wrong way, wrinkles can occur.
2.2 Causes of material defects

This section explains the four most important deviations or problems of handling flex foil. These problems determine the layout of the concepts, discussed in chapter 4.

2.2.1 Difficulties in coiling a flex foil

Reel density or hardness is probably the most important factor in determining the difference between a good and bad reel of flex foil. Reels that are coiled too soft will go out of round while coiling or will go out of round when they are handled or stored.

As a reel of flex foil material winds, tension builds inside the reel, which is known as in-wound tension or residual stress. If these stresses become greater as the reel is coiled, then the inner wraps toward the core will loosen. This is what causes the reel of flex foil to dish while coiling or telescope when they are handled or being uncoiled. If such a reel of flex foil "telescopes" before it is knitted into parts, the knitted parts of flex foil are said to be skewed, see subsection 4.7. To clarify this phenomenon try to roll a dart of a rectangular piece of paper. Cut a piece out of this dart and unroll it. The paper (with an arc) you see is called a skewed paper.

2.2.2 Flex foil skew

When the edges are longer on one side with respect to the other, the flex foil is said to be skewed. During the production of the plastic film sheet, the thickness is determined by the distance between two rollers. If these two rollers are not aligned, the thickness of the flex foil is not constant along its width. This can result in internal forces during cooling in the production process and difference in length of both edges of the flex foil.

Skewed flex foils form arcs of circles when they are spread out flat on a level surface. (See figure 2.4) The magnitude of the skew is determined by measuring the distance that the flex foil edge is from the center of the cord line on the inside arc formed by the flex foil.
2.2 Causes of material defects

2.2.3 Buckling in etched flex foils

During the production of the flex foil base material the flex foil has little pretension as the basically stress free copper layer is applied. During subsequent etching of the circuit pattern, the release of built-in stress causes local buckling to occur. See figure 2.5. This phenomenon is comparable with the bi-metal effect.

Figure 2.4: Skewed flex foil versus straight flex foil

Figure 2.5: Buckled flex foil
2.2.4 Curl in laminated flex foils

Unequal planar expansion of flex foils before they are laminated together is one of the most common causes of curl in laminates.

Most laminating processes are designed such that the thermal expansion of the two flex foil materials is matched. However, hardly any two materials have exactly the same coefficient of thermal expansion, so there is always some difference after the flex foil have cooled to room temperature. When one flex foil is very stiff compared to the other, there is usually no curl problem. However, when the two flex foils have similar moduli and are of similar thickness but have different thermal expansion rates (when they are cemented together or when only one flex foil grows from some other source), the laminated structure is likely to curl, shown in figure 2.6. Curl in laminates is caused when one of the flex foils either shrinks or grows more than the other after they are laminated together.

The principle is the same as buckling, but results in a different problem. Curl occurs at the whole width of the flex foil while buckling occurs locally.

Figure 2.6: Curl in laminated flex foils and coated flex foils

Curl can also occur when two flex foils that are joined that do not have the same planar elongation at the moment they are fixed together in the laminating process.
2.3 Effects of material defects on component placement accuracy

In this section the loss of accuracy due to flex foil out of plane deformation is discussed. If components are placed on a non-flat, high placement accuracy cannot be guaranteed. To determine the order of magnitude of the problem of placing a component on a non-flat this section discusses some models of different buckle heights and buckle widths with respect to component size and interspacing (space between two components).

In practice a buckle or wrinkle can have some slight stiffness due to the dome-shaped form. Also, if a component is placed in the solder paste, buckled or wrinkled flex foil can have resistance to shift due to the adhesive forces of solder paste and component.

In the models, the stiffness of the buckle or wrinkle and the resistance to shift of the buckled or wrinkled flex foil are not taken into account to take the worst case scenario. It’s clear that the buckle or wrinkle can move underneath the component during placement. In the next study will be specified what kind of buckles or wrinkles in the flex foil cause problems.

Figure 2.7 shows a buckle with height $h$ and radius $R$. The buckle is supported by a stiff carrier.
2.3.1 Collision between components

Figure 2.7 shows how the XY-robot places component 2. While the robot places the component non-flat flex foil will be pressed to the support table. While this happens component 1 will rotate and a collision between component 1 and component 2 can occur.

In this example the desired interspacing is 75 $\mu$m. From figure 2.8 it’s clear that for 75 $\mu$m interspacing a maximum buckle height of 0.1 mm is allowed to prevent collision.
2.3.2 Misconnection of component

Figure 2.9 shows two solderpads (large dots under the component) onto which the component has to be placed. Ideally, the material moves as well to the left as well to the right like in figure 2.9.II. The solderpads will remain in right position. The component will be connected properly. While the component is placed on the foil, the buckle can move away from under the component. In the most extreme case, it will lay flat at one side of the component (figure 2.9.III). All the material has been moved to the left side of the component.

![Figure 2.9: Misconnection of component due to shifting of buckled flex foil](image)

Figure 2.10 shows the relation between deviation $\Delta s$ and radius $R$. Decreasing $R$ involves increasing the deviation.

![Figure 2.10: Placement accuracy as function of buckle radius](image)
2.4 Causes and effects of wrinkling of thin flex foils

The wrinkling of thin flex foils has been analyzed in many stages and there are a number of technical approaches that have been developed over the years. Many mathematical models provide information about size, wavelength, amplitude and the direction of these wrinkles. In this section several ways of stretching are investigated with a finite element analysis.

In this section several models are built to obtain insights in the behavior of flex foil during tensioning it. The models obtain insight how structural wrinkles exist and some of them show how to stretch a flex foil without these structural wrinkles. In the first paragraph the length to width ratio of a flex foil will be discussed.
2.4.1 Effect of length to width-ratio of a flex foil

In this paragraph tensioning with respect to the length to width ratio of the flex foil is evaluated. In this FEA the model a force is applied at the corners. Figure 2.11 shows three models with different length-to-width ratio’s: 1:1, 1:2 and 1:4. The blue tension area’s in these figures are the zones where no positive stresses ($\sigma \leq 0$) in widthwise direction are realized. The other colors in de FEA models are positive stresses. It can be seen from the figures, applying a force at the corners has it’s limits with respect to tension the flex foil in y-direction.

![Figure 2.11: stress in y-direction $\alpha_F = 45^\circ$](image)

**Figure 2.11:** stress in y-direction $\alpha_F = 45^\circ$

**Conclusion**
Applying a force at the edges no stress in y-direction can be realized.
2.4.2 Effect direction of force vector

In this FEA model the forces are applied with the force vectors crossing each other in point M, (figure 2.12). By changing the angle of the force vector from 45 degrees to less than 45 degrees an extra undefined zero tension zone (blue) exist between the points were the forces are applied.
2.4.3 Applying a force at the edges or at the whole width

In this figure two stress situations are shown, tension the flex foil in x-direction with applying a force and the edges and a stress distribution with applying a force at the whole width of the flex foil. Tension the flex foil at local points involves high local stresses near the clamps, this manner of stretching also results in negative stress zone near the clamp. The distributed tensioning in figure 2.13 results in homogenous stress distribution, with no high stress area’s. Furthermore, in the situation with local appliance of a force, the problem arise that near the clamps more material is moved in transport direction than in the middle of the flex foil. This can be a reason for starting the flex foil to wrinkle and cause problems in the next machine.

2.5 Definition of working area

In the left figure of 2.14 three zones in the stress-strain diagram are shown. Zone 1 represents the tension to flatten out flex foil with buckles, the second zone is the elastic zone and the third zone is the plastic deformation zone.

In the right figure of 2.14 two different characteristics of flex foils are given. Flex foil #1 has no zone 1. This flex foil has no buckles and is initial flat. The material is thick enough to resist compressions in the laminating process, discussed in section 2.5. Flex foil #2 represents
a flex foil with buckles. Before the elastic region starts for this flex foil, first the buckles have to be stretched and flattened. This is the point were the tension applied to this flex foil is at a sufficient level, further increasing the tension level only results in elastic elongation. If components are placed in the solder paste on a highly elongated flex foil, bad solder joints occur if the tension is removed afterwards. The working point of the stretch mechanisms in chapter 4 is at the transition point of zone 1 and zone 2. So in this figure the working points are: point $p$ for flex foil #1 and point $q$ for flex foil #2.

In the experimental setup for a tested PET flex foil with 0.25$\mu$m thickness and 480 mm width, the elongation to remove all buckles is $\approx 3-4$ mm, with a tension force of $\approx 50$ N. The force is applied in the same way as in the lower figure of 2.13 distributed along it’s width.
Chapter 3

Experimental setup AX3

3.1 Flex foil vacuum support table

Most concepts discussed in chapter 4 are based on the use of vacuum to hold down the flex foil. Because this is an important parameter in all concepts, an experimental setup has been realized to evaluate its feasibility. Because the use of vacuum proved to be a good way to hold down the flex foil, the experimental setup is integrated in the AX pick and place machine to investigate the difficulties with transporting of the flex foil. The obtained insight can be used to evaluate the concepts discussed in chapter 4.

The dimensions of this experimental setup are 480 mm x 480 mm. This is the real width of the transportbeam in its current configuration and the desired maximum width for the flex foil to be held down. It consists of two parts. The first part, the base or bottom plate, consists of milled channels (1.5 mm x 3 mm). The second part, the cover plate, consists of drilled holes of 1.1 mm diameter.

![Experimental setup, before and after use of vacuum](image.png)
The vacuum-volume is:

\[ V_{\text{vac}} = V_{\text{channels}} + V_{\text{holes}} \]  
\[ V_{\text{vac}} = 20 \times 470 \times 1.5 \times 3 + 19 \times 19 \times \frac{1}{4} \times \pi \times 1.1^2 \times 2 = 42.3 + 0.69 = 43.0 \text{cm}^3 \]

Figure 3.2: Experimental setup bottom- and cover plate

In the catalogue of PIAB, a vacuum pump is selected. With pump type P3010, model Pi-12-3 and a feed pressure of 0.314 MPa, the air consumption is 0.44 Nl/s\(^1\). This results for the evacuation times of the experimental setup can be seen in table 3.1.

<table>
<thead>
<tr>
<th>Vacuum level [-kPa]</th>
<th>Theoretical evacuation time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.0027</td>
</tr>
<tr>
<td>20</td>
<td>0.0090</td>
</tr>
<tr>
<td>30</td>
<td>0.0193</td>
</tr>
<tr>
<td>40</td>
<td>0.0413</td>
</tr>
<tr>
<td>50</td>
<td>0.0705</td>
</tr>
<tr>
<td>60</td>
<td>0.1088</td>
</tr>
<tr>
<td>70</td>
<td>0.1643</td>
</tr>
<tr>
<td>80</td>
<td>0.2640</td>
</tr>
<tr>
<td>90</td>
<td>1.2900</td>
</tr>
</tbody>
</table>

\(^1\)Normal liters per second
3.1 Flex foil vacuum support table

3.1.1 Insights obtained from the experiments

- What kind of buckles or wrinkles do flat out?
  
  Because of the presence of copper (extra stiffness) some buckles don’t flat out while applying the vacuum. The local dome shaped flex foil will not collapse under vacuum appliance. This problem is solved by stretching the flex foil in transport direction first to create a flat situation before vacuum is applied.

- What is the level of vacuum needed for flattening?
  
  To hold down the flex foil, approximately -25kPa vacuum pressure is needed. This is an indication, because thickness and initial flatness varies with different types of flex foil.

- Some flex foils have pre-punched holes, these are often used for connecting switches or lamps. What is the influence of these pre-punched holes?
  
  Too many holes lead to too much pressure drop and leakage. A leakage of about 20\(\text{mm}^2\) still resulted in a proper hold down. More leakage needed more air flow, which was not available. If a flex foil contains too many holes to make use of the squared grid shown in figure 3.2, prefabricated cover plates can be used with vacuum holes not located at the positions of the holes.

- Is curl solved?
  
  Since curl arise only with the stiffer flex foils, curl can’t be solved by the vacuum. An extra mechanism is needed to hold down the edges. In the experimental setup a strip of aluminium is used to force the flex foil in its z-position within 1 mm.

- What is the suction time until the flex foil flattens?
  
  Table 3.1 gives a summary of theoretical suction times for different vacuum levels. This values are good assumptions if the flex foil is stretched before vacuum is applied. If the flex foil is not stretched before vacuum is applied the flex foil is first sucked to the table at the position of the holes. If the flex foil 'shuts' these holes, the flow resistance increases and suction time become very large.

- What is the relation between the applied vacuum pressure and friction force between flex foil and cover plate?
  
  By measuring the friction force while sliding the flex foil over the cover plate during vacuum appliance, a relation between vacuum pressure and sliding force can be found:

  \[
  C_1 \approx \frac{F_{\text{pull}}}{P_{\text{vacuum}} \times A_{\text{coverplate}}} \approx 0.25 - 0.3
  \]  

  The constant \(C_1\) is a function of the friction coefficient (\(\mu\)) between cover plate and flex foil, effects of non-uniform pressure distribution over the cover plate and effects of flex foil ”shutting” the vacuum holes.
3.2 Flex foil transport mechanism in AX3

As mentioned in the preface, this project is in close co-operation with the customer Hella who finance the project partly. To convince Hella that flex foil transport is feasible with a minimum modification of the AX a quick and practical solution is taken to implement flex foil transport in the AX3 platform. This quick solution is possible for Hella, because the flex foil used by Hella is flat in it’s initial condition. Stretching the flex foil before the vacuum is applied, is not necessary.

First, the working-principle will be explained. It starts with applying vacuum to the transport beam to suck the flex foil to the table. Now components can be placed. The transportbeam can make a few indexes, after every index step the placement robots start the pick and place of the components. After the last index step, the grippers hold the flex foil in position. The transportbeam makes its hoist movement (return stroke), while it switches to blower air to realize an approximately frictionless return-stroke. The flex foil is guided over bowed caps at the run-in and run-out of the AX-machine. This prevents curling of the flex foil, since per definition a foil cannot curl or bend around two axis.

At the side edges of the transportbeam strips in length direction are mounted, under which the flex foil is guided to prevent curl in the AX-machine. (See figure 3.4).
Figure 3.4: Appliance of adjustable strips for flex foil width to prevent curl
While the transport moves a gap exist between the run-in and transport beam and the run-out and transport beam. To prevent sagging of the flex foil (bend through due to gravity) tensator spring are installed. (See also figure 3.2)

In next diagram all actions in one cycle are shown:

Figure 3.5: Timing diagram for experimental setup of AX3
Chapter 4

Concepts

In this chapter several concepts are discussed. In the first section a summary of the specifications for hold down- transport- and stretch-mechanisms are given.

In the discussion of the concepts the support table has the function to realize a stiff support during placement of components. A large deflection of the support table will lead to misalignment of a component. Another function of this support table is to hold the flex foil in position. During placement the foil has to be flat without buckles to guaranty placement accuracy. Two further points of interest are discussed: how the flex foil is transported through the AX-machine and how the foil is flattened before the vacuum is applied. Some mechanisms have a combined function of stretching and transporting, while other concepts need two submodules to realize this. In every concept the foil is guided as close as possible along the component feeders, to minimize the travel-time of the pick and place robot.
4.1 Explication of terminology

For the discussion of the concepts of flex foil handling one schematic figure of the AX is used (figure 4.1) and therefore a few important terms are listed in the table below.

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base run in / run-in-module</td>
<td>RIM</td>
<td>Entrance of the AX-machine for flex foil</td>
</tr>
<tr>
<td>Trolley</td>
<td>-</td>
<td>Holder for 24 feeders</td>
</tr>
<tr>
<td>Compact placement robot</td>
<td>CPR</td>
<td>Picks and places the components</td>
</tr>
<tr>
<td>Wide placement robot</td>
<td>WPR</td>
<td>Double working area w.r.t CPR</td>
</tr>
<tr>
<td>Transportbeam</td>
<td>TB</td>
<td>Transports PCB’s or FCB’s through the AX-machine</td>
</tr>
<tr>
<td>Base run out / run-out-module</td>
<td>ROM</td>
<td>Exit of AX-machine, transport to next machine</td>
</tr>
<tr>
<td>Feeder</td>
<td>-</td>
<td>Contains components and feeds them to placement head</td>
</tr>
</tbody>
</table>
4.2 Use of adhesive tape in a vacuum environment

In this concept a conveyor belt is used to offer a stiff support during placement of components and secondly to transport the flex foil. The de-reeler at the beginning of the production line is placed in a vacuum environment (a box with vacuum), together with two reels double-sided adhesive tape ($\approx 3$ mm width). The conveyor belt runs through this vacuum environment. While moving the conveyor belt in transport direction the flex foil and tape are unrolled and both “taped” to the carrier. The tape is present at the edges of the flex foil. Leaving the box, when the flex foil is taped to the conveyor belt, results in a force perpendicular to the foil:

$$F_{\perp} = (P_{atmos} - P_{vac}) \times A_{flexfoil}$$  \hspace{1cm} (4.1)

Because of the difference between the cycle times of the screenprinter and the pick and place machine, the screenprinter is able to make the same stroke as the maximum desired stroke of the conveyor belt.

Width adjustment, to handle different flex foil can be done by shifting one reel of adhesive tape in width direction.

![Schematic layout of using adhesive tape (front view production line)](image)

**Figure 4.2:** Schematic layout of using adhesive tape (front view production line)

**Conveyor belt dimensions**

The part of the production line were the conveyor belt runs through is approximately 8m in length. For a metal conveyor belt with a thickness of 0.3 mm the diameter of the driver- and idler pulley is given by:

$$D = \frac{t \times E}{\sigma} \approx 300mm$$  \hspace{1cm} (4.2)

Taken the belt life expectancy in account, it’s clear from the table below 300mm is proper diameter.

<table>
<thead>
<tr>
<th>Pulley diameter to belt thickness ratio</th>
<th>Belt Life expectancy</th>
<th>Total production time [weeks]</th>
</tr>
</thead>
<tbody>
<tr>
<td>625:1</td>
<td>10000000 cycles or greater</td>
<td>238</td>
</tr>
<tr>
<td>400:1</td>
<td>500,000</td>
<td>116</td>
</tr>
<tr>
<td>333:1</td>
<td>165,000</td>
<td>38</td>
</tr>
<tr>
<td>200:1</td>
<td>85,000</td>
<td>19</td>
</tr>
</tbody>
</table>
The conveyor belt can be supported by either support rolls or a fixed table with a teflon coating. Appendix E shows how many support rollers are needed to support the conveyor belt in a proper way. Because the large amount of rollers and their bearings a table with teflon coating is preferred.

Conclusions

Advantages

- Extra stiffness is supplied to the flex foil by taking a stiff flex foil carrier
- The vacuum force is only working at the flex foil, therefore no extra traction force is needed to move the conveyor belt
- No hoist movement is needed (w.r.t. transport beam in AX)
- The construction can handle flex foil which want to curl or buckle

Disadvantages

- The adhesive tape has to be peeled off if the flex foil leaves the production line
- The screenprinter needs an extra mechanism to be able to make the same indexes as the conveyor belt
- The metal conveyor belt deflects while placement of component
- If a metal conveyor belt is used, the mass of the belt is 21 kg. (mass of the transport beam in AX = 35 kg)
- Skewed flex foils cannot be handled in this construction

To prevent the deflection of the conveyor belt and the length of the conveyor belt (extra mass), in next subsection bringing in vacuum at the bottom of the conveyor belt is discussed, the conveyor belt is only running at the working area of the pick and place machine to minimize the moving mass.
4.3 Vacuum conveyor belt

To hold down the flex foil while making an index stroke or placing components, a vacuum conveyor belt is used (figure 4.3). The conveyor belt is used to offer more stiffness for small and thin flex foils, to guarantee an accurate transport.

After explanation of this concept with the use of the timing diagram of figure 4.4, the following sub-modules are emphasized:

- vacuum conveyor belt
dimension conveyor belt
- tracking of the conveyor belt
- fixed support and vacuum appliance
- positioning flex foil at conveyor belt
- drive mechanism

![Diagram of vacuum conveyor belt](image_url)

**Figure 4.3:** Vacuum conveyor
Working principle:

- The conveyor belt starts running over a fixed support where vacuum is applied continuously.
- The flex foil will flatten, when it enters the AX-machine with an extra mechanism installed before the run-in of the pick and place machine.
- After each index the robots start pick and place components.

![Timing diagram vacuum conveyor](image-url)

**Figure 4.4:** Timing diagram vacuum conveyor
Fixed support and vacuum appliance

In figure 4.5 the fixed support is shown. It consists of a plate with local surface treatment and 19 milled vacuum channels ($P_-$) of 3 mm x 2400 mm. The surface treatment is the appliance of chromed layers (3mm) near the vacuum channels to prevent wear and offer the transition area from vacuum to atmospheric pressure, see figure 4.5 and 4.6.

The conveyor belt, which is running over these vacuum channels, consists of holes with a mesh of 25 mm x 25 mm. Here the vacuum is supplied to the conveyor belt at the locations where it’s needed: just under the holes in the belt to suck the flex foil to the conveyor belt. The parts of the conveyor belt where no vacuum is desired, atmospheric pressure ($P_+$) is supplied to limit friction force.

In figure 4.6 the pressure distribution over one vacuum channel is given ($P_-$), surrounded by two atmospheric channels. The areas next to the vacuum channels are micro-chromed to prevent wear due to friction. So, in the channel a vacuum pressure is acting on the belt, this vacuum pressure decreases from $P_{vac}$ to $P_{atmos}$ over the width of one chromed layer. This assumption is taken in the calculation of the friction force $F_{fv}$. The resulting $A_v = (3 + 2 \times \frac{1}{2} \times 3) \times 2400$. $F_{fv}$ is the main resistance to the motion of the conveyor belt $F_{fv}$ created by the vacuum between the belt and fixed support, given by:

$$F_{fv} = \mu PA_v = 1700N$$  \hspace{1cm} (4.3)

where $P$ is the magnitude of the vacuum pressure minus the atmospheric pressure (-25kPa) and $A_v$ the total area of the vacuum working area like described above. For the friction coefficient $\mu = 0.25$ is taken.
The wear of the chromed areas per year can be calculated with the following formula:

\[ h = \frac{k \times F_v \times v \times t}{A_{\text{chromed}}} \approx 1.1[\mu m/\text{year}] \]  

(4.4)

with:

\[ v = 1[m/s] \]

For \( t \) is considered that the AX-machine is running 16 hours a day, 6 days a week, for one year at maximum capacity. \( t \approx 5000hrs \) The wear factor for the chromium layer is \( k \approx 0.001 \times 10^{-15} \)

The total power consumption caused by friction and acceleration of the conveyor belt is given by:

\[ P = (F_v + F_{\text{accel}})v = 1.8kW \]  

(4.5)

The accuracy of one index stroke is a function of tracking of the conveyor belt and the accuracy the flex foil is positioned at the conveyor belt.
Vacuum conveyor belt

- Dimensions of conveyor belt

To dimension the transport mechanism the following relation for band and roller is given:

\[
\frac{t}{D} = \frac{\sigma_{\text{bend}}}{E}
\]  \hspace{1cm} (4.6)

From equation 4.2 and the belt life expectancy taken into account, the thickness of the metal belt is taken 0.3mm. For the metal belt alloy, the type 17-7-CH-900 is taken from table 6. in [Tec04a]. This alloy has a Yield Strength of 1655 N/mm².
Tracking of the conveyor belt

Given that a metal belt will not significantly stretch under tension, tracking a metal belt can be more difficult than tracking other belt types. A metal belt will not stretch to compensate for:

[Haw02]

1. Lack of system squareness or alignment
2. Uncontrolled pulley shaft deflection
3. Belt camber

Camber, or edge bow, is the deviation of a belt edge from straight line. Every belt has some camber, metal belt camber is typically 0.2 - 0.5 mm in 1m. [Tec04a]

Figure 4.7: Amount of camber and axis pulley adjustment for metal belt

When placed in a squared two pulley system and tensioned, one edge of the belt will be tensioned more than the other because it has a shorter edge circumference. This will cause the belt to track away from the tight edge of tension towards the loose edge when the belt is rotated. To compensate for this lateral movement a pulley axis adjustment is required. In figure 4.7 two 2-pulley driven system are shown. In the left figure two pulleys are adjusted to compensate for belt camber. In the right figure of 4.7 the driver roll has a fixed orientation, while the idler pulley is adjustable. The driver roll is fixed to prevent loss of stiffness due to an adjustment.
Positioning flex foil at the conveyor belt

The flex foil is held down by the vacuum at the conveyor belt. When making an index-stroke any point of the flex foil at the conveyor belt will describe a straight line. (transport direction). Any point on the flex foil with a little skew (Discussed in chapter 4.7) will have the following problem:

![Diagram of conveyor belt and flex foil](image)

**Figure 4.8:** Schematic layout walk-away foil

Seeing from the idler-pulley, during an index-stroke, the side-edge of the flex foil will shift laterally. When the flex foil shifts lateral, it will run into the geometric boundary of the AX-machine and wrinkle. So, before the flex foil enters the AX-machine the flex foil skew must be compensated. One way to compensate is to force the flex foil in it’s right way, this means the flex foil has to be straightened before it enters the AX-machine. To straighten the skewed flex foil before it enters the AX-machine, a tension profile like in figure 4.9 has to be provided. This tension profile results in a moment action on the flex foil.
Chapter 4: Concepts

Stretch mechanism to straighten the flex foil

As can be seen in figure 4.10 before the idler pulley a bowed cap is installed. This bowed cap is divided in a few vacuum zone’s ($P_1 - P_{12}$). By controlling the vacuum pressure in the bowed cap for each zone separately ($P_1 - P_{12}$), the desired tension profile can be achieved to straighten the flex foil. In this situation zone 12 has more vacuum than zone 1 has. If a straight flex foil is transported through the production line, the vacuum pressure in all zones will be the same.

Calculation example:
A flex foil (width=500mm) is taken with a skew rate of 1 mm/m and a maximum stiffness of 2.5e5 N/m. For straightening the flex foil a friction force (at the component side) of 250 N is desired between flex foil and bowed cap. This friction force is linear decreasing along it’s width. The friction force is achieved by using a vacuum level $dP$ of -12.5kPa at zone 12.
Drive mechanism

To determine which transmission has to be used, the index accuracy of the metal belt is taken \( \Delta s = 50\mu m \). For the encoder at the motor 2000 steps per revolution is choosen, and for good control 10 pulses per step (\( \Delta s \)) are needed. This result for the transmission ratio in:

\[
\frac{2\pi r_{driver\ roll}}{N_{encoder}\Delta s} \approx 1 : 20
\]

(4.7)

In the left figure of 4.11 two drive mechanisms are shown, the lower one has a double timing belt system (1:4 and 1:5) while the upper mechanism has a large gear wheel (diameter of pulley) with a small pinion (1:10) in combination with a timing-belt(1:2). Because of the reduction of 1:10 of the gear transmission, the stiffness of the timing belt feels this reduction quadratical. \((k_{belt} \times 10^2)\) The upper transmission can reach higher stiffness w.r.t. to the double timing belt.

![Drive mechanism + reduced dynamic model](image)

**Figure 4.11:** Drive mechanism + reduced dynamic model
Conclusions

Advantages

- The moving mass of the conveyor belt is only 7.5 kg
- Large index stroke’s are possible, which is ideal for low-volume placement
- The combination of metal belt and support plate offers a stiff underground for placing components

Disadvantages

- A high friction force exist between vacuum slider bed and metal belt
- The high power consumption is only due to overcome this friction force
- Skewed flex foils have to be straightened before they enter the AX-machine, thicker, wider flex foils are stiffer and therefore higher forces are needed to compensate for the flex foil skew
- If a smaller flex foil has to be transported through the AX-machine, some vacuum channels have to be switched off. Doing that results in a differential loading at the pulley and starts the metal belt to shift laterally
- There is a virtual play in this construction of $\frac{2W}{c} = 0.23$ mm The high friction forces between conveyor belt and support plate have need for a strong stiff drive mechanism

Straightening before entering the AX-machine for skewed flex foils implicit that not the whole scope of flex foils can be handled in this machine due to the used forces.

In the next two sections, two methods are given which handles flex foils in a complete different way. Because the flexible support table (4.4) is mentioned a few times in previous brainstorm during the concept design and the tenterframe (4.5) is discussed a lot in literature they are included in this report.
4.4 Flexible support plate

In this concepts the use of a flexible support plate is taken. The working principle starts with a flat situation of the support plate where more length of flex foil is present then the length of the support plate itself. To flatten out the flex foil, two clamps clamp the flex foil to the support plate at the entrance and exit of the working area of the PR’s. The support plate makes a curve with radius R by actuating it in the middle. The edges of the support plate are fixed. The main advantage is that since the flex foil is bent around the y-axis, the flex foil cannot bend around it’s x-axis, and will lay flat to the plate in all directions.

![Figure 4.12: Working-principle of the flexible support table](image)

The radius R is a function of the length of flex foil on the support table minus the support length. To see what curvature has to be realized, the stroke of the actuator is plotted against the desired elongation.

![Figure 4.13: Curvature of support table](image)

For an elongation of 3 mm, it’s clear from figure 4.13 that the actuator has a stroke of about 70 mm. Since there exist a free space of about 6-7 mm between pick and place robot and support plate and the z-stroke of the pick and place robot limited to 6 mm, the maximum allowed elongation can be less than 0.1 mm.
Conclusions

Advantages

- A simple construction is used to stretch the flex foil
- Bending around one axis means that the flex foil flattens also around the other axis.

Disadvantages

- The lift of the bowed support plate for more than 6 mm is not possible (what is needed) due to the available space between support plate and placement robot.
4.5 Tenterframe

Tenterframe applications, like in figure 4.14, are often used in the textile industry. At both sides of the flex foil a frame with bistable clamps is installed. In this situation, a front-frame at the component (trolley) side, and a rear-frame at the robot side. When the foil enters the machine the frames have a little toe out, in figure 4.14 an exaggerated toe out is shown. When the flex foil enters the tenterframe, it will be clamped by the bistable clamps. The clamps are guided through a rail. Due to the toe out, the flex foil stretches in y-direction. The amount of toe out can be adjusted for different flex foils. In the component placement area, the clamps run parallel.

![Figure 4.14: Schematic layout of tenterframe](image)

To tension and transport the flex foil in x-direction two small conveyor belts are installed at the run-in and run-out of the machine (figure 4.15). Tension in x-direction is built in by different velocities ($v_2 - v_1$) of the conveyor belts. If the tension in the flex foil reaches a certain level, the conveyor belts start running with the same velocity ($v_2 = v_1$).

![Figure 4.15: Drive mechanism](image)
The poisson ratio is defined as:
\[ \nu = -\frac{\epsilon_y}{\epsilon_x} \]  \hspace{1cm} (4.8)

With this relation it’s clear that if there exist a strain in y-direction, a zero or negative strain in x-direction exist. (See the blue zone’s in figure 4.16) The x-vector of this strain is perpendicular to vector of the y-strain. This means if the clamps tension the flex foil in y-direction, they have to shift a little in x-direction. Therefore, the connection between two clamps in the rail has a lower stiffness \( k \) than the stiffness of the flex foil itself (figure 4.15). The transport mechanism feels the stiffness of the flex foil.

In figure 4.16 this phenomenon is clarified with an finite element model.

**Conclusions**

**Advantages**

- Stretch mechanism is able to remove buckles
- Curl cannot occur since the foil is gripped at a lot of points
- The mass to be transported is minimized to the sum of the clamp masses

**Disadvantages**

- Because of the poisson ratio, some stress-area’s (blue) have zero or negative tension, which means no stretching is available at these zones
- A lot of components are needed to realize the flex foil transport
- Skewed flex foils cannot be transported in this configuration
As said this is a common mechanism used in textile industries. In the situation for flex foil there is no need for widthwise tensioning. In next sections two mechanisms are discussed which can handle skewed flex foil and have the benefits of previous concepts.
4.6 Transport beam and one tensioner

In this section the concept for foil handling in the AX with the use of the transportbeam and one tensioner at the run-in-module is discussed. After explanation of the whole concept, the following sub-modules are emphasized:

- run-in-module
- transportbeam
- run-out-module
- tensator springs.

Figure 4.17: Transportbeam and one tensioner

Figure 4.17 shows a schematic front view of the AX. Clear to see are the run-in section (RIM) where flex foil enters the pick and place machine and the run-out section (ROM) where the flex foil leaves the pick and place machine. The transport beam like it's used in the current configuration of the AX is used.

The working principle is explained with help of the timing diagram, shown in figure 4.18. The timing diagram starts with the condition that nowhere vacuum is applied and that the AX-machine is filled with flex foil. This happens for example when the system is rebooted.

- First vacuum is applied to the Run in module (RIM) and the Run out module (ROM).
- To stretch the flex foil, the RIM moves a little upstream. The elongation of the flex foil is brought into the buffer. The elongation cannot be done by the ROM since no sagging of the flex foil between AX and the next machine (reflow oven) is allowed.
- Now the flex foil is flattened so the vacuum can be applied to the transportbeam. The whole surface of flex foil where components have to be placed on, is sucked to the transportbeam.
- The robots start to pick and place components.
After the pick and place actions the transportbeam makes an index stroke and transports the flex foil. The flex foil between the RIM and transportbeam and the flex foil between the ROM and transportbeam are supported with tensator-springs to prevent sagging. (Tensator springs see page 51).

The index strokes of the transportbeam and the pick and place action taken place several times, until the transportbeam reached it’s maximum stroke.

If the transportbeam has reached it’s maximum stroke, it makes a return stroke (hoist). During this hoist movement blower air is supplied to the transportbeam so it can move back frictionless to it’s origin.

During this hoist movement the run-in and run-out-module apply vacuum to the flex foil to guarantee it’s position. Disconnection between flex foil and system means that the position information is lost.

At the end of the hoist movement a CCD camera in the transportbeam can search for a fiducial presented at the flex foil to get information about it’s position.

Transport beam

A very common way to hold down paperwebs or flex foil for processing is via a vacuum underground. In figure 4.19 a 5-segment vacuum support plate is shown.

1The width of 1 segment is a typical AX linear measurement. It’s the width of for example one trolley. The AX3 has three of such segments, the AX5 has five
The support table consists of air-permeable cover plates or cover plates drilled with holes. These cover plates lay on bottom-plates where channels are milled in, just under the drilled holes. A vacuum pump withdraws air from the bottom-plates. Differential air pressure holds the flex foil to the support table. This support table can function like the walking beam in the current configuration of the AX.

Before the vacuum is applied the flex foil is stretched like discussed above. If the flex foil is not stretched before vacuum is applied the problem described in appendix \( G \) occurs.
Curl prevention

If the vacuum is released from the transportbeam, the flex foil can curl around it’s x-axis, to prevent this a aluminium strip is mounted to the transportbeam. If another flex foil width is desirable, the strip can shift in y-direction and fixed at the new position. (Also discussed in section 3.2 see figure 3.4)

RIM - Run in Module

In figure 4.21 the run-in-module is shown. The vacuum plate can be manipulated in x- and y- direction. During the stretch actions, the vacuum plate is forced in -x direction. To compensate for the flex foil skew the run-in-module can also move in x-direction. At the edge of the run-in-module, an edge detector is installed. If the flex foil shifts too much to the side edge, the edge sensor will detect that lateral shift, and it will be compensated in the next stretch action. The vacuum plate (with the flex foil) will move in y-direction.

![Figure 4.21: RIM- Run in module](image)

The size of the run-in- and run-out-module are specified by the length of the appeared slip front. During tensioning there is an equilibrium between the force applied to the flex foil and the friction force caused by the applied vacuum:

\[ F_{tension} = F_{friction} \]
\[ \sigma t b = l_{slip} b \mu P_{vacuum} \]
\[ l_{slip} = \frac{\sigma t}{P_{vacuum} \mu} \approx 150[mm] \]

To be sure the length of the run-in-module is large enough, the dimension for the run-in-
module are taken: 300 × 500 mm. (l × b)

**ROM - Run out Module**

The run-out-module is a fixed vacuum plate, it is able to create vacuum and produce blower air.

**Tensator spring**

To compensate for the free length between the run-out-module and the transportbeam and run-in-module and transportbeam tensator springs are used to prevent sagging. In this concept the tensator springs are 90 degrees rotated (zy) with respect to the tensator springs in figure 3.2 to load the tensator spring in it’s plane (to feel $h^3$).

**Conclusions**

This concept is a modification of the AX to handle flex foil. The critical elements are discussed and a few of them are proved in the experimental setup of the AX.

**Advantages**

- The x-y movement of the run-in-module takes care of the flex foil skew
- Buckles are removed and the extra length is brought in the buffer
- Most parts of this concept are used in the experimental setup and therefore evaluated on feasibility
- Constant vacuum during index strokes means that the flex foil will not move w.r.t. to the transport beam during indexing, the position remains determined

**Disadvantages**

- The transport beam has a limited stroke
- Still there is a large moveable mass needed for transporting a flex foil
- Flex foil skew is solved by the x-y movement at discrete times, which means that during this action tension is built in the flex foil

In this configuration the flex foil is shifted laterally at discrete times. Because a skewed flex foil has a constant radius, it should be guided or steered continuously. This is discussed in next section. Also in next concept the moveable mass is eliminated.
4.7 Fixed vacuum slider bed

In this concept a fixed vacuum bed is used, at the run-in and the run-out vacuum transport belts are installed. After explanation of the whole concept, the following submodules are emphasized:

- handling skewed flex foils
- run-in-module and run-out-module
- fixed support plate

![Diagram of Fixed Slider Bed]

**Figure 4.22:** Fixed sliderbed

In figure 4.23 a timing diagram is shown. First, the working principle of this concept is discussed: The explanation starts with the condition that the flex foil is present in the AX-machine, but without pre-tension. This happens for example when the system is rebooted.

- The run-in and run-out module have permanent vacuum.
- To stretch the foil, the belt of the run-in-module turns a little upstream, the elongation is accepted by the buffer.
- If the flex foil is flattened, vacuum can be applied to the fixed support table. The whole area is sucked to the support table at once.
• Pick and place actions can be done by the robots.

• If the pick and place robots are ready, blower air is supplied to the fixed support table to create a frictionless situation for transport. It’s important there is no friction during this index, because this friction leads to an elongation or virtual play of the foil.

\[ s_v = \frac{2W}{c} \approx 0 \quad (4.12) \]

The fixed slider bed will switch from vacuum to blower air every index step.

• The two transport belts start running and transport the flex foil through the AX-machine.

• Just before the flex foil reaches it’s position, the run-in-module stops turning, the transport belt at the run-out-section keeps going until the desired tension in the flex foil is reached, which will result again in a flattened flex foil. This run-out-module is force-controlled.

• The support plate can apply vacuum again and pick and place actions can be done.

• etc...

![Timing diagram fixed sliderbed](image)

**Figure 4.23:** Timing diagram fixed sliderbed
4.7 Fixed vacuum slider bed

Handling skewed flex foils

The run-in-module has a steer/guide function for skewed flex foils, this module will guide the flex foil through the AX-machine as close as possible along the front side of the AX-machine (to avoid enlarging the pick-place distance).

In section flex foil skew is discussed. To explain how this skewed flex foil can be transported through the AX-machine, the flex foil is imagined as a circle segment, shown in figure 4.24.

Imagine how the circle segment (flex foil) can rotate about its center or how the circle segment can be transported from one transport belt to the other without moving the center point. The transport belts with their centerlines have to cross the center of the circle. If these centerlines do not cross the center of the circle, the center of the circle will move. To realize this, two options are given in figure 4.24. The left figure, represents the situation where the transport belts have only a rotation adjustment to align it in the right position for proper flex foil steering.

In the right figure the right transport belt (run-out) is fixed and is installed perpendicular to the AX-machine. To guide the flex foil in a proper way, now the left transport belt (run-in) has an adjustment in y- and θ-direction.

Figure 4.24: Circle segment transport
Run-in-module

The determine the amount of y-adjustment and rotation of the run-in-module, figure 4.25 is given for different flex foil skew-radii.

Figure 4.25: Adjustment in y and θ for Run-in-module

To align the run-in-module an adjustment of 0-2.4 mm in lateral direction is desired and for rotation θ an adjustment of 0 – 0.25°. The transport belt adjustment can be done like figure 4.26. Two adjusting screws x₁ and x₂ will determine θ, while the adjusting screw ‘y’ determines the lateral shift of the run-in-module.

Figure 4.26: Adjustment of run-in-module
If a new coil of flex foil is installed in the production line, the run-in transport belt runs parallel with the AX-machine. If the flex foil has some skew, an edge sensor will detect lateral shift of the flex foil while running. Now the adjustments screws are used to correct for the transport direction by turning the run-in transport belt. As long as the edge sensor detects lateral shifting the run-in module will be rotated until the flex foil runs properly which means: no lateral shift and running as close as possible along the front side of the AX-machine.

In figure 4.27 the two rollers have their bearing in the plates. The plates are part of partly closed box. The vacuum area, a top plate, shuts the box partly and creates a stiff re-encasing for the rollers.

![Construction of run-in-module](image)

**Figure 4.27**: Construction of run-in-module

**Run-out-module**

The run-out-module is as discussed above a vacuum conveyor belt, **without** an y- and $\theta$-adjustment.

**Fixed vacuum support plate**

For the fixed vacuum support plate the same configuration is used as discussed in section 4.6. The only difference is that in this situation the support plate doesn’t move but is fixed.
Conclusions

Advantages

• A stiff support is offered during placement of components
• The stretch mechanism is able to remove buckles in flex foil
• Skewed flex foils are guided/steered instead of stretched through the AX-machine
• Because the conveyor belt always has contact with flex foil the position is always determined
• The conveyor belt and pulleys are the only moving mass

Disadvantages

• The influence of wear w.r.t. to increasing friction coefficient is not predicted
• Vacuum is used to steer and stretch the flex foil. Because of differential loading as result of the vacuum appliance if a small flex foil is transported, the metal belt can shift while running.
Chapter 5

Conclusions and recommendations

5.1 Conclusions

The introduction to reel to reel flex foil transport in chapter 1 gives the insight for the reason for this report, it describes the diversity of flex foils and explains the limitations and specifications for the transport and stretch-mechanisms, and flex foil support during placement of components. The orientation of the copper patterns in the flex foil, pre-punched holes, the width and thickness of the flex foil have a lot influences on the behavior of the flex foil.

Since component placement accuracy only can be guaranteed for flat(tend) flex foils chapter 2 discusses all causes of material defects which results in non-flat and non-straight flex foils. Placement of components on a non-flat flex foil can result in a misconnection or collision between components while placing. To properly flatten a non-flat flex foil, the flex foil has to be tensioned at the whole width of the flex foil, not at discrete positions.

To held down the flex foil during placement of the components, vacuum is used in most concepts. To obtain insights in the problems with the use of vacuum for holding down the flex foil an experimental setup is built.

To obtain insights in transporting flex foil through the AX-machine, the AX-machine is modified to prove flex foil transport was possible. This is done not only to obtain the insights of problems in transporting but also to convince Hella, a potential client for this reel to reel production line, that flex foil handling in the AX-machine is possible.

5.2 Design choice

In section 4 several alternative stretch- hold down and transport mechanisms were discussed. By discussing the concepts, it became clear what the influences of all deviations of the flex foils are. In the last concept with the fixed vacuum slider bed, all discussed problems are manageable. Flex foil should not be forced in it’s right way, but steered. Introducing high tension to stretch the flex foil or high friction in transport the flex foil results in a need for stronger, stiffer and more power consuming mechanisms. In the concept of the fixed vacuum
slider bed the moveable mass is minimized. The index-step in transport is not limited, which is ideal for low-placement volume.

**Support during placement of components**

A simple and accurate solution for holding down the flex foil during placement of components is by a vacuum support. This solution is tested in the experimental setup and used in the 1:1 model built to evaluate the difficulties in transporting flex foil and prove it’s feasibility. To create a homogenous vacuum force an air-permeable foam-plate or wire-mesh can be used.

**Stretch mechanism**

The difference in the discussed stretch mechanisms is the possibility to stretch in length- and/or widthwise direction. In the production process of flex foil there is only a pretension in length direction. In the last discussed concept, a fixed vacuum slider bed, this tension situation can be achieved and therefore a non-flat flex foil will flatten.

**Transport mechanism**

The concepts discuss a few different transport mechanisms. The main advantages per concept are very close related to the quality of the flex foil which is used. In the last concept, a flex foil with all discussed deviations can be handled. It can handle a wide range of flex foils. Transporting the flex foil is a combination of the run-in-module en run-out-module, with these two modules tension can be built in the flex foil.
5.3 Recommendations

These recommendations are based on the fixed vacuum slider bed which is theoretically proven the best concept for transporting, stretching and supporting a wide range of flex foils in the reel to reel production line.

- Vacuum is used to steer and stretch the flex foil. Because of differential loading as result of the vacuum appliance if a small flex foil is transported, the metal belt can shift while running. It’s recommended to investigate the lateral movement caused by these differential vacuum forces.

- Further engineering and realization of the fixed vacuum slider bed concept has to be done.

- The run out module can be replaced to the end of the production line (after the inspection table). It’s recommended to investigate the influence of heating the flex foil in the reflow oven with respect to the performance of transporting and stretching the flex foil if the run-out-module is placed at the end of the production line.

- The combination of the run in module and the run out module defines the performance of stretching and transporting the flex foil. Therefore it is recommendable to investigate the controllable of the two system.
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Appendix A

Flexible circuit examples

Figure A.1: Examples for the use of flexible circuits
Appendix B

Reflow soldering

What is a Temperature or Thermal Profile? High quality, low defect soldering requires identifying the optimum temperature profile for reflowing the solder paste. Achieving SMT process consistency means repeating this profile over and over. Every solder joint on every board needs to be heated similarly if the desired soldering results are to be accomplished. From the solders point of view, it does not matter what the heat source to the solder joint is. What does matter is that the heat is applied to the solder joint in a controlled manner. The heating and cooling rise rates must be compatible with the solder paste and components. The amount of time that the assembly is exposed to certain temperatures must be defined and maintained. In other words, the solder reflow profile must first be defined and then maintained.

The Typical Profile The reflow profile is defined by the relationship of temperature versus time during heating. A typical profile consists of three heating slopes (the time vs temperature relationship or rate of temperature rise) defined by Figure 3-1. This three step profiling approach has been commonly used since the early days of SMT. Each solder paste defines the heating slopes and time and temperature limits within each slope. It is best to consult your solder paste supplier to determine the exact heating condition required for the paste you are using. For the purpose of discussion, we will use the traditional three step profile, which is typical of RMA pastes. The three step heating profile slopes are called preheat, dryout, and reflow.

Preheat In the preheat section, the goal is to fully preheat the entire SMT assembly to temperatures between 100C and 150C. The most critical parameter in the preheat section is to control the rate of rise to between 1-4C/second. The main concern is minimizing thermal shock on the components of the assembly. For example, multilayer ceramic chip capacitors can be vulnerable to cracking if heated too fast. In addition, rapid heating can cause the solder paste to spatter.

Dryout The second heating section, referred to as the dryout, soak, or preflow zone, is used primarily to ensure that the solder paste is fully dried before hitting reflow temperatures. It is characterized by a consistent temperature (often between 150C - 170C) for an extensive (60-120 second) time period. The dryout portion of the profile acts as a flux activation zone for RMA solder pastes. Dryout provides thermal stabilization of
large and small components to ensure uniform heating as the SMT assembly enters the reflow zone. Convection ovens have reduced the need for the thermal stabilization, as the entire profile tends to be uniform (referred to as h Delta T, defined as the temperature difference between the warmest and coldest component lead on the board).

Reflow  The reflow section of the profile elevates the solder paste to a temperature greater than its melting point. For Sn63/Pb37 eutectic solder, the melting temperature is 183°C. This temperature must be exceeded by approximately 20°C to ensure quality reflow for every solder joint lead. The amount of time the solder joint is above the melting point is referred to as the wetting time or timeover. The wetting time is 30 to 60 seconds for most pastes. If the wetting time is excessive, intermetallic layer may form in the joint, which result in brittle solder joints. Excessively slow cooldown while the paste is liquidous can also cause the solder joint to consist of a larger grain structure, resulting in a potentially weaker solder joint. Common cooling rates are controlled between 1-2°C/second. Many reflow ovens have water-cooled or refrigerated cooling sections so the timeover and cooling rates can be precisely controlled.
Appendix C

Surface mounting device - AX

In this chapter some detailed information about the surface mounting device AX is given. The three most important modules are discussed: transport module, pick and place module and the component feeding module. The component pick and placement platform from Assembléon is called the A-Series platform. The A-series platform consist of three type of machines:

The 3-segment frame AX3 The optimal output for the AX3 is 45k-90k cph.

The 5-segment frame AX5 The optimal output for the AX5 is 75k-140k cph.

The fine pitch version AQ-1 Accuracy up to 25µm

![AX machine - front view](image)

**Figure C.1:** AX machine - front view

---

1[kcph]: kilo components per hour
C.1 Transport module

The AX base contains a transport unit for PCB’s that transports PCB’s simultaneous through the AX-machine. It transports the PCB’s with the walking beam principle, discussed in appendix F. Further, the AX base contains a run-in section, where boards from the previous machine are received, and a run-out section, where boards are transferred to the next machine. The AX transport module feeds the PCB’s from the run-in section to the run-out section in a number of steps (indexes or strokes). After each index, the placement robots will place components on the PCB’s.

C.2 Pick and place module

In this section it’s clarified how the components are picked and placed with the use of a board alignment camera for high accuracy.

Robot and placement head

Both compact placement robots (1) as well as standard placement robots (2) can be found on the AX-machine. Functionally they are the same, but the width of a compact placement robot is half the width of a standard placement robot. Each robot is fitted with a placement head and a board alignment camera. The main function of the robot is to position the placement head in x- and y-direction over the work area of the pick and place module. The main function of the placement head is to pick, place and measure SMD components. It positions
the components in z- and \( \theta \)-direction. It is also capable of locating fiducials (markers) in the working area.

**Board alignment**

The board alignment camera can be used for fiducial alignment. Fiducials are markers produced as part of the artwork of the PCB. Figure C.4 represents a small part of the total area of a flex foil. When captured by the vision system the fiducials relative positions are analyzed and this data is then used to compensate for the geometrical deviations of the flex foil with respect to the CAD-drawing of the flex foil. This compensation can be done with measurement of 2 or more fiducials.

Board alignment refers to the interaction needed between placement robots to perform a board alignment. For AX, there are the following board alignment modes:

**Local board alignment** In local board alignment mode, each PR is able to align the board autonomously. Local board alignment requires no interaction between placement robots or between placement robots and transport mechanism during alignment.

**Distributed board alignment** In distributed board alignment, measurement results from one or more placement robots are used to perform a board alignment. The board alignment results are distributed to all placement robots that must process the board. Distributed board alignment has an accuracy penalty.
The board alignment camera is also used for the position detection of feeders and toolbit exchange unit (see below).

The AX makes use of eight different nozzles to handle the total component range from 1.5 x 3.0 mm up to 17.5 x 17.5 mm and round Ø 24.75 mm. The nozzles are stored in a toolbit exchange unit, each placement head has one of such a unit in its working area, where nozzles can be changed.

C.3 Component feeding module

In the front of the AX-machine the trolleys are installed. Each trolley can store 24 feeders. There are several feeders which can be used. For example: (twin-) tape feeding, where the components are stored in a tape. This tape consist of two layers, in the pick area the top layer is removed and the components can be picked. The board alignment camera can also be used to pick components from the feeder.
Appendix D

AX specifications

To evaluate the specifications of the flex foil-transport systems discussed in this report, the current main specification for PCB-transport is given, this specification is based on 20 compact placement robots.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tact time</td>
<td>0.024 sec.</td>
</tr>
<tr>
<td>Output</td>
<td>150.000 cph</td>
</tr>
<tr>
<td>Highest accuracy class</td>
<td>50 µm</td>
</tr>
<tr>
<td>0201 interspacing</td>
<td>100 µm</td>
</tr>
<tr>
<td>Placement quality</td>
<td>&lt; 20 PPM</td>
</tr>
<tr>
<td>Component range</td>
<td>0.6 x 0.3 mm to diagonal 24.75 mm (twin-) tape, (twin-) bulk, surftape</td>
</tr>
<tr>
<td>Feeding types</td>
<td>2.5N to 8N</td>
</tr>
<tr>
<td>Placement force</td>
<td>50 x 50 mm</td>
</tr>
<tr>
<td>PCB range min (LxW)</td>
<td>460 x 390 mm</td>
</tr>
<tr>
<td>PCB range max (LxW)</td>
<td>3720 x 2240 x 1290 mm</td>
</tr>
<tr>
<td>Dimensions (incl. feeders)</td>
<td>L= transport direction</td>
</tr>
</tbody>
</table>
Appendix E

Number of support rollers in the concept using adhesive tape in a vacuum environment

To determine how many rollers or supports are needed in the placement area to place a component with a placement force of 8N, and a maximum sagging of the conveyor belt of \( d_{z1} \approx 1\, mm \) while placing, a Finite Element Analysis is done. Several situation are modeled, with varying distance between the rollers. For a distance of 50 mm between the rollers, the maximum deflection for a belt with a thickness of 0.3 mm, varies from 0.25 mm in the middle to 0.8 mm at the side-edge. Increase the belt thickness to 0.4 mm resulted in \( \approx 0.6\, mm \) sagging at the edge of the belt.

\[
\frac{1}{2} F = 8\, N \\
\frac{1}{2} l
\]

Figure E.1: Model of bending conveyor belt. Left) Front view. Right) Side view

In the placement area (2400 \( \times \) 500\( mm \)) there is a need for:

\[
\frac{2400}{50} = 48\text{rollers(supports)} \tag{E.1}
\]
Figure E.2: Deflection while placing components at middle and side edge of conveyor belt with 8N
Appendix F

Walking beam principle

Figure F.1: Walking beam principle
Functional description:

- When the board is allowed to enter the AX-machine the run-in transport belts are started. A board is allowed to enter the machine (A) after the transport beam has made its last index step.

- The transport belts transport the board into the machine at high speed (0.35 m/s).

- The front edge of the board triggers the low speed sensor and the transport slows down to low speed (0.05 m/s) to ensure that the board is stopped gently by the stopper.

- After the low speed sensor is triggered the transport belts are stopped after a time delay.

- The transport beam lowers (B) and moves to the pick up position in the run-in (so called return stroke (C)).

- The transport beam moves upward (E) and picks up the board.

- The transport beam transports the board through the working area. The transport beam moves in index steps (F).

- During the return stroke (C) the board rests on the transport rails. During all other movements of the transport beam the board is clamped between the transport rails and the support strips.

- When the run-out is empty the transport beam is allowed to make its last index step.

- When the board reaches the last board position on the transport beam and the transport beam makes a return stroke the front edge of the board triggers the run-out entrance sensor.

- The run-out transport belts are started.

- The transport belts transport the board (D) into the run-out at high speed (0.5 m/s).

- When the board reaches the end of the run-out it triggers the run-out exit sensor.

- When the board is allowed to leave the machine the run-out transport belts switch to transfer speed. A board is allowed to leave the machine when the next machine in the flow line accepts it. The transfer speed is configurable to match the speed of the next machine in the flow line.

- The transport belts transport the board out of the machine at transfer speed.
Appendix G

Vacuum suction without prior stretching

The air under the stretched flex foil is withdrawn at once. While doing that, the flex foil will first come close to the support table at the position of the vacuum holes, and ”shut” these holes. If the holes are shut by the flex foil and the material between the holes are not close to the support

![Diagram](image)

**Figure G.1:** A. initial condition flex foil, B. vacuum holes shut, C. wiremesh

More air must be withdrawn from under the flex foil, which costs more effort and time because of the flow resistance between hole and flex foil. Theoretically it is desired to withdraw air not at discrete positions but from the whole surface while not losing the desired support stiffness. This can be achieved with a wire mesh or a foam plate. Actually, it’s a large vacuum chamber, with a large number of supports. In the experimental setup a ”300 mesh” is used, which indicates $300 \times 300$ wires per $\text{inch}^2$.

Another way of vacuum suction without prior stretching is supplying vacuum from the middle to the edges of the vacuum support table.

If buckles exist in the flex foil above the support table and the vacuum is applied at once to the whole area, it’s possible the buckle will remain. Because, per definition, there’s too much length of foil present at the support table. It’s comparable with lay down a floor covering, when you place the whole area at once to the ground, in the middle there exist a surplus of
material which cannot be removed anymore. So, the way to prevent this is by unrolling the floor covering to the ground. This unrolling is comparable with bringing in vacuum from the middle to edges. Unrolling is not possible while we are dealing with a continuous flow of flex foil which is running through the machine.

![Diagram of transport beam with vacuum plates](image)

**Figure G.2:** Top view transport beam with vacuum plates

In figure G.2 the schematic layout of the support table is given. Smart vacuum means withdrawing air from the centerline to the edges. There are two options to realize this: the first brings in vacuum from:

\[ B - B' \rightarrow C - C' \] (G.1)

and in the same time from:

\[ B - B' \rightarrow A - A'. \] (G.2)

Shortly,

\[ A - A' \leftarrow B - B' \rightarrow C - C'. \] (G.3)

The second brings in vacuum from:

\[ D - D' \leftarrow E - E' \rightarrow F - F'. \] (G.4)