ID 3701

MORPHING SHEET MATERIALS

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Abstract

Rapid prototyping techniques have not yet given a solution to create prototypes consisting of large sheet-like shapes. Currently used methods like vacuum forming are time consuming because a negative shape has to be created. Materials that can deform itself in the wanted shape could make this process faster and easier.

To explore the possibilities in this field a literature study of existing self-deforming materials was done followed by experiments with shrink-film as a representative for the self-deforming materials.

The literature study consists of analyzing available shape-memory materials on their suitability for the use as a rapid prototyping tool. Based on several criteria a selection was made out of the overview of available shape-memory materials. Materials that change shape under the influence of light seem to be most likely suitable for the purpose mentioned earlier.

By means of experimenting, a better understanding of the behavior of shrink-film was achieved. The possibility to shape it in different settings was also studied. Sandwiching different materials in between shrink-film and changing the connection between these materials can give a rough estimate on the resulting shape.

Introduction

With the upcoming possibilities of computer controlled production processes using Rapid Prototyping Tools we are researching ways to control deformation in sheet material without the use of a mould. Our research is divided in two main phases. The first phase consists out of exploring the short history of RPT and more different ways of controlled deformation. We will create an overview of methods, materials and resulting conditions and offer conclusions to the possible ways of deformation without the use of a constant applied force. This pre research will not affect the results in our eventual project, but is important since we want to understand and compare new and older methods (costs, duration, material). This second phase of the project is discovering and exploring new ways of deformation using shrinking foil and rubber or foam. Controlled deformation in shrinking foil is possible by heating the sheet material locally and in this way bending the sheet using only the force within the shrinking foil, enabled by heat. This way we have found a cheap way of transforming sheet material in a lot of possible custom shapes. This method, when operational and in optimal condition, would provide to be very useful in the casing design production processes, for instance, vacuum cleaners, car hoods and other larger products. Since all the computer controlled deformation processes like RPT are only affordable and useful when producing smaller and more complicated products the main goal of this research is to find a possible way of deforming larger sheet material.

PART I: Literature research

Introduction

There are many ways to produce a part or a product, most of them time consuming and costly. In the early developing stage of a product it is not unlikely that changes have to be made, satisfying either the consumer or the production supervisor. Therefore the use of a mould is time consuming and especially costly. Prototypes of products or parts hard to make, therefore a quick and cheap production provides positive outcome for every design. Rapid Prototyping overcomes some of these problems by shortening the process, directly printing a product based on computer generated models. Adaptations, inconsistencies and difficulties can be easily discovered and changed in the early stages of the production process. In the short history of self deformation, memory materials and other methods of deformation without the use of a mould there are four main categories. Deforming (sheet) material by heat, light, electricity and magnetic force is researched. We created an overview of possibilities based on pre set key-items such as the used material. Furthermore, we discussed every important opportunity and eventually drew conclusions to what method would be the best, easiest and less costly to use.

Interpretation of the assignment

Exploring the possibilities of controlled deforming and fixating sheet material by external influences, without the use of a mould.

Research Questions

1. LITERATURE STUDY

What are the possible ways of shaping plastics without the use of contact force?
  Material used?
  By what means is deformation achieved?
  What is the resulting condition of the material?

2. CATEGORIZATION BY TYPE OF ENERGY

Light	Spectrum
	Direction
Heat	Radiation
	Convection
	Conduction
Electricity	

3. SELECTION BY USEABILITY

Resulting condition of the material
Environmental conditions
Geometric dimensions of the deformation
Speed of deformation

4. WHICH OF THE ABOVE IS MOST LIKELY SUITABLE FOR THE USE AS IN RAPID PROTOTYPING?

5. Literature study of the chosen method
    - Overview of literature
    - Specifications of material
        - Strength
        - Toughness
        - Shape set
    - Specifying the chosen method

6. Mathematical model of grid deformation by changing the length of one rib.

Method

We explored ways of controlled deformation for polymers by using search machines as www.scopus.com, www.scholar.google.nl, www.polymerweb.com and the TUD library To choose a method of deforming polymers we had to set up various criteria.
Because we want the deformed material to be solid in the end we have to look for a method where the resulting condition is either solid or elastic, but in the last case with the possibility to harden it. The environmental conditions should be accessible enough for the period of time this research is led, they should be held within the budget as well. The dimensions of the deformed material in our research should be as large as possible, but since most previous research is done on a small (macro) scale it is very difficult to meet this demand. The best thinkable way to explore the possibilities of enlarging the dimensions of an existing method is to experimentally discover tem. One more important issue is time, we are looking for the shortest amount of time possible, but we have to keep in mind that the research is about quality over quantity.

Resulting condition	solid or elastic (with the possibility to harden)
Environmental conditions	lowest temperature, easily adjustable machinery (cq experimental conditions)
Dimensions material	as large as possible
Speed	as fast as possible, but less important

Result

Used energy	Area	Material	Properties . what kind . how . state . extra . speed	Reference
Light	**Spectrum**			
	UV (> 260nm)	[HEMA, BA, HEA-CA, PPG2M560]	. copolymerisation of previous materials become a memory material . crosslinking of IPN polymer gives a temporary fixed shape. . solid state . 25 degrees	*Light induced shape-memory polymers* *[light induced polymer002.pdf]*
	UV (365 nm)	Poly[oxy(methylsilylene)] [*PHMS*]	. photoisomerization . solids (expand 10-400 %) . at 298 K	*A new opto-mechanical effect in solids* [reversible shape changes in solids.pdf]
	laser	Azobenzene liquid-crystalline [*azo LC*]	. Light induced material . film (10-50 µm) . laser intensity (0,1-0,3 W/cm2) . deformation is obtained if beam orientation is parallel or orthogonal to the film alignment	*Polymer film with optically controlled form and actuation* [viewmedia.pdf]
Heat	Radiation			
	Convection			
	Conduction	polylactide-co-poly(glycolide-co-caprolactone) [*PLAGC*]	. memory material . film (150-250 µm) . recovery at 45 deg (12s) . solid	*Biodegradable shape memory polymer* [biodegradable shape memory alloys.pdf]

	Conduction	Liquid crystals [*LC*]	. crosslinked polymer . reversible orientation . heat induced (+/- 200 deg.) . thermal treatment results in dimensional change. Isotropisation is accompanied by a shrinking along the fibre axis	*Multi-oriented and fibrous liquid crystalline networks based on linear mesogenic polymers* [multi-oriented LC.pdf]
Electricity	120 kV	Liquid crystals [*LC*]	. molecular (polymer) orientation differences in thin film . different orientation obtained by variable time and voltage	*Disclinations and their interactions with thin films of side chain liquid-crystal polymers* [microscopische molecuul orientatie veranderingen.pdf]
	-0.322 / 0,872 V	LiClO4 strip	. LiClO4 aqueous solution contraction/extension up to 20% of its original length . polymer film (12-14 µm) . elastomer	*Polypyroll artificial muscles* [artificial muscles.pdf]
Magnetic force		Elastomers with addition of Fe	. poly(dimethyl siloxane) . shape change	*Smart composites with cotrolled anisotropy [smart composites with controlled anisotropy]*

Charlotte Lelieveld

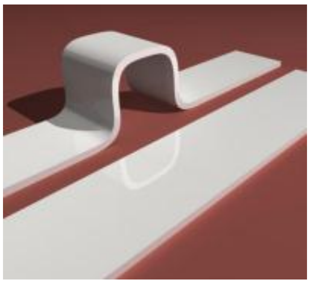


Figure 1: morphing floor panels

To orientate more on self deforming materials like artificial muscles we made an appointment with Charlotte Lelieveld, a winner of 10.000 euros with Young Wild Ideas for innovative, nearly impossible designs. At the time we were there she had been waiting quite a while for her orders, which meant she wasn't really into her project anymore. The basic idea is based on memory materials, which have a zero form and a second, variable, form. When in the variable form and heated, the memory materials will go back into their original zero form. Self deforming furniture was born. She couldn't really tell us a lot about the actual process of deformation since she didn't have any realistic samples yet. But she could tell us about some other interesting facts, though not really related, it was interesting to see a Japanese artist sculpture mathematical objects using magnetism and iron based fluids. Sachiko Kodama made all sorts of forms possible due to magnetism as seen on the following picture. The reason why we think this could be of importance is because the magnetism makes the solution solid, which could mean a mould based on magnetism (see references for more information)

Figure 2: magnetic art

Discussion

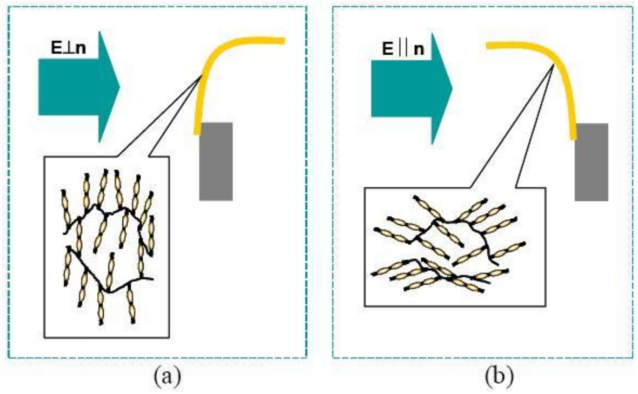
The researched methods are *possible* methods, we will continue doing experiments with shrink-film either way, whatever the outcome of this evaluation. It is also possible that with a reasonable and feasible outcome we will try to set up an additional experiment using the parameters given by research.

First in this evaluation we want to exclude some subjects to make a final statement easier. A method using magnetism is a very difficult way to deform or de-orientate a polymer string, there has been research but it is still very young and limited. On top of that, by 'smart composites with controlled anisotropy' it is necessary to make a composite with Fe. This method is not common or reasonable enough to experiment with.

With electricity it is a similar but different situation. Most commonly applied in artificial muscles, electricity uses electrodes to guide the current through the material. The current running through causes a volume change in the polypyrrole which is the basic fundament for the artificial muscle. According to the article the volume change is hard to control due to electrical contact difficulties. The polymer used consists of bilayers or trilayers of polypyrrole which are hard to get. The current directed over the material in one direction results in contraction of the muscle, turning the current around results in a relaxation of the muscle. The environment used for these experiments is a aqueous solution of LiClO4, necessary for the current, changing the shape of the polymer (one direction) takes about 90 seconds. Thus we decided to exclude this method due to environmental problems and the type of material used. Above that, if we would transfer this method to our basis of research (deforming large scaled materials) we would need a very large artificial muscle, a large bath of LiClO4 and we wanted to avoid direct contact with the material, which is not possible because of the use of electrical wiring. The other article on the subject electricity is about molecular orientation of thin films in liquid crystals, this doesn't seem likable at first but molecular orientation (concentric, excentric, spiral, one direction etc) could prove to be very useful when deforming polymers. The orientation change ultimately results in a shape change if we would and could apply this principle on solids or elastomers. The article provides useful information about the orientation in thin films. The thin film is inserted in a liquid which makes the thin film float, the copper grids below provide the currency necessary, an accelerating voltage of 120 kV, to change the orientation of the orientation of the polymers. Though, as the article states, time is an important factor for variations in orientation, though it is still impossible to understand what the exact variations in orientation are, there are no models to simulate this process yet. So we came to the conclusion that methods using electricity are a bit out of focus on the actual problem we are trying to counter.

The leftovers are heat and light induced shape changing polymers. This decision is not nearly as easy as the previous conclusions. There are a few articles which use Liquid Crystals as well ('Polymer film with optically controlled form and actuation' for light and 'Multi-oriented and fibrous liquid crystalline networks based on linear mesogenic polymers' for heat). The last article is not very useful as it is totally about liquid crystalline structures, but contains information about shrinking along the fibre axis of the aqueous solution. It states that varying the temperature the orientation will be either done or undone due to phase transitions but we would rather not work with liquids because it means hardening them would be difficult if we want the structure to remain. The first article 'Polymer film with optically controlled form and actuation' contains information about mechanical shape deformation in azobenzene polymer films. This transformation is due to the reorientation of the liquid crystalline (LC) in the polymer film. This reorientation is realized by optical radiation and forces a trans-cis orientation in the LC ordering. The trans-cis orientation is dependant of the used UV wavelength. The film is heated to 85 degrees before the light was emitted. The used wavelength in this article varies between 366 – 514 nm. The deformation takes place in only a few seconds and is unidirectional, towards the source of power. This deformation due to light seems very useful to our research.

CONCLUSIONS



(a) (b)

Figure 3: polymer orientational change

Our search for possible deformation methods has led us only to one conclusion. Although we are already deep in the research of shrink-film we wanted to look and expand our knowledge as well around different deformation methods. The most likely to use would be deformation by light. Not only is this method more accessible, it is also very precise and quickly done. The material used consists of azobenzene polymer film and liquid crystalline moieties. This is a solid polymer, when heated to 85 degrees (which is a low temperature compared to other methods) it will weaken but this is only necessary for the deformation process, after this it will cool again and the material will have a solid resulting condition. Although in the article the research is done on small thin films, we recon it will be possible for larger (still relatively thin) polymer sheets. We imagined a kind of laser printer head going over the sheet material, heating it locally and in patterns, the material will bend in a positive or negative direction depending on the perpendicular or parallel direction of the power (laser) source. It will become a complicated process because of the shape changes the sheet material will make, the printer head has to somehow adjust to this. But for easy shapes, like an exterior of a vacuum cleaner (fluent shapes and only one positive curvature) we think it will be well possible.

Resulting condition	solid
Environmental conditions	85 degrees, use of UV-light and laser.
Dimensions material	article states thin polymer films
Speed	for thin films less then a few seconds.

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Materials that can change shape

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Sachinko Kodama
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PART II: Experiments

Introduction

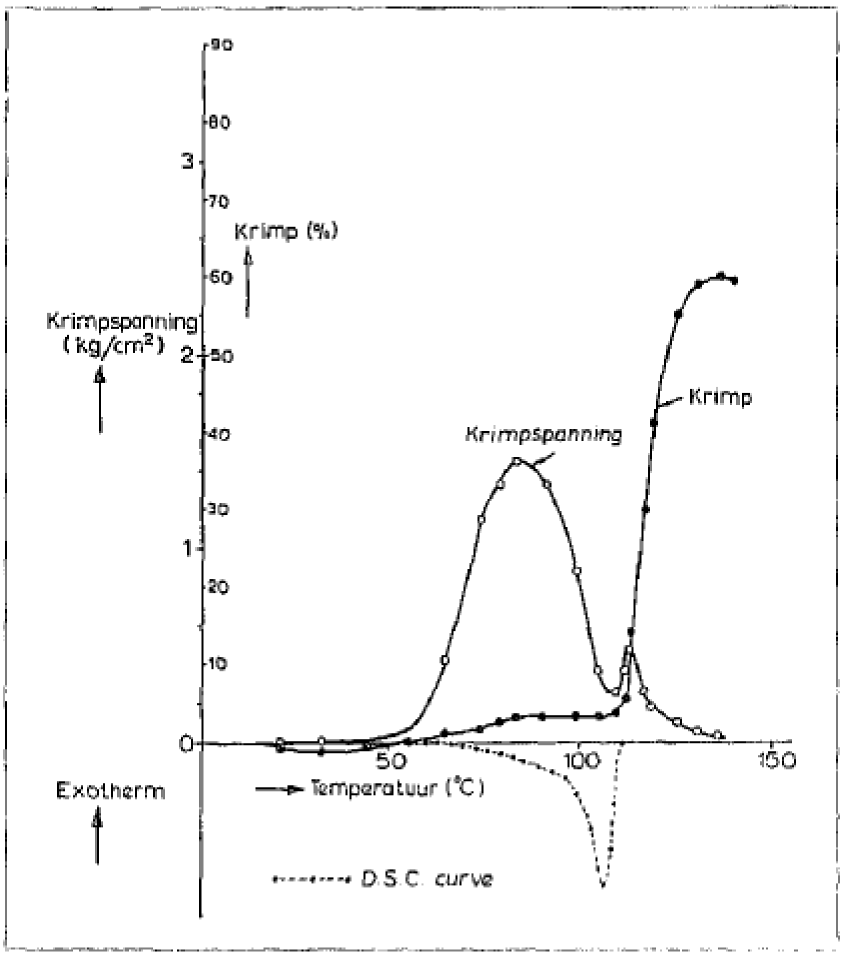
As discussed earlier the purpose of this project is to deform a sheet material without a contact force, as detailed as possible. Shrink film has the property to deform when heated. In these experiments, our main goal is to direct the amount of shrinkage in the foil. When we will be able to control the place, direction and amount of shrinkage we will also be able to ‘bend’ the sheet of shrink-film with heat. For that we will need to know the force within the foil, to discover the possibilities that shrink-film has in deforming itself and other materials. There has been little research done on this topic, a few articles give us some information about the amount of shrink and used temperatures, but information is mostly rare. The first approach will be to see how shrink-film reacts on different temperatures, local heat and applied force. We will also try to see if the foil can deform other sheet materials like cell rubber and packaging materials. With all the previous we will experiment the possible freedom in deformation, with different sandwich materials, different connections between the materials, different heating processes and different dimensions.
After each experiment we will conclude if there is more research needed, whether it would be possible with this gathered data to actually form large sheet objects like car hoods or vacuum cleaner casings.

Method

The application of shrink-film in the experiments is an inexpensive way to explore the possibilities of deforming sheet material as mentioned earlier. The foil represents a whole group of “memory materials”. In other words: it responds to external influences by changing shape.
We have done several experiments to explore the possible power of shrink-film. The shrinking foil is the key-component of the sandwiched material to initiate the deformation. Testing it will be crucial to understand the behaviour with regard to the temperature-shrinkage relation.

Characterizations of shrink-film

Fig. 3.
Krimp, krimpspanning en DSC-curve als functie van de temperatuur voor ld PE (Stamylan) krimpfolie verwerkt onder standaardcondities.



(KORTLEVE, G. 1974)

The graph above describes the tension and shrinkage of warm-deformed plastic film. This shows that the tension in the foil grows while shrinkage is little. This type of film will shrink when it is free to do so. When met by constraints it will stop shrinking and the resulting tension is little.

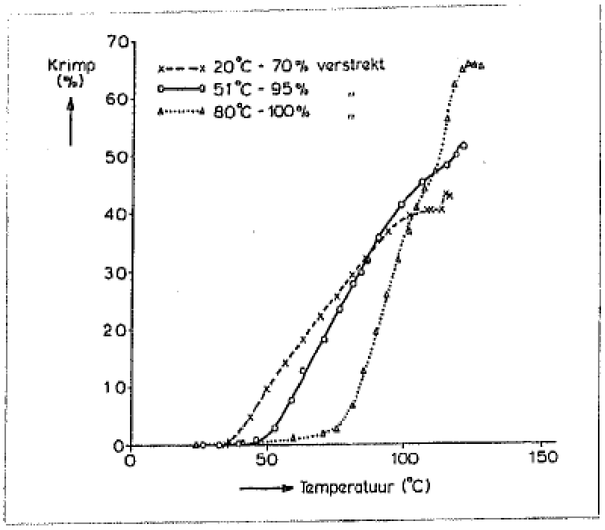
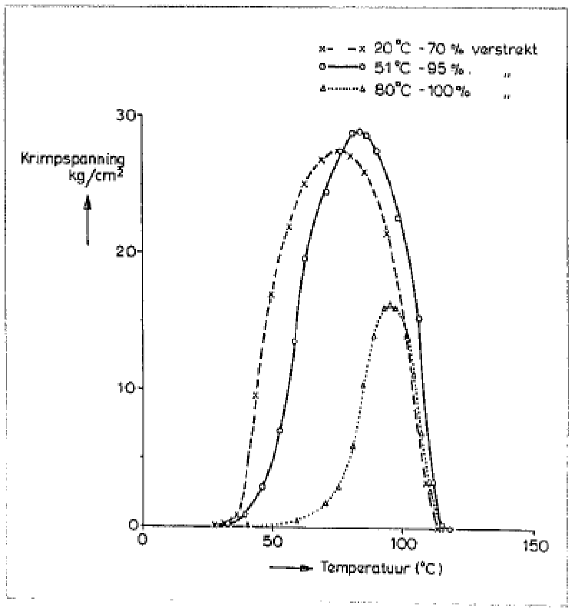


Fig. 4.
Krimp van bij verschillende temperaturen verstrekte ld PE folies als functie van de temperatuur.

Fig. 5.
Krimpspanning als functie van de temperatuur van bij verschillende temperaturen verstrekte ld PE folies.



(KORTLEVE, G. 1974)

These graphs describe the behaviour of cold-reinforced shrink-film. As can be seen in the left graph, the amount of shrinkage has a linear relation towards the temperature increase. The tension in the film increases in the same temperature range.

To make deformation possible the shrink-film will have to exert a force on the material that is to be deformed. Whilst exerting this force the actual shrinkage has to take place. Otherwise, no or little deformation will take place.
Comparing both types of film gives the following results:

	warm-deformed	cold-reinforced
shrinkage	up to 65%	up to 65%
temperature range	110-150°C	50-130°C
max. tension	up to 1.5 kg/cm^2	up to 30 kg/cm^2
@ temperature	80°C	70-80°C
		Maximum tension up to 20 times as high and in the temperature range when shrinkage occurs

When we combine the above it can be concluded that cold-reinforced plastic film is the most useful in our experiments.

In this second part of the research we want to research the possibilities of shrink-film as compared to self deforming materials like artificial muscles.
But there could be a few problems which may occur when experimenting with shrink-film and the core materials. It’s obvious that it will shrink, but will it have enough force to co-deform another material? It could also prove to be difficult to heat the shrink-film to start the shrinking process and at the same time not to burn or overheat the core material. To test and see the differences we have set up a few variables.

Variables

Shrink-film	Cold-reinforced	
	Warm-deformed	
Core material	LDPE	0.5 mm
	Cell rubber (closed cells)	3 mm
	Cell foam (open cells)	10-12 mm
	Paper	0.1 mm
Sandwich construction	Pegs	
	Adhesive	
	Staples	
	Sewing	
Heating process	Normal lighter	
	Hot air gun	
	Soldering Iron	
	IR lamp	
Grid	Dimensions of the grid can be changed to get different effects on deformation.	

The core material will make significant difference in the deformation. A material like LDPE is much stiffer than for example the open cell foam, this means the shrink-film will have to use more force to co-deform the core of the sandwich, this can also be influenced by the thickness of the chosen material or the number of used layers. Other differences can be the insulation of heat, will the core absorb all heat or just do the opposite. Will the core material burn or melt under the influence of heat? Furthermore, the directions and strength of deformation will be dependant on the way of construction of the sandwich. For all construction methods, the dimensions of the grid are of big influence to the actual deformation. The deformation can be dependant on the way the shrink-film and core material will be heated, the more controlled and precise the better results we will get.

Therefore we have performed the following tests.

. Tension test of heated shrink-film
. Temperature test on shrink-film
. Sandwich tests, use of different materials
. Double bend tests
. Connection tests, different sandwich constructions

Result

Experiment 1: Heating shrink-film in an oven

Setup:

6 samples of shrink-film (size x by y)
Oven with oven rack in the middle, preheated

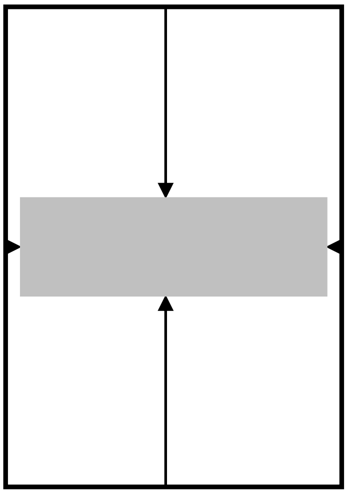


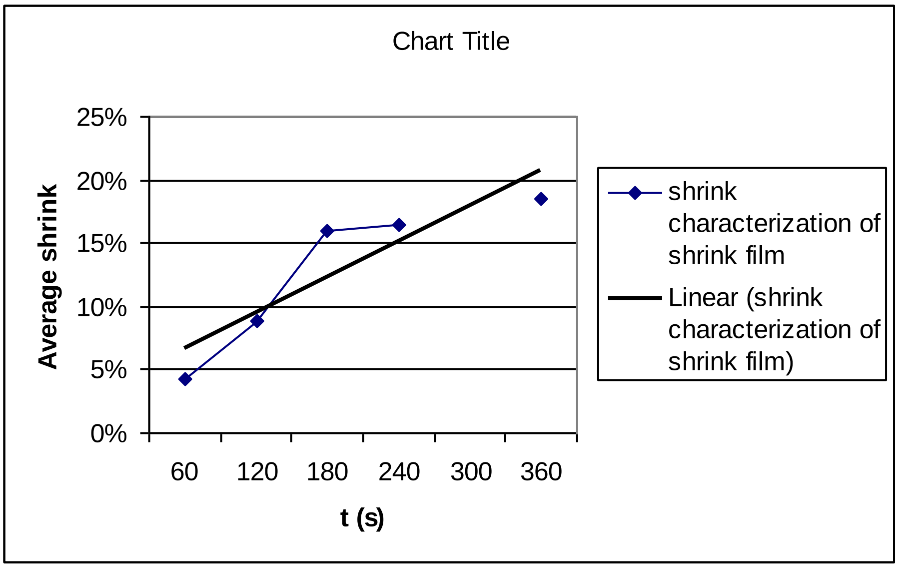
Figure 4: expected shrinkage of the foil

Without any constraints the film will shrink freely when the film is exposed to temperatures between 40 and 120 degrees Celsius.
At 115 degrees Celsius both types of shrink-film used in the research done by Kortleve will shrink. We use this temperature to get an idea of the time during which shrinkage will take place and to investigate what kind of shrink-film we have.

One sample at a time was put on a sheet of paper to prevent the foil from clinging to the metal rack. Paper with sample was put in the oven on the rack. After removing the sample from the oven it was allowed to cool down at room temperature for 1 minute.

Experiment results:

sample	x	y	T	t	^x	^y	^x	^y
1	200	201	115	60	12	5	6%	2%
3	208	208	115	120	19	18	9%	9%
6	200	200	115	180	33	31	17%	16%
5	200	200	115	240	31	35	16%	18%
4	200	200	120	360	39	35	20%	18%



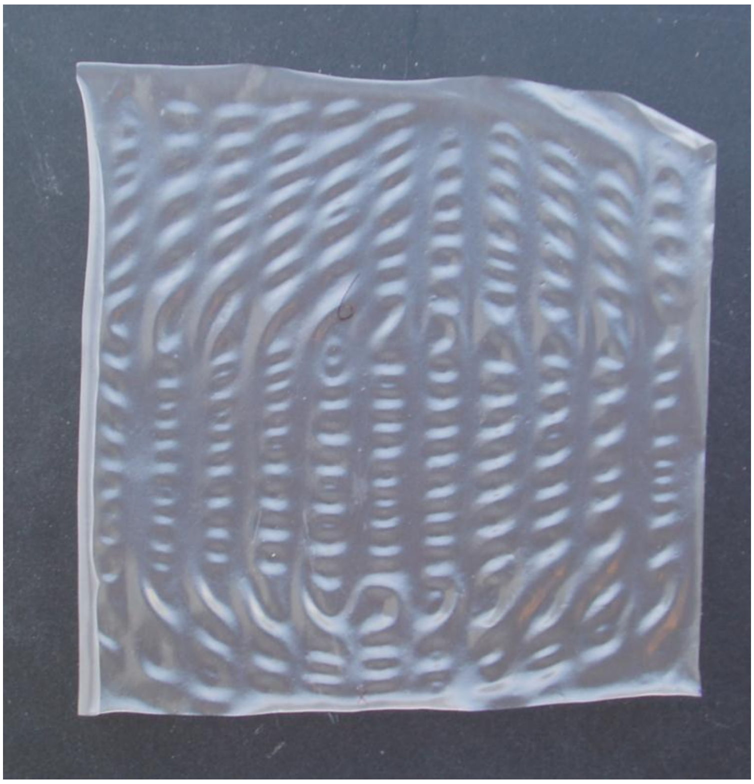
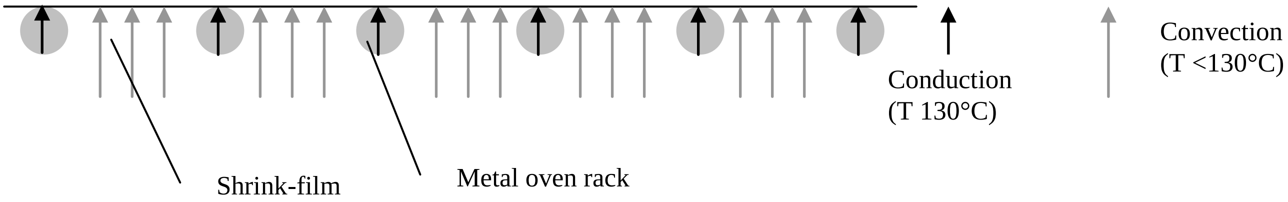


Figure 5: Pattern occurring in samples

The results show a maximum shrinkage of 20%. This is considerably less than expected. Also a pattern can be seen as showed in Figure 5. This pattern was found in all the samples. Taken in mind that the pattern width is the same as the oven rack, the pattern seems to be caused by extra shrinkage where the shrink-film has been heated by conduction.

Local shrinkage seems to be possible by using conduction. Heat transfer to the foil might be better achieved by conduction than convection.

To find out if our assumption is right, a sample was placed on an aluminium sheet which was preheated in the oven. Shrinkage did occur, but no pattern could be seen after cooling down.



Conclusions:

The results show a relation between a linear relation between heating time and shrinkage of the film. Contrary to what was expected the shrinkage little and happened slowly. We assume that the heat of the air in the oven must have dropped considerably during the placing of the samples. This theory can be supported by the patterns in the shrink-film mentioned earlier. The oven rack enables a higher local temperature of the shrink-film at the parts where the metal contacted the shrink-film. The expected uneven shrinkage in different directions of the foil, as showed in Figure 4 did not occur.

Experiment 2: Heating shrink-film by flame

Setup:

4 samples of shrink-film, different sizes
Lighter (flame temperature +/- 180 degrees Celsius

In this simple experiment we try to achieve controlled deforming of the shrink-film by heating it with a lighter flame. The temperature of the flame exceeds maximum temperature at which the shrink-film will deform. Exposing the film for only a short period of time to the flame will prevent the film form overheating and melting.

The film was heated in the marked area, trying to shape it into Figure 7

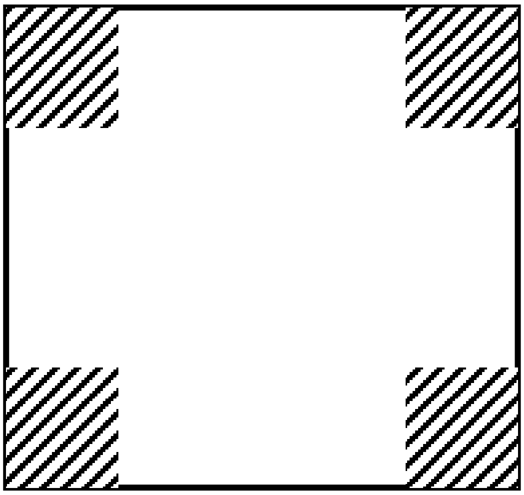


Figure 6: areas of shrink-film to be heated

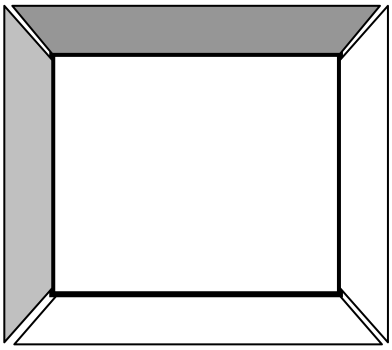


Figure 7: wanted result

It must be stated that this experiment was purely explorative. In this setup it was fairly difficult to direct the heat to a small area. The result it displayed in Figure 8

Figure 8: resulting shape, containing water

Experiment 3: Shaping cell rubber

In this experiment we want to co-deform the rubber with the abilities of the shrinking foil, with the rubber as a bottom layer and the foil on top. Because there is only one layer of shrinking foil, the bending deformation will be only one directional as the foil contracts the cell rubber upwards. There are a few possible ways to connect the rubber to the foil. Gluing the two layers together, sowing or using pegs. Stitching was preferred for its detailed connection, strength and little interference with the materials to be connected.

Setup:

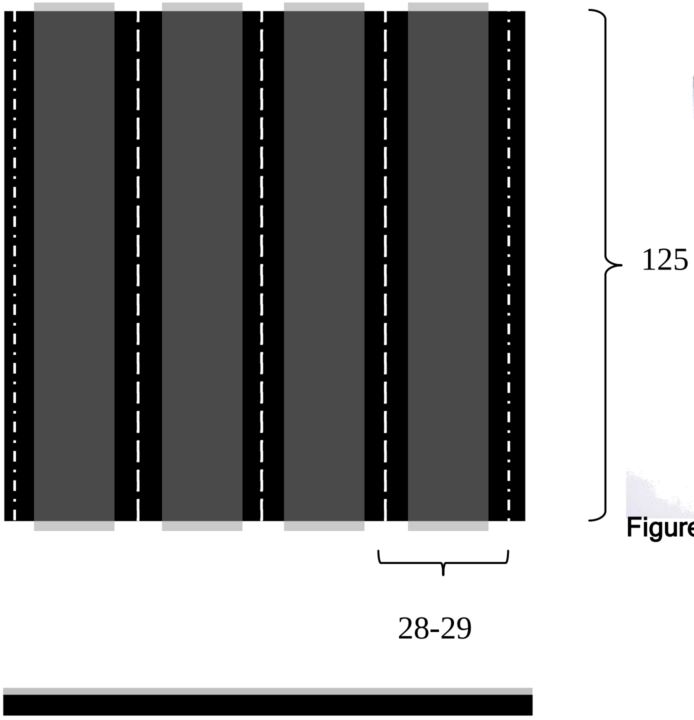


Figure 9: photo of sandwich

Figure 10: schematic representation of sandwich

3mm cell rubber
1 layer of 0.5mm shrink-film
Stitching in lines at 28-29mm distance

Marked areas in Figure 10 are heated with lighter flame (180°C)

Observations:

When heating the film which is attached to the cell rubber it could clearly be noted that it passes through several stages, of which we will give a short description.

1. Weakening – the film relaxes, turns more transparent and starts expanding
2. Bubbling – the expanding continues and causes bulges in de film
3. Tensioning – while still more transparent than normal the film tensions, bulges disappear
4. Shrinking – forceful shrinking takes place when cooling further, back to normal transparency

In stage 4 the deformation of the sandwiched material takes place. The shrink-film has caused the cell rubber to bend and is pulling at the stitching to which it is attached

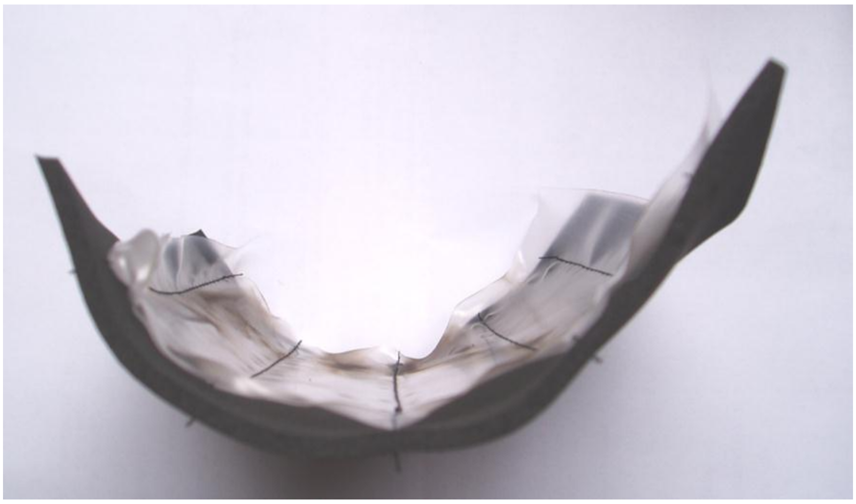


Figure 11: resulting shape

The stitching, in combination with the cell rubber, prevents shrinking of the film in the other direction as showed in Figure 12. The shrink-film is not constrained at the edges of the sample in between the stitching, so shrinkage in the stitching direction does occur there.

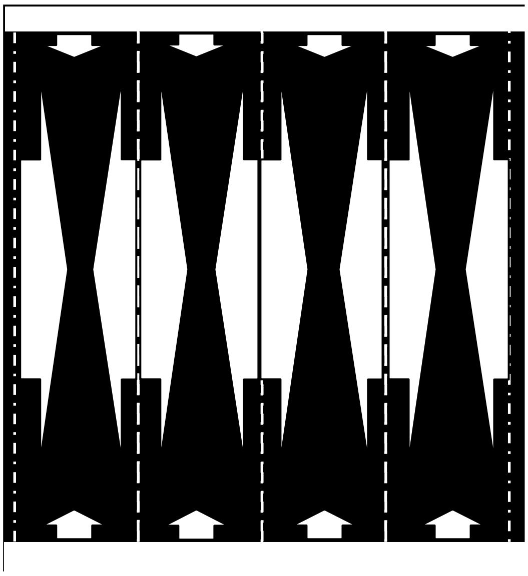


Figure 12: occurring shrinkage

Conclusions:

Only the forceful shrinking of the film which takes place when cooling to room temperature makes the sandwich change shape.
Connecting the shrink-film and cell rubber by stitching gives the shrink-film the possibility to exert its mechanical work on the stitching.
The stitching prevents shrinking in the other direction

Experiment 4: Force exerted by shrinking foil

The conclusions of this experiment are crucial for the rest of the research, this is because the core material in the sandwich construction needs a strong enough force to actually deform. When the shrink-film proves to be too weak it will never be able to deform the core material

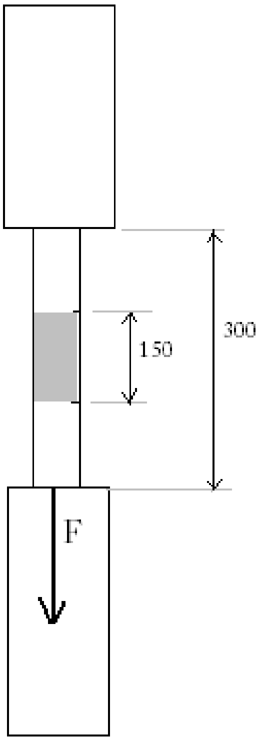
Setup:

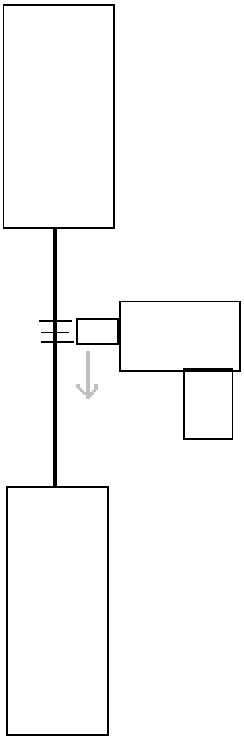
6 samples of shrinking foil (380 x 25 mm x 0,1mm)
Hot air gun (Metabo, heat 5, air 1)
Temperature at 25mm from exhaust 175°C
Diameter of exhaust 10mm
Tensile test bank: Zwick material Prüfung type 066955

Temperature of air from hot air gun:

d (mm)	T (°C)
20	190
50	110

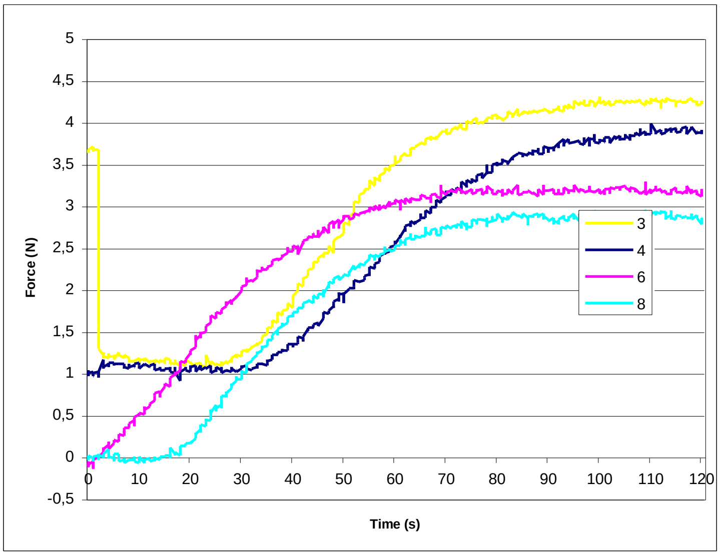
Interpolated temperature at 25mm = 175°C

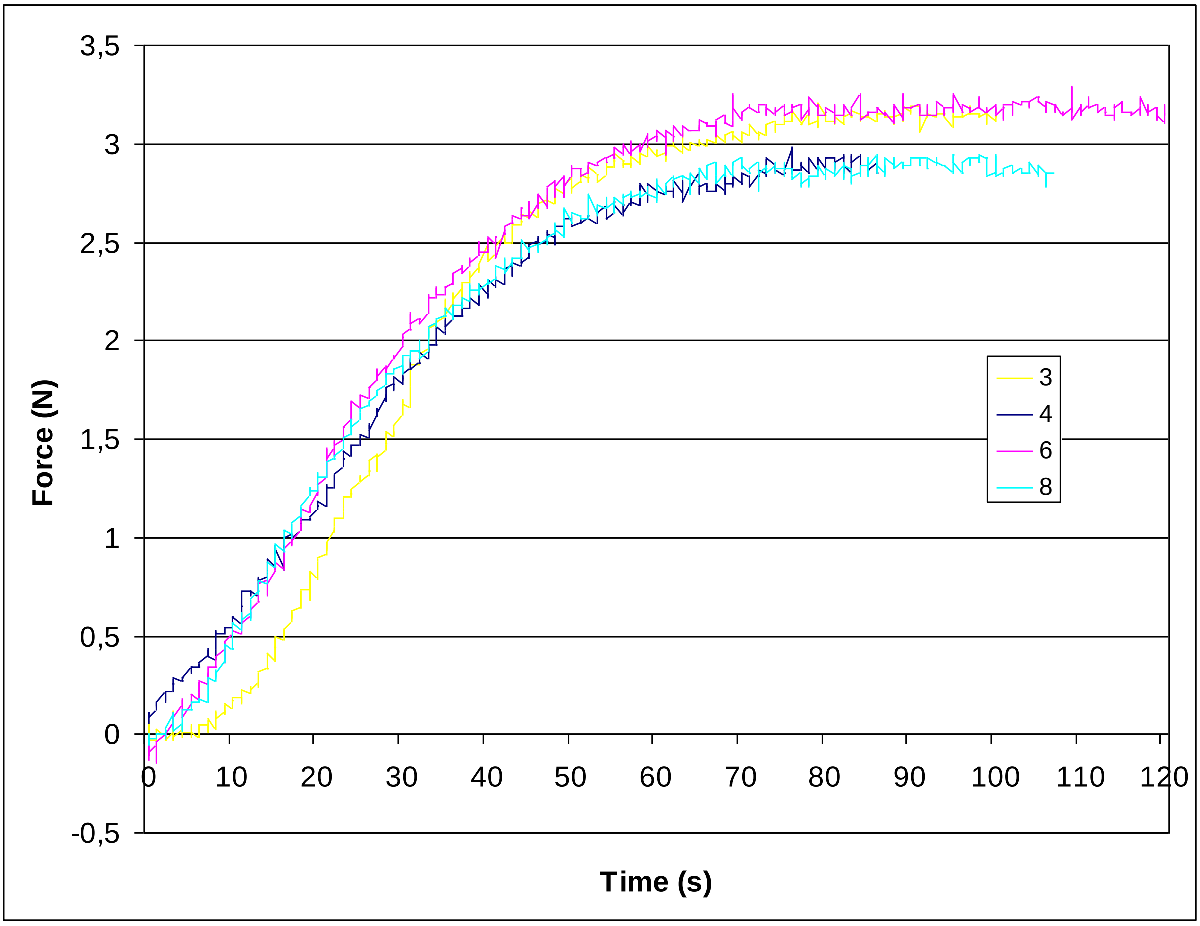




Measurements:
Vertical force F caused by the tensioning of the shrinking foil after heating it with the hot air gun

Results:





The results in this graph have been corrected for two errors:
Series 3 and 4 were measured without resetting the tension bank to zero, so these results have been adjusted with the following formula: correction = result -1.1
All series have been adjusted for time. As can be see in the original result the tensioning starts at different times. This was caused by different starting times for the

heating of the shrink-film. All results have been moved over time to set the starting point of the tensioning to zero.
Series 3: $t_{corrected}$ = t-25; Series 4: $t_{corrected}$ = t-30;
Series 6: no correction; Series 8: $t_{corrected}$ = t-18;

Conclusions:

The results display a force exerted by the foil cooling down to room temperature of +/- 3N. The dimensions of cross-section of the foil used are 0,1mm x 25mm, so this results in a tension of +/- 12 kg/cm^2, which corresponds to the results of Kortleve, G, 1974.
Kortleve however, conducted the experiments in a different setting, where shrinking of the foil was combined with the measuring of the force exerted.

Experiment 5: controlled deformation

Setup:
3mm cell rubber
1 layer of 0.5mm shrink-film
Stitching in lines at 28-29mm x 28-29mm

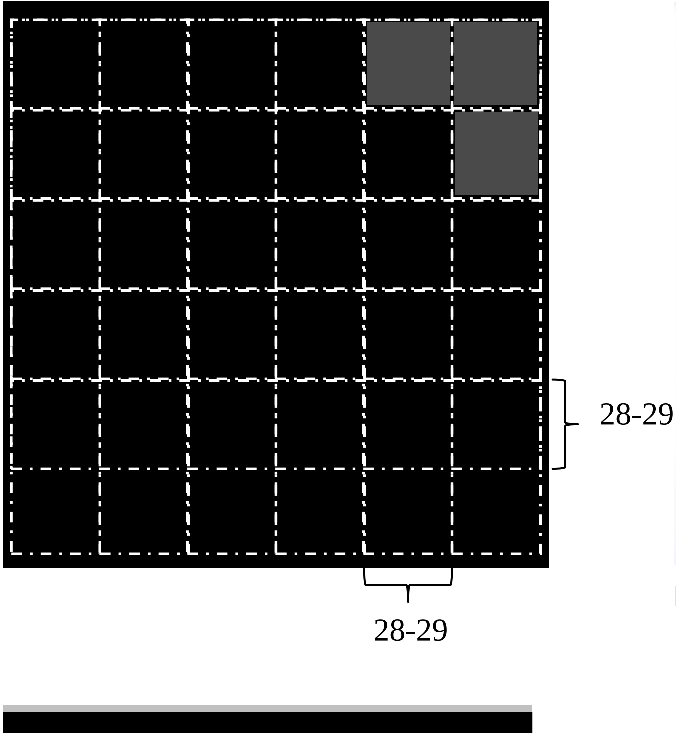


Figure 14: schematic representation of sandwich 5

Figure 13: Cell rubber with shrink-film

Local heating of the material could make more controlled deformation possible. To test this, the stitching has been expanded to a grid.
Marked areas in Figure 14 are heated with lighter flame (180°C), which should cause the tensioning of these parts and thereby causing the upper right corner to curl upwards. The restrictions caused by the stitching might cause a problem.

Figure 15: resulting curl

As can be seen in Figure 15 the heating did cause the sandwich to curl. The force exerted by the shrink film shaped the cell rubber in the only possible way.
The edge of the material is free to move upward, contrary to the rest of the cell rubber, which is constricted. The resulting movement caused by the tensioning is displayed in Figure 16, the grey arrow combines the white ones.

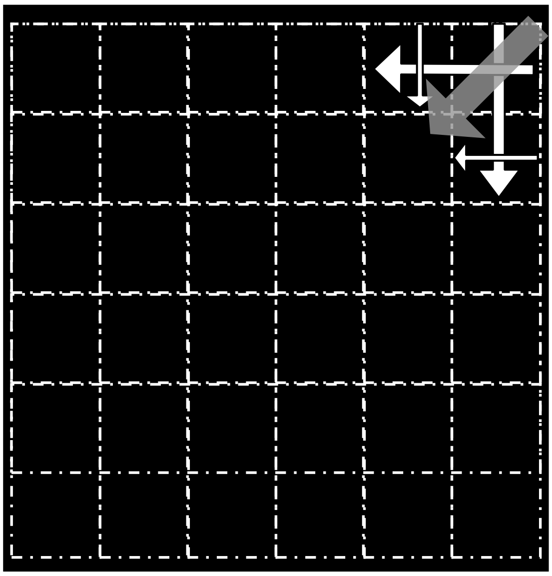


Figure 16: resulting force causing shape change

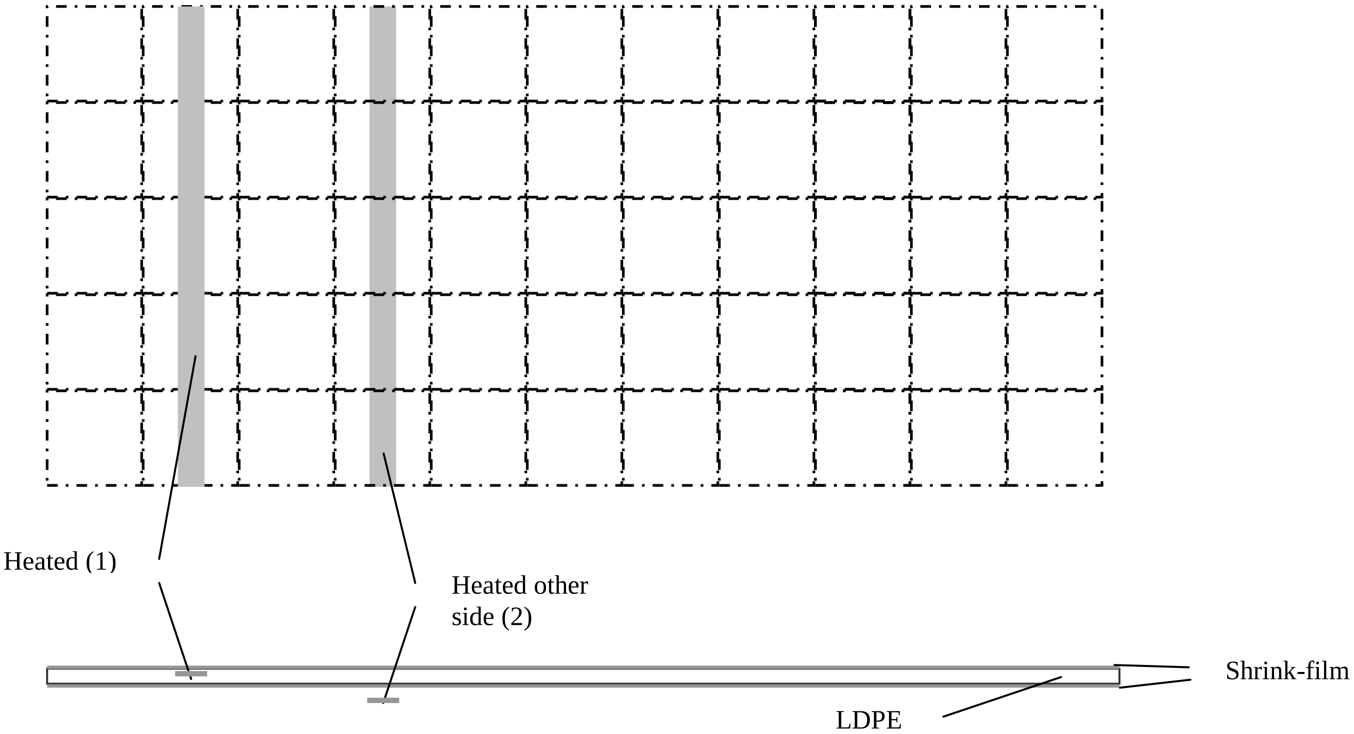
Conclusions:

The resulting shape change can be predicted by examining the forces that the shrink-film will exert on the core material via the stitching. The resulting force will give an indication of the direction of shape change. The amount of change depends on the resistance of the core material to deformation in combination with the force exerted by the shrink-film.

Experiment 6: Changing the grid size and sandwich material

Setup:

Shrink-film
LDPE (0,5mm)
Grid size (12-13 mm) x (12-13 mm)
Stitching



Areas 1 and 2 are heated by a 180°C Lighter flame.

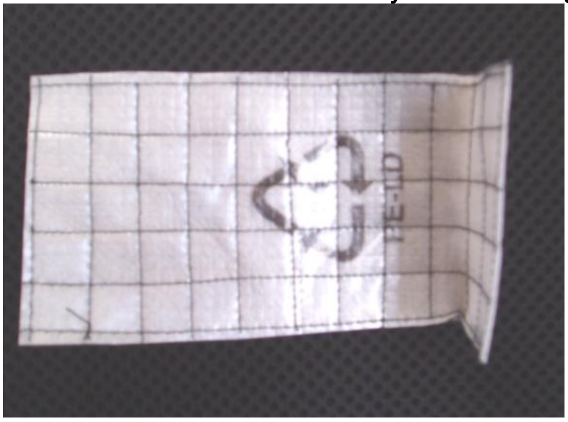


Figure 17: top view after heating (1)

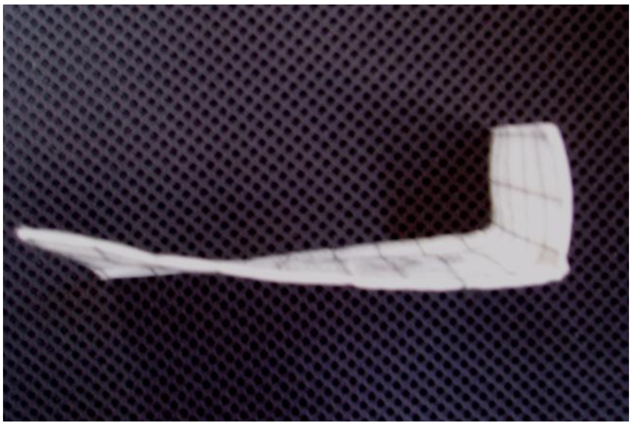


Figure 18: side-view after heating (1)

Figure 19: Side-view after heating (2)

Conclusions:

The resulting deformation was a ninety degree angle on the heated lines. This unexpected result might have been caused by the change in core material. Considering the fact that the same shrink-film is used and thus the same force is exerted the LDPE must be less resistant to deformation. It is also much thinner than the cell rubber.

Discussion

This second part of the research is mainly meant for explorative studies on the possibilities of shrink-film. We sought to experimentally explore, more likely than conclude or defy earlier research. Therefore we will discuss what we have seen in our experiments.
Because the research consists mostly of experiments, to create more clarity, we chose to evaluate every experiment next to the description of the experiments. though a short evaluation is necessary.

We started to analyze and deform only shrink-film, this formed the basis of our further experiments. These test showed us the direction and the way shrink-film deforms under the influence of heat. What really stood out was the difference between heat convection and conduction in deforming the shrink-film. Conduction makes the material weaker and the deformation is less predictive. More important is the research done on the sandwich construction and how the shrink-film reacts to the core material. There is a real difference in stages of shrink whether the shrink-film is constrained or not. When not constrained, the shrink-film will almost immediately shrink. But when the film is constrained and heated it will show different stages as the cooling or shrinking process takes place. As seen in experiment 3 the main stages of the heated and constrained shrink-film are the following.
. weakening
. bubbling
. tensioning
. shrinking
Because the actual shrinking process takes place in the last stages, a few consequences are attached. In the early stages of the shrinking process the material is weak, so when a force is applied in this stage the material will stretch. When this occurs the shrink-film will not be able to shrink the way it would when no force was applied. Even when we remove the force after stretching the shrinkage will not be relevant. Another difference between constrained and unconstrained is the stage of tensioning, on of the later stages of shrinking of constrained shrink-film. In this stage the film is cooling down and shrinking, but because the material is constrained the tension inside the shrink-film will build up, so the earlier formed bubbles go away and a flat and transparent surface will appear. It is only after this that the actual shrinking takes place, the tension builds up more and will eventually overcome the force that stays within the core material of the sandwich construction, the small force that holds the core and film down. Because of the shrinkage in the grid the sides will be ‘pulled’ together and eventually cause deformation. When the force in the core material is too high, nothing will happen except for the tensioning of the shrink-film to its maximum.
The heating process is very important for the pursued shrinkage, therefore the use of different tools is necessary for optimal results. We found that a normal lighter is reasonably precise and the temperature, when held at a certain distance, is adjustable enough to control the shrinkage in the shrink-film. For better quality we used a hot air gun, this heater spreads the temperature more equally. But this advantage can also become a disadvantage, because it spreads the hot air widely heating just one grid with small dimensions is very difficult. For further research this

can be solved by mounding a ‘mouthpiece’ on the hot air gun for more precise heating. For our research the use of a lighter was the most convenient and precise.

There are many variables in the sandwich construction, the core material, the thickness of the core material, the dimensions of the grid, the temperature, the used construction etc. the only constant factor in these experiments is the used shrink-film. The core material has a big and logical influence on the deformation, the stiffer or harder the material is, the more difficult it will be to deform. Furthermore, the dimensions of the grid are dependant on the thickness and stiffness of the core material. How thicker and stiffer the core material the larger the grid size has to be, since more shrink (force) is needed for deformation. The main reason for the experiments was to discover the possible ways of deformation, the freedom of possible shapes. Already single curvature is possible in all directions, which gives us a realistic freedom in shape alternation.
According to our experiments the best deformation is obtained using LDPE as core material for the sandwich construction, this is because it has the right properties compared to the maximum shrink of the shrink-film, deformation is easily obtained. It is possible to make a ninety degrees angle after shrinkage. This is really high compared to the estimated sixty degrees maximum of cell rubber and the zero degrees deformation with the, very thick, open cell rubber. Another difference between the two materials is the isolation, heating one side of the sandwich will also influence the shrink film on the other side. This effect could be wanted, especially when aiming for higher angles. What will happen is that one side will shrink after heating, but because of the lower isolation, the other side will weaken and due to the force that is created by bending, this side will need to stretch. This way we can get cleaner surfaces. This effect can be obtained by taking a thinner sheet of core material as well. Using paper and open cell rubber as a core material did not give us significant changes in results, at least not in the settings we used.
Now for the way of construction, creating a grid can be done in several ways. Sowing the grid as we have done is a time consuming though effective and strong method. The shrink-film stays reasonably intact although the sowing machine pinches holes through the foil. Even though the foil is damaged and as stress levels increase due to temperature changes, the foil will not tear apart. Sowing also offers the opportunity to create a reasonably precise grid which is more difficult using other methods like glue.

Conclusion

With this research we have formed the basis of a new possible way of rapid prototyping. There are many subjects left unexplored, to optimize the process more research is needed. Though combining our results we can draw several conclusions.

First of all, it is possible to create a bended curvature in sheet material, using shrink-film. Since the film has the properties to deform only with a force of 3 N, a weak core material is needed. LDPE was thin and relatively strong, therefore making it nearly idealistic right using it as a core material. For more variations in toughness, multiple layering of the core material will result in different deformation.
To deform these materials a grid is still necessary, the dimensions of the grid had to be large enough for the shrinking foil to ‘pull’ the material upwards. When the dimensions of the grid would be too small the shrink foil will not have enough force to make the deformation possible. For the future it will be necessary to know exactly what changes occur in grid deformation, therefore mathematical models are needed to predict the deformation.
In our experiments we had little success in forming a double curvature, though we think it will be possible when an optimal core material is found. Since a double curvature demands for the core material to disappear in the places of deformation, this core material has to melt or even shrink along with the shrink-film. Only then will it be able to form smooth surfaces instead of bubbled and irregular curves like we have seen. We also thought of a different grid to obtain double curvature, a grid with six edges or more could make the shrink film pull in more different and more specific directions. We used larger dimensions for the square shaped grids, a higher resolution could also deform the material more specifically and directed.

References

G. Kortleve (1970), ‘Karakterisering van krimpfolie’, Nederlands Reologische Vereniging, Geleen.

APPENDIX

ORIGINAL ASSIGNMENT

Explorative experiments with self-deforming sheet material.

Currently available Rapid Prototyping technologies are very good in creating compact and complex objects. For the creation of relatively simple embodiments of concept designs they are less suitable, because they are expensive and slow if large volumes must be built. These simple embodiments often consist of a freeform Shell of some material, with some connection points.

Nowadays shell-type objects are often created by vacuum forming of a sheet material over a mould. It is thinkable to create a simpler and faster process for this shell forming, if we can apply new materials than can deform itself, for example under the influence of radiation or sound.

The task is 1) to explore in the literature which possibilities are already described, and 2) to perform experiments with a solution that has been conceptualized, but not yet tested.

There is room for your own experiments if promising insights come up during the exploration phase.

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