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Development of a laboratory scale origami-pattern folding device

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Abstract

In this study, process methods were researched and developed to be able to fold the paperboard Miura-ori origami pattern. The research was part of the Fold project, where the purpose was to study a new type of folding technology and folded structures. In the case of packaging, this kind of origami structure could be used to replace, for example, bubble and foam plastics that are more harmful to the environment.

The research was done by looking at patents and previous studies on folding machines that have been used to make similar origami patterns. After that, the methods in question were applied and tested to the paperboard materials in use and their suitability was evaluated, after which the process methods were modified to be more suitable for the paperboard through iterative product development.

The most important observations were that the paperboard strongly resists folding and at the same time is a material that tears easily. Because of this, the methods used in the patents were largely not suitable for folding paperboard in the same way as they are suitable for folding metal sheets or composites. However, folding the paperboard could be made easier by cutting the tops of the folds open and softening the paperboard by moistening it. In this case, the paperboard's folding resisting property disappeared, and the paperboard became easier to mould.

As part of the thesis, a production tool was developed, which made it possible to relatively easily and quickly manufacture one specific Miura-ori structure from paperboard for, among other things, impact resistance tests. The device developed during the work can be further developed into an automatic mechanical machine.

Keywords origami, Miura-ori, prototype, folding, paperboard

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Tiivistelmä

Tässä diplomityössä tutkittiin ja kehitettiin prosessimenetelmiä, joilla pystytään taittamaan kartongista Miura-ori origamikuviota. Tutkimus oli osa Fold-projektia, jossa tarkoitus oli tutkia uudentyyppistä taitteluteknologiaa ja taiteltuja rakenteita. Pakkausten tapauksessa tällaista origamirakennetta voitaisiin käyttää korvaamaan esimerkiksi ympäristölle haitallisempia kupla- ja vaahtomuoveja.

Tutkimus tehtiin perehtymällä patentteihin ja aiemmin tehtyihin tutkimuksiin taitoskoneista, joilla on tehty samankaltaisia origamikuviota. Tämän jälkeen kyseisiä menetelmiä sovellettiin ja testattiin käytössä olleille kartonkimateriaaleille ja niiden soveltuvuutta arvioitiin, jonka jälkeen prosessimenetelmiä muokattiin kartongille sopivammaksi iteratiivisella tuotekehityksellä.

Tärkeimmät havainnot olivat, että kartonki vastustaa voimakkaasti taittumista ja on samaan aikaan herkästi repeävä materiaali. Tämän takia patenteissa käytettävät menetelmät eivät suurelta osin soveltuneet kartongin taittamiseen yhtä lailla kuin ne soveltuvat metallienlevyjen tai komposiittien taittamiseen. Kartongin taittamista voitiin kuitenkin helpottaa leikkaamalla taitosten huiput auki ja pehmentämällä kartonkia kostuttamalla sitä. Tällöin kartongin taittumista vastustava ominaisuus hävisi ja kartongista tuli helpommin muovautuva.

Osana opinnäytetyötä kehitettiin valmistustyökalu, jonka avulla kartongista pystyttiin valmistamaan suhteellisen helposti ja nopeasti yhtä tiettyä Miura-ori rakennetta muun muassa iskunkestävyystestejä varten. Työn aikana kehitetty laite voidaan jatkokehittää automaattiseksi mekaaniseksi koneeksi.

Avainsanat origami, Miura-ori, prototyyppi, taitos, kartonki

Table of contents

Preface and acknowledgements

I want to thank my thesis advisor PhD. Jarmo Kouko for his helpful advice and guidance during the whole thesis process. I also want to thank Professor Petri Kuosmanen for his counsel from the academic point-of-view.

I am also grateful to the people involved in Fold project at VTT and Aalto University for helping me during development process and for background information regarding the whole project. Special thanks to Research Scientist Tomi Kankkunen for the background information he provided.

Lots of credit also to Aalto University’s workshops and their workshop masters. I could have not developed even a slightest prototype without the resources provided by them.

Gratitude must be also shown to caffeine which boosted me to write when I was feeling tired and to Italian red wine which opened the verbal locks in my head when I was feeling stuck.

In vino veritas.

Otaniemi, 24 April 2023
Vertti Vainio

Abbreviations

LPO	Lateral pattern orientation
TPO	Transversal pattern orientation
MD	Machine direction
CD	Cross direction

1 Introduction

In this section the background, problems, objectives, limitations and methods of this study are stated.

1.1 Background

Forest industry and especially paper industry has been for decades an important export sector in Finland but due to digitalization, the demand for printing paper has dropped and it will in the coming years according to Statista's research (Statista, 2023). It is likely because many consumers have moved from paper to more ecological and more compact digital form. Luckily for the industry, to fill this ecological and financial gap, the demand for cardboard is rising due to globalization and increasing online ordering. Consumers order in increasing rate goods online which means increase in demand for all kinds of package materials.

As the demand for paper is decreasing and for cardboard and other packing materials is increasing, old paper machines are turned into cardboard and paperboard machines (Packing strategies, 2017). The difference in paperboard and paper is their thickness and basis weight. Paperboard can be made by layering multiple sheets of paper together to create a thicker, more robust material (Figure 1). There are many types and thicknesses of paperboards available, and their weigh is measured with g/m^2 (grams per square meter) value. In this research I will be using the term 'paperboard' for all paper sheets with 120-300 g/m^2 weight so basically for all thick papers.

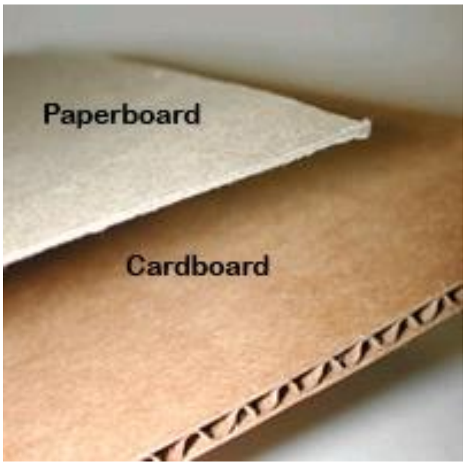


Figure 1. Paperboard and cardboard. Paperboard is thick piece of paper and cardboard is a corrugated sandwich structure made from it (crcog.net, 2023)

The good properties of the paperboard are its lightweight, relatively good impact resistance, low price and biodegradability. Unlike plastic, paperboard does not end up forming islands in the oceans and it is also made from renewable natural resource. That is why it is good alternative for replacing plastic as a packing material.

With different manufacturing methods plain paperboard, which is basically just thick paper, can be made into more durable structures such as honeycomb structure and corrugated cardboard (Figure 2). These sandwich structures use in advantage the paperboard's great tensile strength and stiffness preventing the cardboard structure from buckling. The result is a stiff and light structure. Problem with the sandwich structures is their inability to reform. The structures come out of the machine as they come and stay stiff which limits their usage in certain applications.

Figure 2. ***a)*** *Honeycomb structure (rebul.com, 2023)*
b) *Corrugated cardboard (lakkapaa.com, 2023)*

Miura-ori origami pattern (Figure 3) could be an alternative structure to be used as a package material replacing rigid sandwich structures and environmentally unpleasant materials such as polystyrenes and bubble wraps.
The origami structures properties are good impact resistance, re-formability around shapes and its pleasant design. Good impact resistance and compressive strength are properties that make it worthy alternative for honeycomb and corrugated cardboard. Its re-foldability and pleasant design are properties what makes it superior because it adds value to the companies and their end customers.

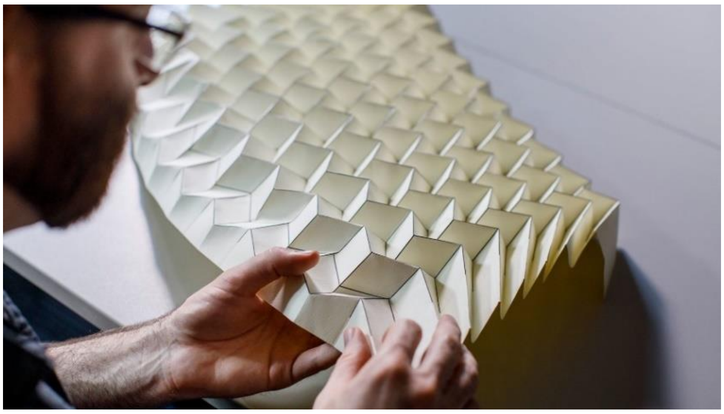


Figure 3. Origamist folding a Miura-ori pattern on a paper (quantamagazine.org, 2023)

Miura-ori pattern can be varied by changing the angle β or parallelogram sides lengths b and a (Figure 4c). The pattern can be even varied more making many different sizes of parallelograms or making totally different shapes instead of parallelograms. Then it is not called Miura-ori anymore and I will not focus on those in this study. A recent study of folded packages presents more on different shapes and patterns. (Palmu, 2019)

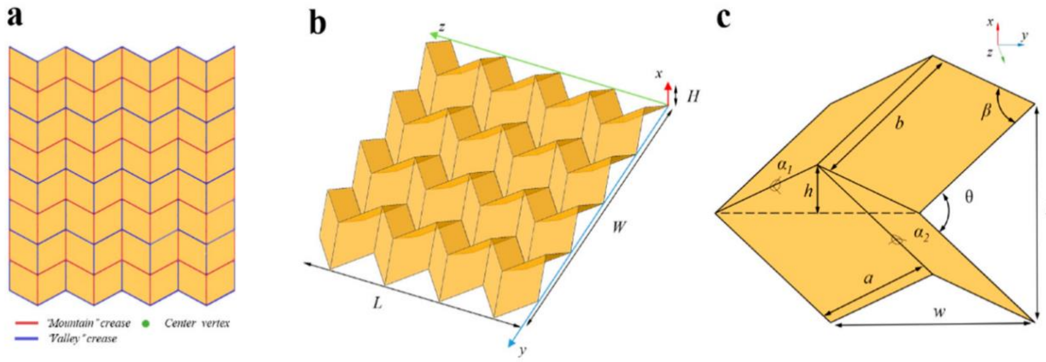


Figure 4. ***a)*** *'Mountain' and 'Valley' patterns on a flat sheet* ***b)*** *Folded and stable Miura-ori pattern* ***c)*** *Dimensions of a single Miura-ori cell (Yu et al., 2020)*

1.2 Research problem

Suitability of Miura-ori patterns for different applications was investigated in Fold-project at VTT and Aalto. For this research it was essential to create test data related to the impact resistance and compressive strength of the Miura-ori structures. The compressive tests need several repeats for adequate statistical results. Problem has been that the samples which are then crushed in the compressive tests, have been folded by hand, which is slow and laborious process. Hand folding one 15 cm x 15 cm sample of small Miura-ori pattern can take several hours. A lot of samples with uniform quality are needed for valid research. To overcome this problem, a laboratory scale process machine was needed to be designed and build.

1.3 Research objectives

The objective of this study was to develop and compare different manufacturing methods for folded structures and their functionalities. Then to build a process machine for laboratory testing quantities and in the end review the properties of the products it can create. Different manufacturing methods can be nip rollers, presses, their combinations and folding machines. The challenge in all of these methods was to prevent the material from tearing.

The pursuits were set to be the scalability of the process machine for industry scale and possible convertibility to manufacture the same *Miura-ori* pattern with different geometrical measures. Also, general machine building guidelines such as manufacturability, service life, maintenance and price were followed throughout the work.

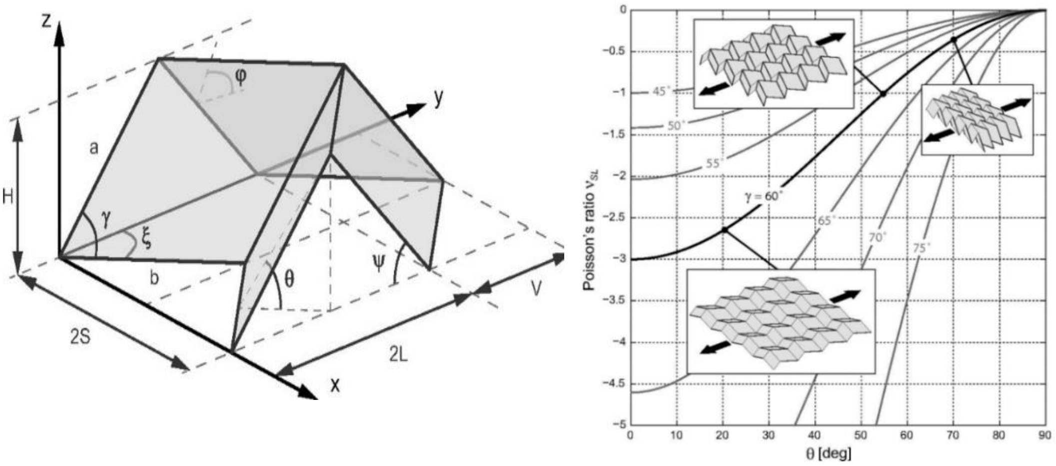


Figure 5. ***a)*** *Miura-ori geometric measures (different symbols than in Figure 4c) (Schenk, 2011)* ***b)*** *On the top right corner is the ultimate folded configuration* ***θ*** *=90°. Poisson's ratio is equivalent to -S/V (Schenk and Guest, 2013)*

The structure can be considered as stable when a certain value of θ is exceeded (Figure 5a). With 90° folding angle for the paperboard, the θ=45°. For parallelogram angle γ=55°, the Poisson's ration goes from -2 to -1 when folded so the width 2S is approximately halved. Value V changes more significantly when folded from θ=45° to 90°.

1.4 Research limitations

In this study I did not focus on the *Miura-ori's* theoretical properties, modelling nor other irrelevant information for machine design because it is in contradiction of my goals. The work was done purely with problem-solving mindset, targeting to design, build and test the machine in operation.

1.5 Research methods

First method of the work was to gather background information and getting deeper into it. VTT had done already some investigation of the topic and the potential materials to be used. A closer look is also taken into a few relevant patents. (Theories)

Then some practical topics concerning my application were studied, such as critical elongation of the material, angle of the fold, machine types and the Miura-ori geometry. (Material properties, machine types)

After that, my product development process was explained from my point-of-view, including arising compromises and decisions which I pursued to overcome with an efficient trial-and-error method. Finally ending up to most suitable machine prototypes. (Development process and prototypes)

Last of the methods was to test the machine operation and review the products it creates. Also, to provide some development suggestions for optimizing and scaling up the machine for larger volumes. These suggestions can work as a springboard for possible industrial scale machine development. (Results and conclusions)

2 Theories

In this section a closer look is taken at already existing manufacturing methods of Miura-ori pattern and a few most relevant manufacturing machine patents.

2.1 Manufacturing methods

In the wide review about the folding technologies by Schenk in his doctoral thesis, manufacturing methods of folded structures were classified into three different types, synchronous method, gradual folding method, and pre-gathering method. (Schenk, 2011)

Synchronous method folds the whole sheet to its final configuration in one single motion folding from both directions at the same time (Figure 6). This overcomes the problem where x-direction shrinks while folding the y-direction and vice versa. On a rigid sheet, the Miura-ori pattern has a property where the folds must be all done the same time or otherwise it causes stress on the unfolded area which could cause a rupture in the material. Material such as paperboard elongates and bends and therefore the following methods may also be suitable if the properties of the processed material are taken into account correctly.

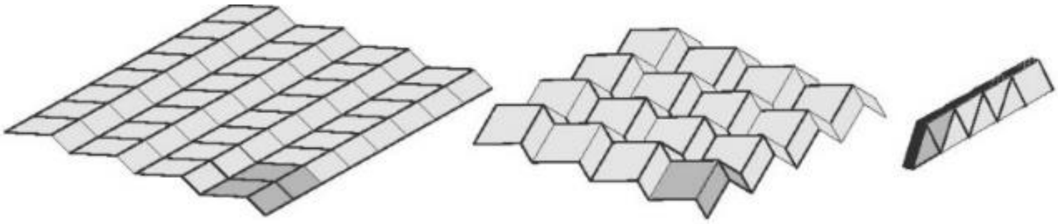


Figure 6. Synchronous folding of the Miura-ori structure (Schenk, 2011)

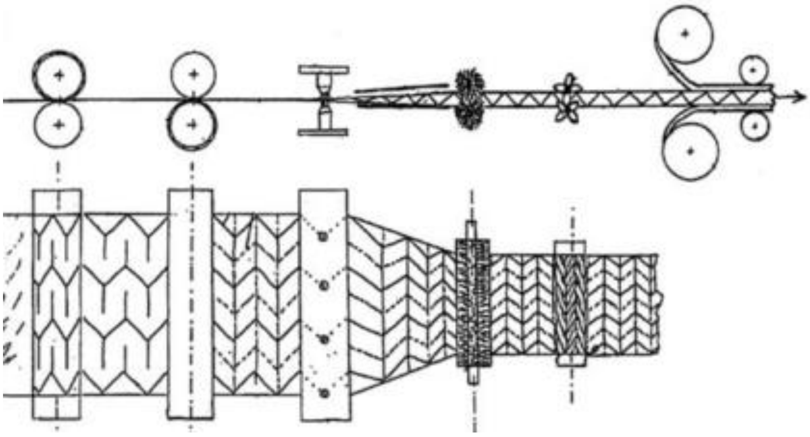


Figure 7. Gradual folding method (Kehrle, 2005)

Gradual folding methods fold the material continuously and step-by-step to its final folded form. Gradual deforming of the sheet material reduces the stresses and thus the strain that forms to the unfolded areas on the sheet. Gradual folding method requires a long processing line and synchronized process stages. First stage could for example cut slits into the sheet to improve foldability. Second stage could corrugate the material in the transverse direction and third stage could apply the needed force to actually fold the material precisely on the pre-cut slits (Figure 7). Finally, the structure can be pressed from the sides to achieve the ultimate folded configuration (θ=90°).

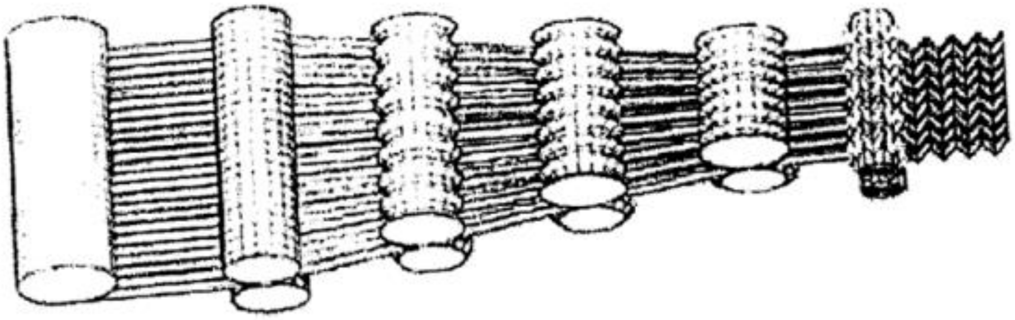


Figure 8. Pre-gathering method (Kling, 2019)

In the pre-gathering methods, the transverse contraction of the sheet material is achieved first with guides or roller nips which guide the corrugated sheet from wider line to narrower line. In the narrow end of the process line, the longitudinal contraction is done with pressing moulds, roller nips or other kind of folding method (Figure 8).

The gradual method and pre-gathering method resemble each other in some ways since the basic principle in both of them is to avoid causing any stress in the unfolded areas of the sheet and it is not always so trivial to tell them apart. They can be both be used for continuous manufacturing process.

2.2 Most relevant patents

There are numerous variations of machines which are designed to make somehow similar pattern that is targeted in this work (Figure 9). They mostly differ in sizes and the angle of the parallelogram in the tessellation pattern. Another difference is that some of the machines are designed for different materials such as composites or metal sheets.

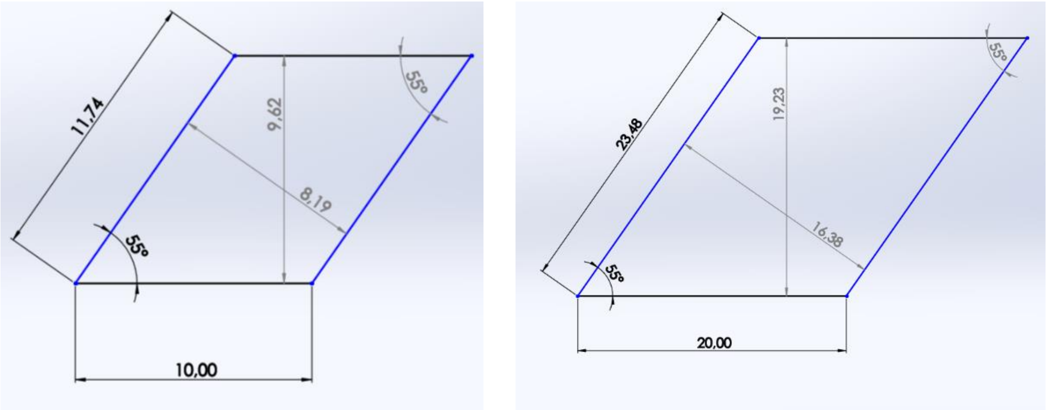


Figure 9. ***a)*** *Original dimensions of the individual parallelogram in the Miura-ori pattern* ***b)*** *The dimensions scaled twice the size*

In my original design task, the parallelogram is quite small with 10 mm and 11.7 mm side lengths and 55 degrees angle as seen on the Figure 9a. The used material was not as ductile as metals and composites tend to be. So, it was expected that some changes had to be made to suit the pre-existing designs for the needs of this design. Otherwise, there is no need to avoid the designs presented in these patents because the machine will not be designed for commercial usage but for laboratory testing usage. Some of the patents are also expired or abandoned.

The folding machine is primarily designed for the small 10 mm pattern, and it is used as a designing goal but for practical reasons, it might be easier to design and build a machine for bigger patterns. The smaller the pattern is the larger the tolerance errors will be. When the machine is hand build, a 1 mm errors may be inevitable which is already 10% of the nominal dimension. The smaller the pattern the more folds and thus more energy input to the same area. Those were the reasons which lead to the scaling up of the size to twice the size of the original dimensions later in the work (Figure 9b).

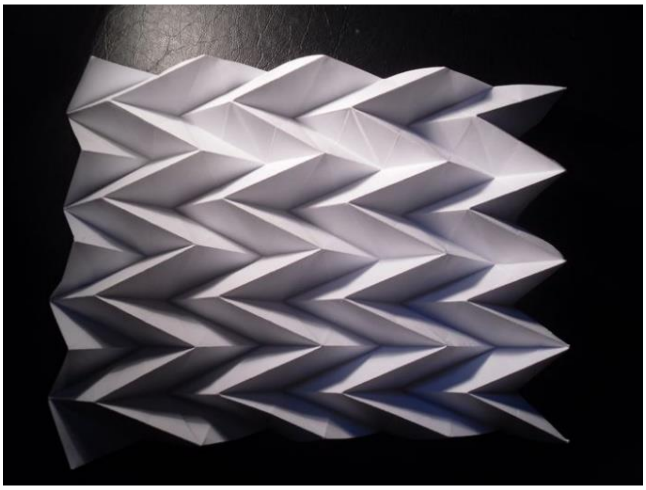


Figure 10. Miura-ori zig-zag pattern (pinterest.com, 2023)

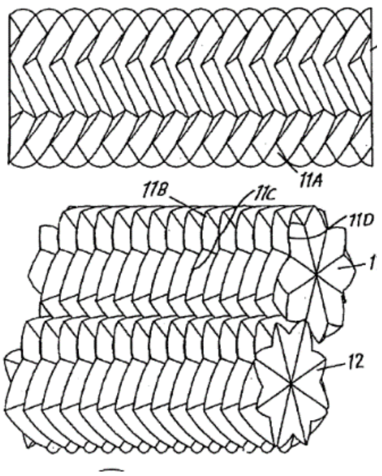


Figure 11.Airbus' patented rolling nips (Kehrle, 2005)

Figure 10 presents the continuous zig-zag pattern in the vertical direction. In the patent by Airbus (Figure 11), the design of the continuously rolling nip is basically the Miura-ori zig-zag pattern projected to a cylinder surface (Airbus, 2015). In this projection to the cylindrical roller nip the valleys in the pattern are kept the same length as they are supposed to be, but the mountains are lengthened. This is due to the greater radius of the mountain while having the same rotational speed as the valley. In this kind of rotational nip, some slippage is inevitable unless the rollers are perfect circular cylinders. Too much slippage may cause the paperboard material to tear or have some other visual damage. To reduce the length difference between mountains and valleys, the folding angle of the nip can be lowered, or the overall radius of the roller nips can be enlarged. The slippage is proportional to the ratio between radiuses of the mountain and the valley. In order to make this kind of design work for paperboard, the folding angle has to be steep enough so the structure holds its shape afterwards, but the slippage of the roller nips cannot be too high.

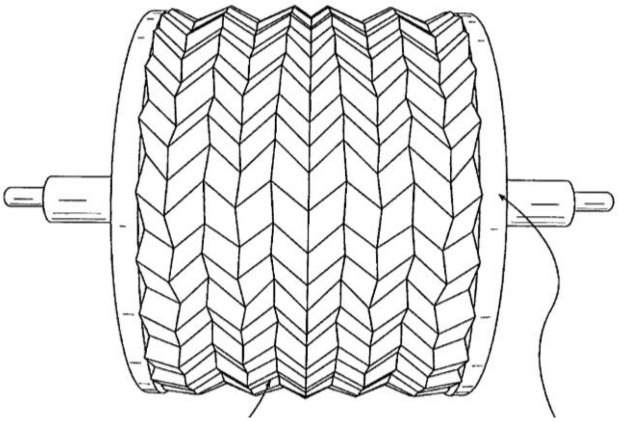


Figure 12.Rutgers university patented rolling nip (Basily et al., 2013)

In the patent from Rutgers university (Figure 12), they have tackled the problem from a different angle, 90 degrees to be more precise. The same Miura-ori pattern is projected to the cylinder surface but rotated 90 degrees. Now the zig-zag patterns are horizontal as in the previous design (Figure 11) they were vertical. This design has the same problem with the slippage of the mountains and valleys, but the folding direction of the pattern is different which affects the behaviour of the sheet material between the roller nips and post processing methods of the folded structure.
Mainly, if the folded structure is stacked along or across the processing line. The percentage of the shrinkage is different depending on which way the pattern is folded, along or across the processing line. More about that topic in the '3.2 Direction of the pattern in manufacturing' section.

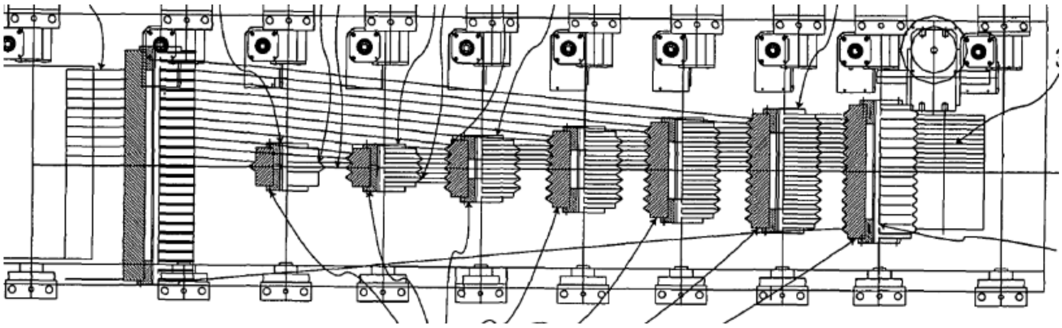


Figure 13. Gradual/pre-gathering folding line patent (Basily et al., 2013)

Another patent from Rutgers university considers the shrinking of the Miura-ori pattern in the transversal direction (Basily, 2013). In their patent the transversal shrinking problem was solved with multiple consecutive roller nips which start to fold the pattern from the centre of the sheet enabling the sides to shrink towards the centre freely and thus preventing the material from tearing (Figure 13). On a side note, this patent is expired.

The expired Russian patent (Zakirov, 2006) has some great features that can be implemented for my design as well. It is not the only patent that has some sort of pre-cutting tool (part 8 in Figure 14) to make pattern cuts halfway through the material but that is very practical way to make the folding lines as precise as possible. Figure 14 is a great example of the gradual folding method described by Schenk (2011).

Practical experience in Fold project has shown that cuts are good method for making the folding a lot easier while folding with hands. The objective is to make the pre-cuts on both sides of the material, on the mountain side of the fold leaving the valley side untouched. In case two different one-sided pre-cutting roller nips are used, then the aligning of the cuts can be tricky. The aligning of the cuts and the folds will be tricky even if the cuts are made only to one side of the sheet material.

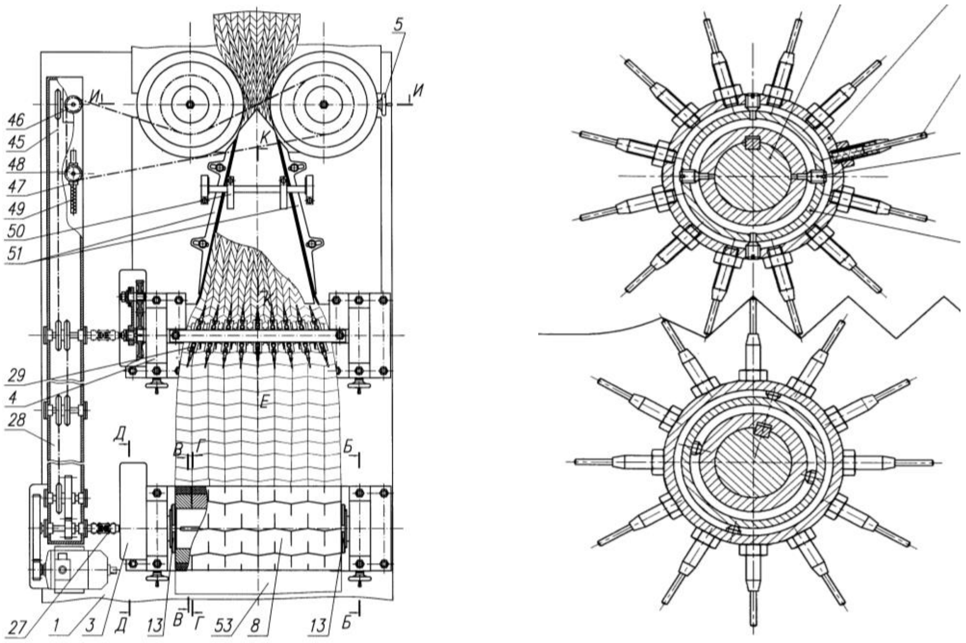


Figure 14. ***a)*** *Gradual folding method*
b) *Side profile of the spike rollers (Zakirov, 2008)*

Another good feature in this Russian patent is the folding spikes (part 29 in Figure 14a) which can be seen in more detail on Figure 14b. While roller nips may be effective as well, these folding spikes allow the material to move more freely and thus preventing stresses and ruptures in the material. The individual folding spikes can be set to their own axis and aligned so that the material is gathered from the sides to the centre without causing any sideway stresses in the material which is not possible with the roller nips.

Lastly a great feature in this design is the side rolling presses at the end of the line which make the folds sharp and permanent. This feature enables lower folding angle in the previous stage which allows more freedom in the design of roller nips for example.

3 Material properties

In this section, a closer look was taken into the properties and methods that affect the foldability of paperboard. Such as fibre direction, pattern orientation, maximum strain, creasing and cutting.

3.1 Direction of the fibres in folding

Paper and paperboard are not typical materials which behave the same way regardless of the directions. They are called anisotropic materials due to their fibre-based structure and fibre orientation created in the manufacturing process. It means that their mechanical properties such as elongation, tensile strength and tensile stiffness are not the same when measured along different directions.

As paper and paperboard are manufactured industrially, the jets (head box) spray the pulp to the same direction as the moving forming fabric. This causes the fibres in the pulp to orientate along that direction and it is called the machine direction (MD). And hence the other direction is called cross direction (CD) (Figure 15).

These two directions have different properties depending on many different process parameters. In general, the material tears easier along the MD (across the CD) since it does not break the fibres, only the bonds between the fibres. Also, the folding along the MD is easier because then the stress affects on the CD which elongates more. On the Figure 16 below, it can be seen that the tension stress curve of the MD is steeper than CD curve, meaning that its tensile stiffness is higher in that direction. But also, the maximum strain in MD is only 2% while in the CD it is 4%. The stresses and the strains are of course different for different materials, but typically the CD has approximately twice as higher maximum strain compared to the MD.

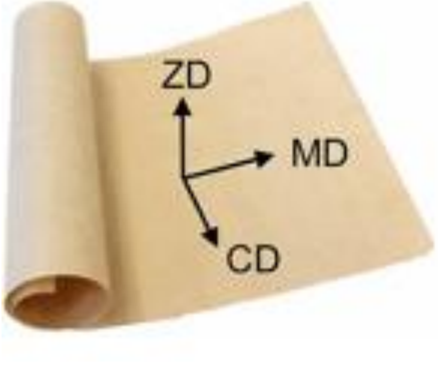


Figure 15. Direction on a paper (Simon, 2020)

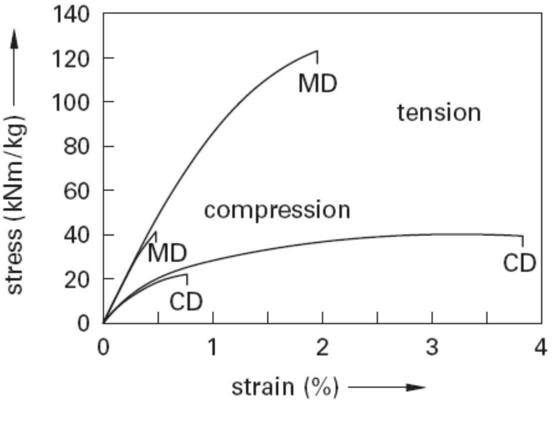


Figure 16. Stress-strain curve (Popa, 2016)

Figure 17. Sushi roller made from bamboo (www.amazon.com, 2023)

The anisotropic behaviour might be easier to understand considering a bunch of rigid sticks which are orientated to the same direction and tied together kind of like the sushi roller on the Figure 17. The way the sticks (pulp fibres) are orientated is the machine direction and you can imagine how much easier it is to fold the sheet of stick so that the sticks won't bend but the bond between them bends, which in this case is the string. That is the folding along the MD. If you fold the sheet of sticks along the CD, the sticks will have to snap thus making it harder.

Of course, the sheet of sticks is over exaggerated example compared to actual paper or paperboard. Some fibres are going to be tilted or even cross ways and the fibres are bendy unlike the sticks. But keeping the sushi roller example in mind, it is easy to remind yourself which way is which.

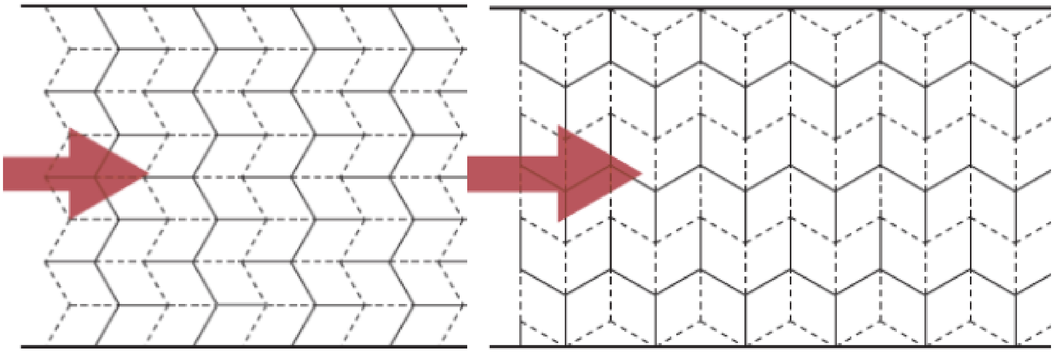


*Figure 18.**a)** transverse pattern orientation on left (TPO)*
***b)** longitudinal pattern orientation on right (LPO) (Schenk 2011)*

How does this property of the material then affect the situation? On the Figure 18, there are two different ways to orientate the Miura-ori pattern to the material. Both pattern orientations have straight folds either along MD or CD and some diagonal folds as well. The diagonal folds at 55 degrees angle may have some small effect on the folding moment but presumably it is quite marginal so it's reasonable to just focus on the straight folds.

The transverse pattern orientation (TPO) on the left figure above, has straight folds along the MD (across CD), which are easier to fold because the maximum strain and stress occurs in the CD making the manufacturing process also easier for the material to go through.

The longitudinal pattern orientation (LPO) would require folds along the CD (across MD), which is the harder direction to fold requiring bending of the pulp fibres. As you can remember from the stress-strain Figure 16, the tensile strength in MD is higher but the maximum strain is half as good compared to CD.

3.2 Direction of the pattern in manufacturing

If the LPO is chosen, the Miura-ori pattern folds up along the line direction which may enable the post processing after the fold to be a bit simpler. The process line would not need any separate presses because the pressing and the packaging can be made at the same time by ‘driving’ the folded structure against a wall or presumably springs so it takes the smallest possible space. In manufacturing point of view, I think that would be the better choice but the earlier section about the foldability along MD or CD suggest that the TPO is more suitable for the material.

On the other hand, cutting the paperboard in to desired length sections, rotate the sections 90 degrees and then manufacture them in the longitudinal pattern orientation would be a plausible method. Then the orientation of the pulp fibres would be correct, and the pattern direction would be easier to post-process. However, the continuity of the manufacturability suffers from the sectioning and rotation.

The TPO is not at least any worse option even though it requires more complicated post-processing. Then the paperboard can be fed into the folding machine straight from the roll without any section and the pulp fibres are then correctly orientated. The post-processing can be done with rollers which press the Miura-ori pattern to its ultimate folded configuration from the sides. To pack the folded structure compactly, it could be rolled around a cylinder or cut into sections which are then stacked inside a box for example.
The Miura-ori pattern shrinks mostly across the line direction in TPO so the most crucial question is could the material stand the transversal occurring stresses without tearing.

3.3 Tearing of the paperboard

The common problem with all reviewed machine types in the later section, is to prevent the tearing of the paperboard. Papers and paperboards are non-linear viscoelastic plastic materials which do not act like elastic materials under stress. Fully elastic materials stress-strain curve is linear and not an arc. Fully elastic material also return to their original form after the stress is released but due to paperboards viscoelastic nature, some of the recovering happens immediately, some happens over time and some of the deformation does not recover at all. These properties can be seen from the curves in Figure 19 on next page.

The non-linearity can be seen from the arc-like stress-curves which start steeply but then eases off. The plasticity can be seen how the strain decreases but does not return to zero when the stress is released.

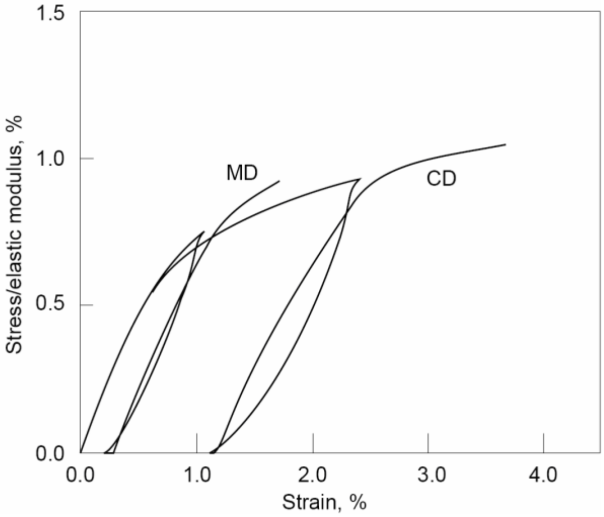


Figure 19. Stress-release-stress test for MD and CD samples. The material is viscoelastic (Niskanen & Kärenlampi, 1998)

The greatest elongation of the material occurs in the corner point of the Miura-ori pattern. The amount of the elongation depends on the sheet materials thickness, the angle of the parallelogram and how folded the whole structure is (angle of θ in Figure 5). Which in this case is the ultimate folded configuration θ=90°. The greatest strain occurs in the CD which is preferred since that direction can withstand twice as much strain as MD. In this following simulation the mountains were not cut nor creased which do in fact ease the stress as seen on the next section. The simulation in Figure 20 are made with 190 g/m^2 paperboard and the TPO.

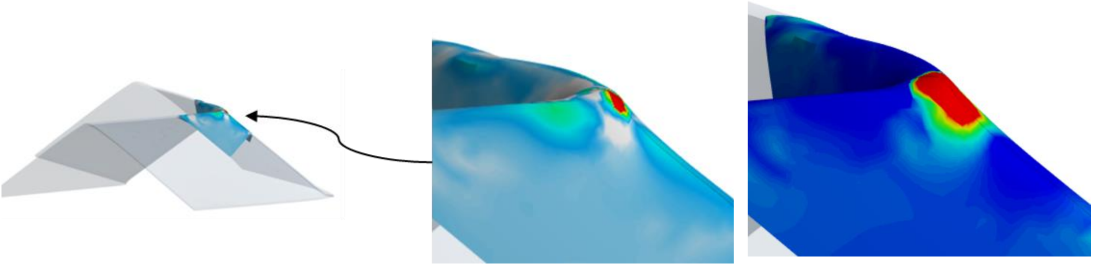


Figure 20. **a)** The corner point **b)** Red=over 2% strain in MD **c)** Red=over 4% strain in CD

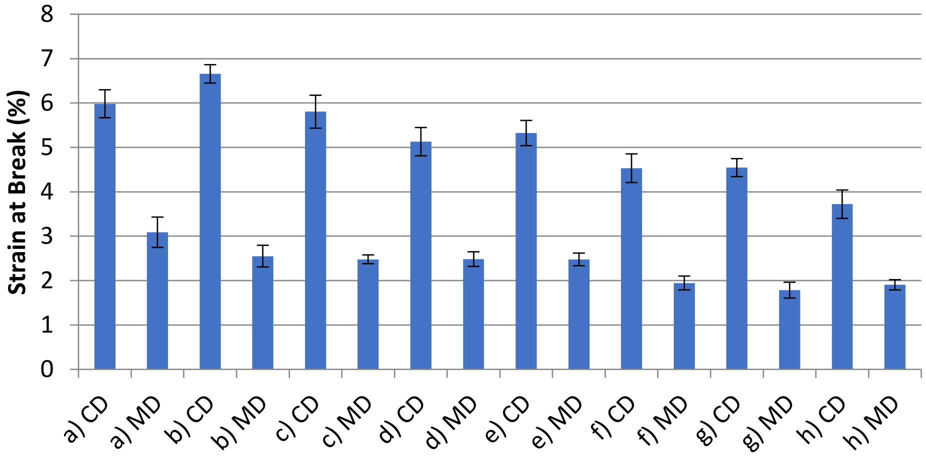


Figure 21.Elongation values at breaking point for 10 different commercially available paperboards. Each material has two values, higher is elongation in CD, lower is the elongation in MD (Oksanen, 2023)

Maximum elongations have been tested by VTT of some commercially available paperboards. The test included different variety of paperboards which some had multiple layers and coatings. The test was done in total for 32 materials in CD (the higher elongation) and in MD (the lower elongation). The average elongation of all those materials in the CD was 4.9% and in the CD 2.2%. The results in CD and MD correlate with each other, meaning that if the elongation in CD was lower so was the elongation in MD. The ratio of the weight adjusted tensile index MD/CD was on average 2.0 with 2.7 being the highest and 1.6 being the lowest (Oksanen, 2023). Meaning that the tensile strength was twice as much in MD than in CD.

From the data of the Figure 21 it would seem that the best material to withstand folding would be the sample **a**, which has maximum strain of 6% in CD and 3% in MD. But for the sake of practicality, the machine must be designed so that it can process different materials as well. So, using the average values as my high limits should be justified.

3.4 Creasing and cutting

Creasing and cutting are methods that can be used to determine the precise folding line on the sheet material. They also reduce the bending moment required folding and the strain which is formed on the mountain sides of the folds.

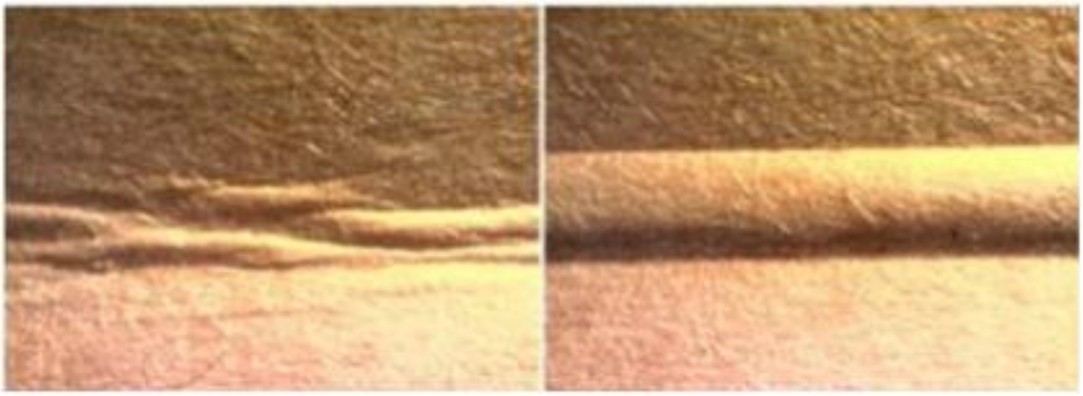


*Figure 22.**a)** uncreased valley side* ***b)*** *creased valley side (Coffin & Nygårds 2017)*

The effects of creasing can be seen in the Figure 22. The creased valley side of the paperboard seem cleaner after the fold than the one with no pre-processing. The visual appeal is significant on the creased fold and since one of the Miura-ori pattern's benefits is the pleasant design, it would be justified to use this method. Although these pictures are taken from very close range, the difference is clear with a naked eye.

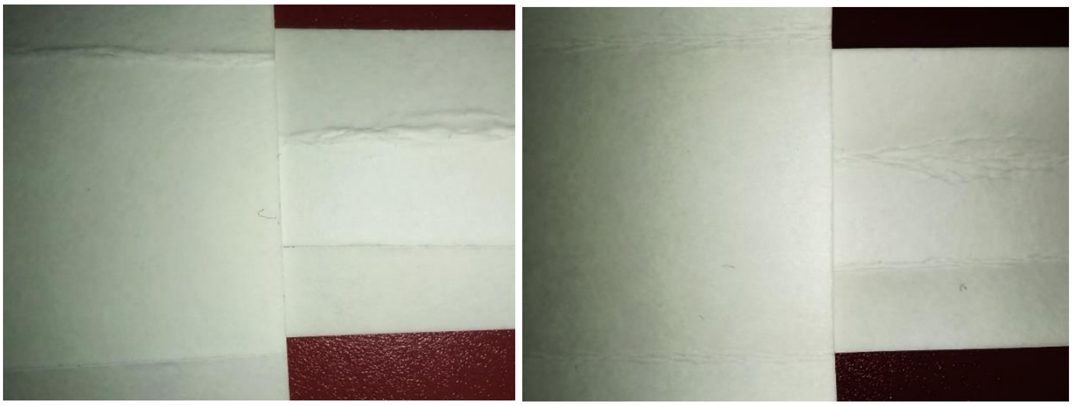


*Figure 23.**a)** Cut and uncut folds on the mountain side* ***b)*** *Valley side*

In the Figure 23a, the effects of cutting the mountain side of the paperboard can be seen. On the Figure 23b, the effects of cutting the valley side of the paperboard can be seen. The left-side samples in both figures have folds made across MD and the right-side samples have folds along MD. The upper horizontal fold lines are from folding without the cuts and lower lines are folds made with delicate cuts.

From the simple experiment in Figure 23 it can be clearly seen that with the cuts, the folding lines are much crisper which obviously makes the folds more visually appealing on both mountain and valley side.

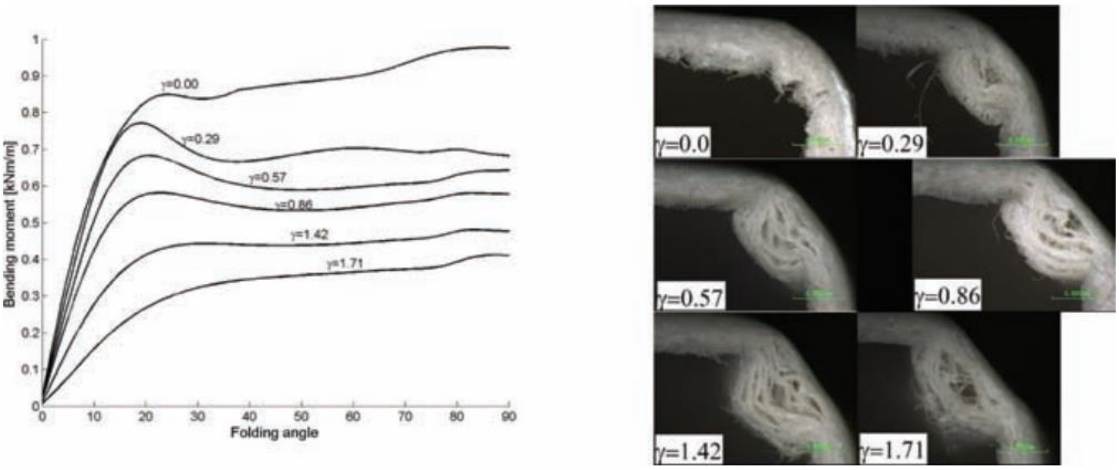


*Figure 24.**a)** Bending moment curve on creased paperboard*
***b)** Cross-sections of the folded regions (Coffin & Nygårds, 2017)*

Creasing and cutting affect the bending moment required for folding. On the Figure 24a above are the folding resistances of various creasing depths in the MD. On the Figure 24b, are the cross sections of the folded regions. Deeper creasing lowers the required folding moment because it allows the different layers in the paperboard to separate from each other. With gamma values over 1.4 the paperboard starts to get severally damaged, and the peak moment does not form any more meaning that the material has lost its strength and is visually damaged. (Coffin & Nygårds 2017)

3.5 Folding angle and spring back

Spring back is common characteristic of almost any material. It used to describe the phenomenon when material is bend to some initial angle and when the moment is released, it bends back a little bit. This is due to the elastic and plastic deformations in the material. When the force/moment is released, the elastic deformation will recover but the plastic deformation will not. Illustration of this can be seen in Figure 25.

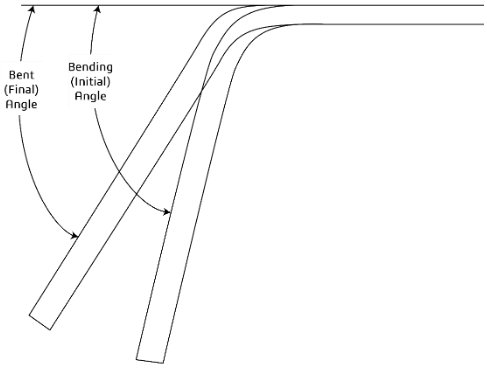


*Figure 25.*a) Spring back phenomenon (spatial.com, 2023)

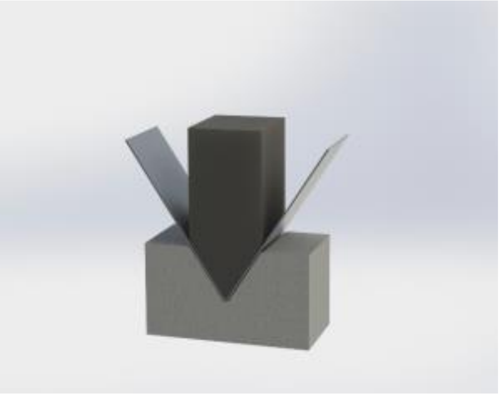


Figure 26. V-die (china-machining.com, 2023)

Exact spring back is hard to calculate because it can be influenced by many different variables such as yield strength, temperature, folding angle and time, for some to mention. Due to paperboards anisotropic structure and its viscoelastic behaviour, testing of spring back over long time with different materials is the only way to obtain precise information.

Testing for four different paperboards with different thicknesses was made at VTT. Test was made by pressing the samples in 90° and 55° angles on a V-die (Figure 26) and recorded the spring back over two days for CD, MD and 45-degree cross direction. The test was made for both sides of the paperboard because the coating/lamination may behave differently depending which side of the fold it is. For my research purposes only the immediate spring back is useful information because the Miura-ori structure will be fully folded together (θ=90°) at the end of the folding process anyways.
The pressing force used in the test was 200 N and speed of the press was 50 mm/min which means quite slow and heavy press for folding paperboard.

First thing I noticed from the data was that the orientation (MD, CD or 45 degrees) did not affect the result significantly nor did the side of the coating/lamination. The results vary only in few degrees so no practical correlation in any way was detected. The tests were conducted twice with the same parameters and those results could vary even up to 7 degrees, so the preciseness of paperboard's spring back was within that scope.

On the Table 1 below are marked the average relaxation angles and the maximum angles immediately after the 90° and 55° pressings. The paperboards are here labelled only by their weights because the product names were not relevant. But do note that they are not the same product with only varying thicknesses. One thing that must be noted is that in this test the folds were made with press force of 200 N and not by actual folding. Different results could be taken if the folds were hand-folded to 90° and 55°.

	185 g/m^2	210 g/m^2	235 g/m^2	280 g/m^2
Avg. 90°	133°	132°	142°	137°
Max. 90°	136°	133°	145°	141°
Avg. 55°	105°	106°	123°	113°
Max. 55°	109°	108°	127°	117°

Table 1. Relaxation angles for four different commercial paperboards immediately after 90° and 55° V-die pressing test (Oksanen, 2023)

From the result in Table 1 can be stated that even 55° folding angle was too wide angle to make the Miura-ori stable on its own. The stable form is 90° or lower in relaxation. In other words, the post-processing side presses to press the structure to the fully folded form will be inevitable. The relaxation angles after 90° folds are significantly larger that after 55°. Challenge is that making 55° folds requires lot slenderer and well-designed parts from the folding machine than what 90° folds require.

It is still unclear if the relaxation angle of 140 degrees is low enough 'starting angle' for the structure to fully fold if only pressed from the sides in the post-processing. It is not trivial to answer the question how large relaxation angle is the limit because different materials have different rigidity. For example, thick paperboard is more rigid compared to flimsy and thin paper. It is unclear how they behave under the side pressing and which 'starting angle' is required for each material.

4 Machine types

In this section, different machine types for manufacturing folded pattern structures are reviewed. The following machine types are not all the possible machine types because there could be basically limitless amount of different methods to do something. Rather these are examples of the most common machine types that has come across from researching different patents and videos from the internet. The machine types fall under one of the three methods which Schenk has defined, synchronous, gradual and pre-gathering method (Schenk 2010).

4.1 Roller nip

Paper and paperboard machines consist of many rollers which are used to move and process the sheet material, so it is quite intuitive to think them suitable for sheet forming process as well. Roller nips benefits are its continuous processing speed which is why it is widely used in processing machines. Hard rollers also do not have any moving parts besides the rollers themselves which makes them quite cheap and easy to manufacture and to maintain. Hard rollers can only manufacture one type of Miura-ori pattern without any change of modifying the geometry unless you change the whole roller to another one.

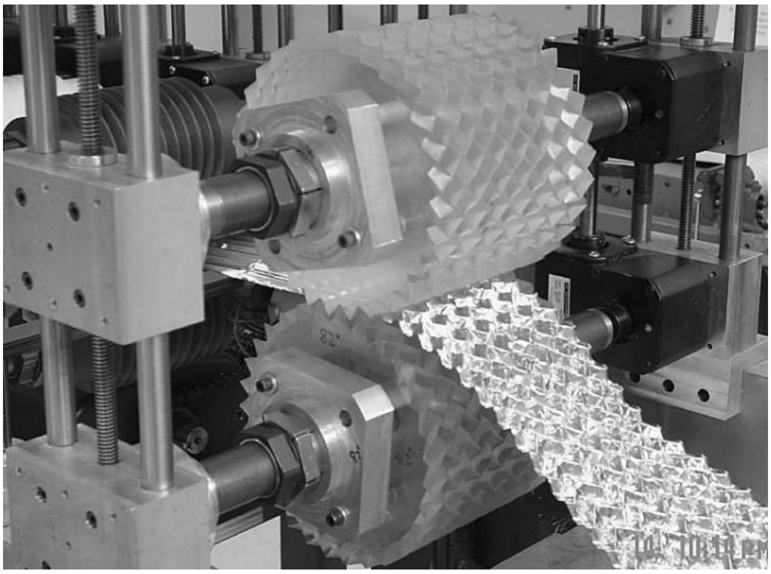


Figure 27. Miura-ori patterned roller nip pressing continuously sheet metal (Basily B. and Elsayed A 2004)

Roller nips are great method for large scale manufacturing and easy-to-manufacture as a prototype machine as well, however it may not the optimal folding method for few reasons.

Firstly, projecting Miura-ori pattern to the cylinder surface does not happen without any contradictions. The geometry of the pattern changes a bit which can cause strains in some areas of the ‘folded’ or rather forced structure on the sheet material. Also, the roller nip does not actually fold the structure. Rather the roller nip forces the structure to take form. Roller nip does work sufficiently on materials which withstand more elongation such as the metal sheet on the Figure 27 but forced pressing can cause weaker materials such as paperboards to rupture easily.

4.2 Press moulds

Pressing method has two pairing hard moulds which force the sheet material between them to its folded structure. The geometrical changes which occur when the Miura-ori pattern is projected on a curved surface do not happen in this machine type because the moulds are geometrically accurate hard surfaces of the very same pattern. Press moulds are also easy to manufacture for prototyping, but the manufacturing capacity is not as good as with roller nips since the process is not continuous. Also, the pressing method is rather forcing than folding.

As a sheet of material is pressed between two moulds, the friction between the mould and material has to be low to enable the material to slide to the valleys and mountains of the desired structure. If the friction is too high preventing the sliding the material is strained by the mould pattern. Straight hard moulds are thus not suitable machine type for materials which are prone to rupture easily. However, some other materials such as elastic plastics or metals could be forced to the Miura-ori pattern just by simply pressing.

In order to make pressing feasible manufacturing method for paperboards, the mould surfaces should be curved at some radius making it more like fusion between roller and press. This method could be sufficient enough for laboratory scale testing. The two curved press moulds can be thought as small sectors from a larger roller nip. If the radius of the curvature is very large, then the geometric changes that occur when the Miura-ori pattern is curved, become very small. The moulds with the most correct geometry will probably be the most suitable ones as well. However, the sheet material probably must be gathered transversally or corrugated longitudinally before such moulds.

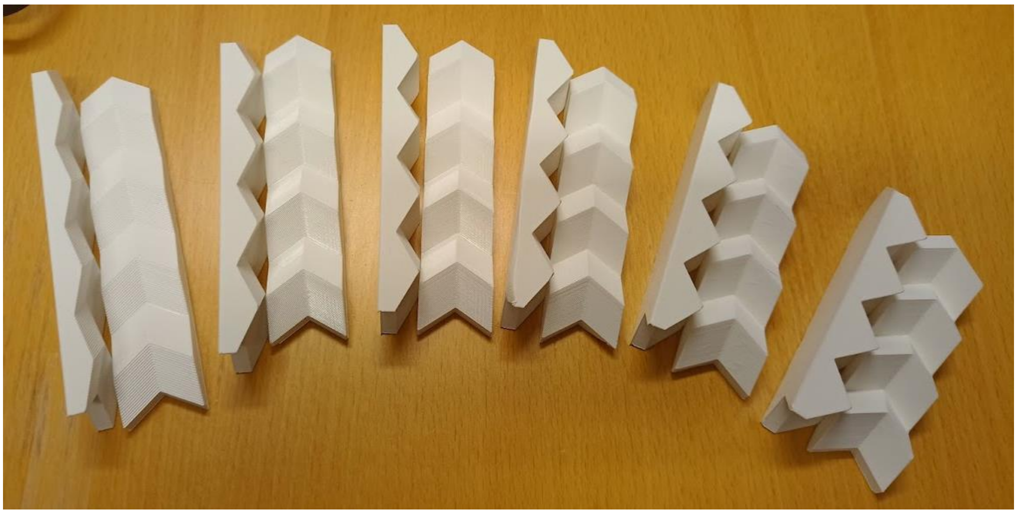


Figure 28. Miura-ori pressing moulds with folding angles: 150°, 130°, 120°, 110°, 100° and 90°

Another developed method is to gradually increase the folding angle sharper each step like on the Figure 28. Starting with almost flat press which barely makes visual folding marks on the sheet. The gradual process requires small shrink and slide of the flat material to reach the valleys and mountains. Gradually moving the processed sheet to sharper and sharper angled moulds prevents the need for large elongation in the material. The drawback of this method is low speed and accuracy. If the processed sheet is misaligned to the next moulds valleys and mountains, this causes unprecise folds and possibly even a rupture in the material.

4.3 Synchronous folding machine

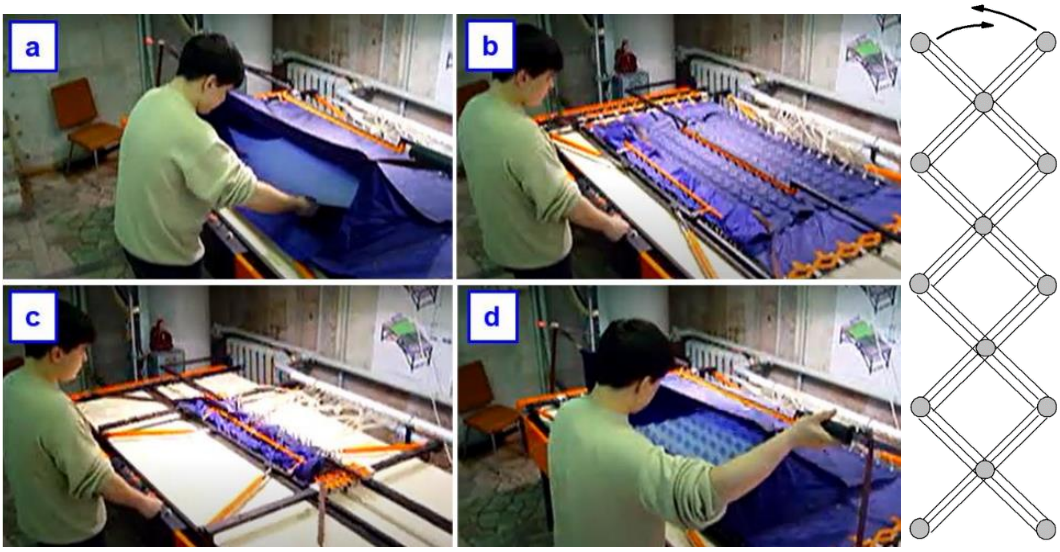


Figure 29.Screenshots from a video of synchronous folding device (CCT Synchronous, 2013). Left side: scissor structure (Zieliński, 2009)

The folding machine in the Figure 29 uses one single motion to fold the desired structure on both in-plane direction. The machine is an example of synchronous folding method. The exact working mechanisms of this particular machine is difficult to tell from the video from which these screenshots have been taken.

However, the folded sheet is placed between the two canvases (a) which keep it firmly in place while at the same time allowing it to fold freely when the machine makes the synchronous fold (c). It seems that some kind of scissor structure (Figure 29 right side) is used to make the folding guidance to the material.

From the video it is also unclear how do the two canvases hold the sheet material so well in place, perhaps vacuum is used. It is also unclear how thick paperboard was used and if much smaller patterned Miura-ori could be made the same way. In the video the parallelogram side length is approximately 30-40 mm.

This kind of machine is suitable for lab scale testing and its convertibility to fold different shaped Miura-ori patterns is also possible. It does not seem to be too complex to manufacture but its scalability to industrial volumes is a bit trickier and would require more complex automation.

4.4 Folding roller

Folding roller in is essentially a fusion between folding machine and a roller nip machine. It has the benefits of continuous processing and the gentle folding method which does not force the sheet material to desired structure.

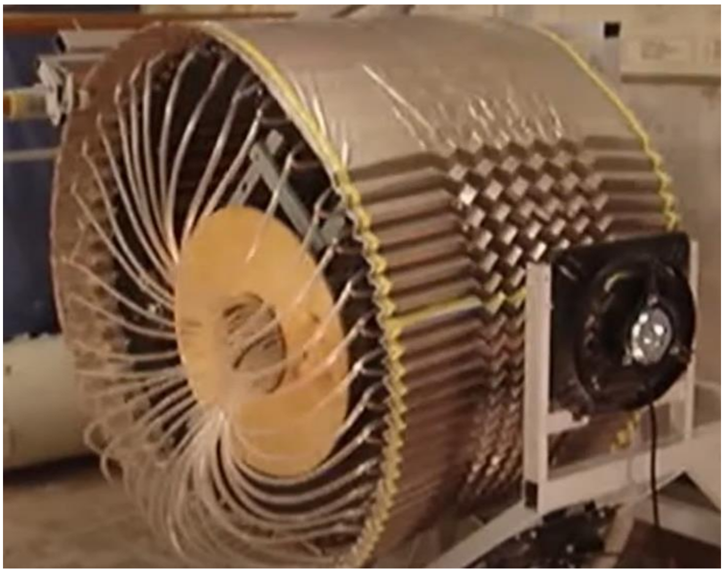


Figure 30. Pneumatically controlled continuous folding roller (CCT Folding roller, 2013)

This machine shown in Figure 30, uses the gradual folding method which is basically integrated into one roller. However, the machine is very complex to build and without a doubt difficult to maintain. The machine uses the roller to move the sheet material slowly and on a certain point it uses pneumatic actuators to fold the surface structure of the roller to desired shape folding the processed material at the same time.

For laboratory scale testing purposes this might be a bit overkill especially because of its complexity. However, if the design could be made fairly easy and the complexity could be simplified, this machine type could stand out as the most potential machine type due to the fusion of the good features of the previous machine types. It is continuous and it does not force the folding.

4.5 Gradual folding machine

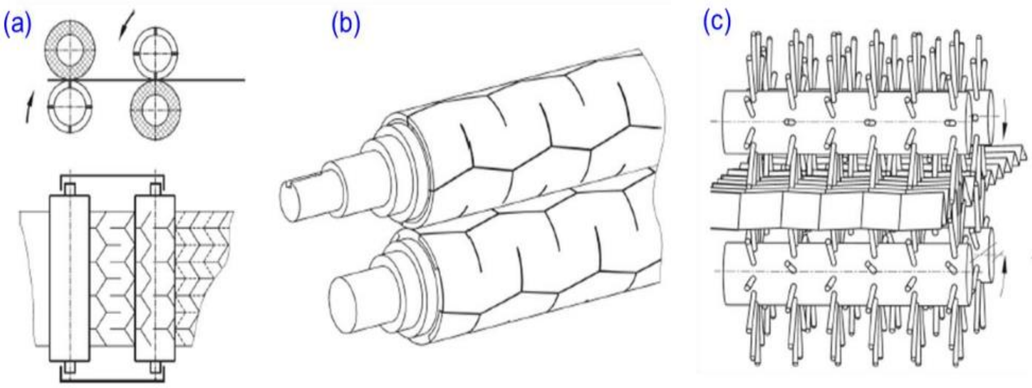


Figure 31. ***a)*** *Cuts are made to both sides of the sheet material with two sets of cutting rollers.* ***b)*** *Pair of cutting rollers* ***c)*** *Pair of porcupine rollers folding sheet material (Zakirov et al. 2006, 2010)*

The machine on the Figure 31 can be considered as a folding machine as well but not a synchronous one. It uses the gradual folding method where folding lines are cut to the material with cutting roller such as in Figure 31b. Later the processing line the actual folding is made. This machine does not force the structure because instead of roller nips or presses, it uses porcupine rollers (Figure 31c) which allow the sheet to fold freely. Post-processing is probably needed to make the folds permanent. A good example of a gradual folding machine is the line setup in Figure 14.

This kind of machine is suitable for lab scale but also for industrial scale machines. The construction of each process stage does not seem too complex, but the stages must be synced together. The geometry of the pattern could also be fairly easily modified by changing the cutting rollers and readjusting the porcupine roller’s spikes, although that would make the machine a bit more complex.

5 Development process and prototypes

In this section I will go through the development process and test the suitability of different ideas. I start by testing the existing ideas from the patents and videos I have researched and then I let the development pick its own lane.

5.1 Starting point of the development process

At the start of the development process, the existing concepts of presses and roller nips were tested mainly because those are the simplest designs. The designing of the 3D-models was simple and the protypes could then be printed relatively fast with 3D-printers. Printing the new prototypes was so fast method for manufacturing small parts, that multiple variations of the same basic design was possible to be made. For 3D-printing, Ultimaker 2+connect printers were used which were provided by Aalto university at their 3D-printing lab that only students are allowed to use. The prototypes were printed from PLA and were tested with paperboard and aluminium sheet cut from a soda can, to compare the effect on more durable material as well. In this section acronyms LPO and TPO were used which refer to the orientation of the pattern compared to the manufacturing line direction (Figure 18).

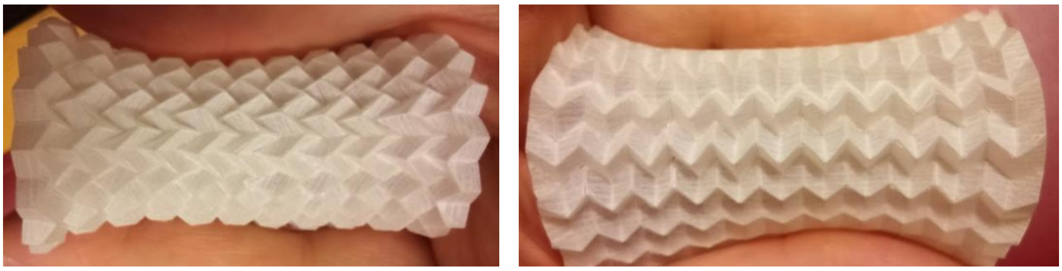


Figure 32.Miura-ori pattern curved to a cylindrical shape. ***a)*** *LPO* ***b)*** *TPO*

One of the first properties that was noticed when the Miura-ori pattern was examined by hand was its capability to curve to both directions as can be seen in Figure 32. Even though the pattern can be curved to a cylindrical shape, it is not perfect. The edges of the sample tend to curve upwards making the ‘cylinder’ narrower in the middle. Bending the pattern like this creates stresses to the material which either tears up the mountain folds or bends the edges upward. From this simple experiment it can be stated that projecting Miura-ori pattern to a cylindrical surface cannot be done without modifying the pattern’s geometry slightly.

5.2 Gradual presses

First thing tested was gradually decreasing the angle for the moulding presses (Figure 33a) because the moulds were easiest to design and to manufacture. The presses were designed with one Miura-ori cell width and four cells length to keep the prints small. With this prototype, the behaviour of a small paperboard piece could be tested between the moulds before trying the same method on a bigger scale.

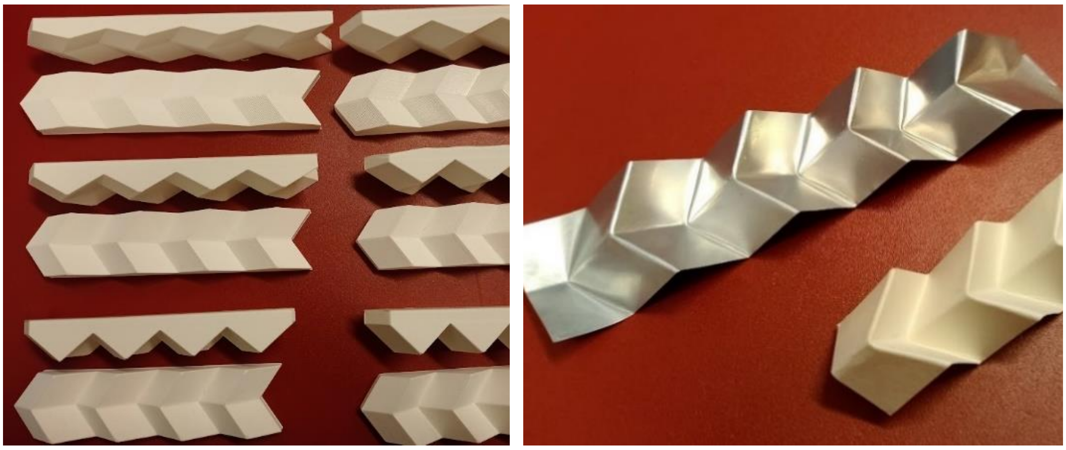


Figure 33.a) Gradually angled pressing moulds, 150°, 130°, 120°, 110°, 100° and 90°
b) Samples of aluminium and paperboard pressed between the moulds

With this prototype, narrow strips of Miura-ori pattern were made to the point where the pattern could be finally folded to the fully folded form. The biggest problem using this method was to a line the gradually folding sheet to the next mould's valleys and mountains. Even for a such a small piece of material, the handling was laborious. If the material was just simply pressed without adjusting the material between the presses by hand, the mountains and valleys formed imprecise. If the material was aligned correctly to the following press, then the folds became crisp as can be seen on Figure 33b.

By scaling up the presses for example 5x5 Miura-ori cells, the handling of the material would become even more laborious and without proper alignment the material would get damaged between the moulds. Therefore, this idea was not taken any further.

5.3 Roller nip prototype 1

As a first rolling nip method, a cylinder profile was designed which would press the pattern in LPO to the material. To prevent excess material and time waste, only the outer rings was designed which could be pressed together by hands (Figure 34), the intend was never to fasten these to axles. In this design the whole area of the Ultimaker 2 printing bed (22 cm x 22 cm) was used to make as big outer ring as possible, also wide folding angle was used. This was done in order to reduce the ratio of lengths between the valleys and the mountains.

Figure 34.First iteration of LPO roller nip

From the computer screen the folding angle sure did seem sharper, maybe because of the lines that the software provides to visualize shapes better. Therefore, it is important to prototype rapidly and if possible, use 3D-printer to make real life prototype before machining expensive parts with CNC-machine. In result the folding angle in this first roller design was way too wide which resulted almost unrecognizable folding lines on the sheet material. For the next iteration the fact had to be accepted that the valleys and mountains will be different lengths and just see if it causes too many problems.

5.4 Roller nip prototype 2

For the second iteration for LPO roller nip, the folding angle was drastically sharpened which then came out to be 90° (Figure 35a). The same limitation for size was used, which was the area of the printing bed, to make the radius of the roller as big as possible. As stated, before in this study, the length difference of the valleys and mountains are proportional to the ratio of radiuses of the valleys and mountains. Thus, increasing the overall radius, the ratio of the radiuses and the ratio of mountain/valley will approach to one.

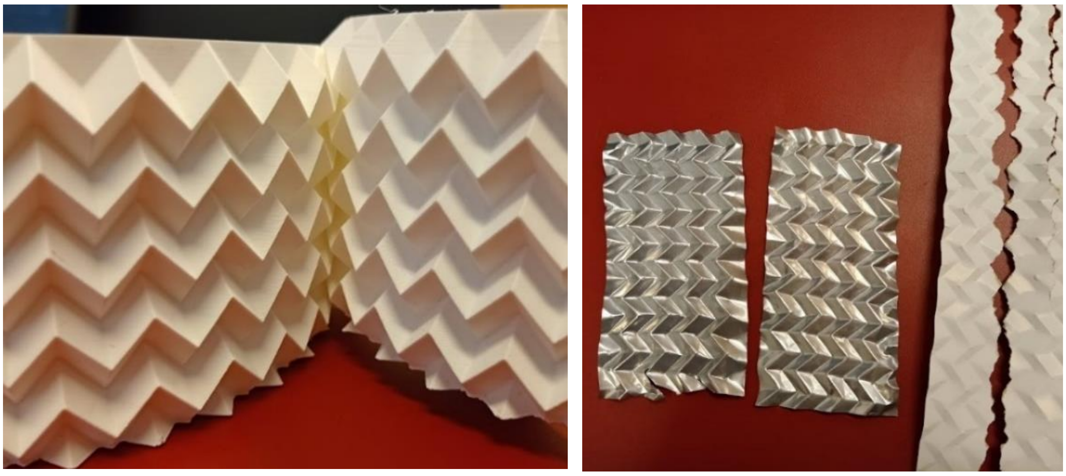


*Figure 35. **a)** Second iteration of LPO roller nip **b)** Samples of aluminium sheet and teared up paperboard*

This prototype was tested the same way as the before, just by pressing the rollers together by hands and rolling a piece of paperboard between the roller nips. This prototype resulted visually clearer folds in the samples than the previous one. Problem in this design was that the paperboard ruptured severely along the MD (Figure 35b). Another problem was that even though the sample (or what was left of it) had clear folding lines in it, it was not able to fully fold just by pressing from the sides. The aluminium sheet survived this test sufficiently and resulted quite nice looking and rigid Miura-ori sheets. Due to LPO design, the sheet materials were prone to slip out of the grip of the rollers. The aluminium sheets had to be first pressed in between the rollers just like in a press and only then the rolling movement was possible without slipping.

As a summary, the paperboard ruptured severely, and the sample was not folded enough for post-processing. If the post-processing would have been possible, a roller with wider folding angle could have been designed to be gentler for the paperboard. For now, the LPO roller design was rejected, and the focus was shifted to the TPO rollers. Although it is not excluded that LPO rollers couldn't work in gradual folding method where multiple rollers with sharper folding angle than the previous roller is put into a sequence (Figure 13), but before such an assembly, simpler methods were tested first.

5.5 Roller nip prototype 3

In the designing phase of the first TPO roller nip iteration, a 12-pointed star sketch was drawn on a plane and another star slightly rotated to another plane which was 10 mm away from the first plane. Then body was extruded from the first sketch to the other. After that, the body was mirrored and made to a repeating pattern. Also, a smaller diameter was designed to be used in this prototype for the sake of faster printing time and total neglection of the mountain/valley length ratio. Consideration of the mountain/valley ratio caused more problems in designing compared to the benefits, so it was neglected. The problems were caused mainly by the ineffective way of modifying parameters in the used CAD software.

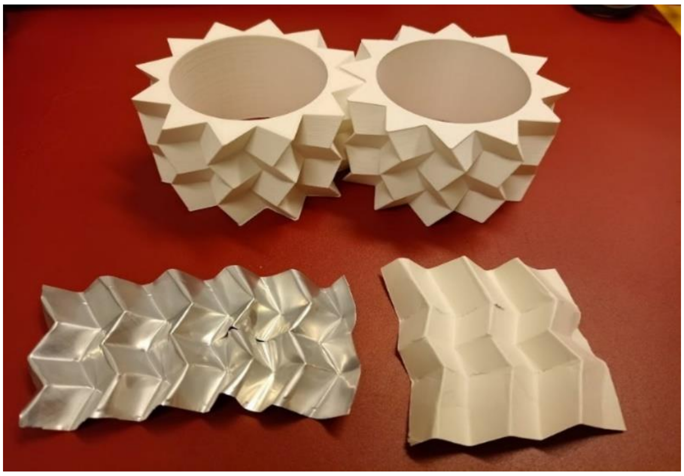


Figure 36.First iteration of TPO roller nip and the samples of aluminium and paperboard

This design resulted quite sharp looking pair of roller nips (Figure 36). One significant improvement compared to LPO roller was that the sheet material was held in place a lot firmer by the rollers. With the second LPO roller, the paperboard and especially the aluminium sheet did not want to get fed in between the rollers without slipping and drifting. The TPO rollers acted similarly with actual gears that grab the sheet material and pulls it in. It was very easy to make samples with this prototype and it gave more hope of the suitability of TPO rollers.

Acting like an actual gear worked well keeping the sheet material in place but for paperboards, this prototype was too rough. It resulted ruptures in many areas of the pattern, especially the corner point. The aluminium sheet did not survive the handling of this prototype neither and it was ruptured from the corner points as well as can be seen from the Figure 36. The angle of the parallelogram is incorrect in this prototype, it is approximately 70 degrees as it is supposed to be 55 degrees. The larger the parallelogram angle is the more the structure will shrink in CD while being in between the roller nips if the folding angle is kept the same. Thus, making the material more likely to tear.

5.6 Roller nip prototype 4

For the second iteration of TPO rollers, the same 12-pointed stars were made to the two plains as in the previous design, but instead of using straight lines, arcs were used. This resulted curved surfaces for the parallelograms (Figure 37). This was kind of experimental prototype which had the purpose of making sharper folding angles. Two straight lines have fixed angle in which they cross each other. Arcs on the other hand can be curved in a way that the crossing angle changes by keeping the arcs' end points still but changing the radius.

Figure 37.Second iteration of TPO roller nip and the samples of aluminium and paperboard

The designing of this on the CAD software was a bit tricky because the parameters that could be changed were the arc length, distance of the two planes and the rotation of the second sketch but the parameters needed to be changed were the parallelogram's angle and side lengths. So, it took quite a while to test and measure how every little parameter modification affected the geometry of the parallelogram.

As a result, better roller nips were designed which were able to make quite good samples, also the geometry was more as desired compared to the previous prototype. But it still ruptured the paperboard and the aluminium sheet at the corner point. The curved surfaces of the parallelograms resulted super sharp corner point to the cylinder surface which can be seen on Figure 37. Also, the designing method of extruding from one sketch to another resulted straight mountain and valley lines. For a rolling nip this is not ideal. The straight lines do not roll smoothly but rather the rolling happens in small steps.

5.7 Roller nip prototype 5

For the third iteration of TPO roller nips, the same kind of arcs were used as in the previous prototype, although it cannot be objectively stated that the curved surfaces offered any real benefits. The mountain edges of the rollers surface were rounded with 0.2 mm radius to prevent the material from being punctured by the super sharp corner point the same way it was on the roller nip prototype 4. Instead of extruding between two sketches, the body was made by sweeping a sketch along very short helix curve which resulted curved valleys and mountains and thus enabling smooth rolling. The pattern was also made smaller, closer to the original 10 mm target size of the Miura-ori. Even though this prototype (Figure 38) had a socket for bearings and axles, the rollers were not mounted but instead just tested by hands as were the previous prototypes. This was the best of the TPO rollers, it did not rupture the corner point as intended but another problem arose.

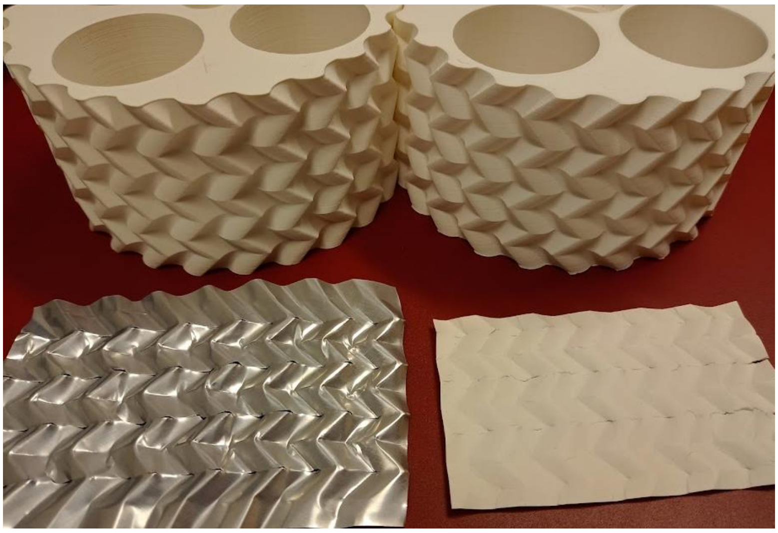


Figure 38.Third iteration of TPO roller nip

In TPO, the origami pattern tends to contract more across the MD than along the MD, in other words the pattern contracts in CD while being in between the rollers. As the two previous TPO rollers had the roller width of 2 Miura-ori cells, this one had the width of 4 cells. If the material can slide barely between the roller when only 2 cells are used, 4 cells made it twice as hard. If the width of the rollers is increased from this, the problem will come inevitably even if the friction between the rollers and the sheet material is low. Figure 38 shows that both tested materials have similar ruptures along the MD, and it is due to this problem.

When the rollers press the folds to the paperboard by force, the material tears. This same problem was with the LPO rollers, and it could possibly be fixed with the gradual folding line method (Figure 13).

At this point it was clear that the folding task is not something that can be done just by pressing with force. The paperboard is just simply too delicate to handle with force. The folding must be done by applying moment which folds the sheet on the right folding line rather than pressing the valley and mountain lines to it. And even though the gradual folding line method is not excluded, I wanted first to focus on the folding problem and leave the gradual folding line method more as backup plan.

5.8 Spike roller

Rejecting the forced pressing method lead to an idea of alinged spike rollers which would push the valley side of the corner point from every forming corner on each side of the paperboard (although this idea is developed from the porcupine rollers in Figure 31c). This would give the sheet material more freedom to move along and across the MD. Making pre-cuts to the paperboard would offer a clear line which the material could fold on. In difference to the porcupine rollers, the spike rollers are mounted individually onto a curved axles in order to gather the sheet material from a wider width to a narrower width and thus allowing the material to contract while being in between the rollers (Figure 39).

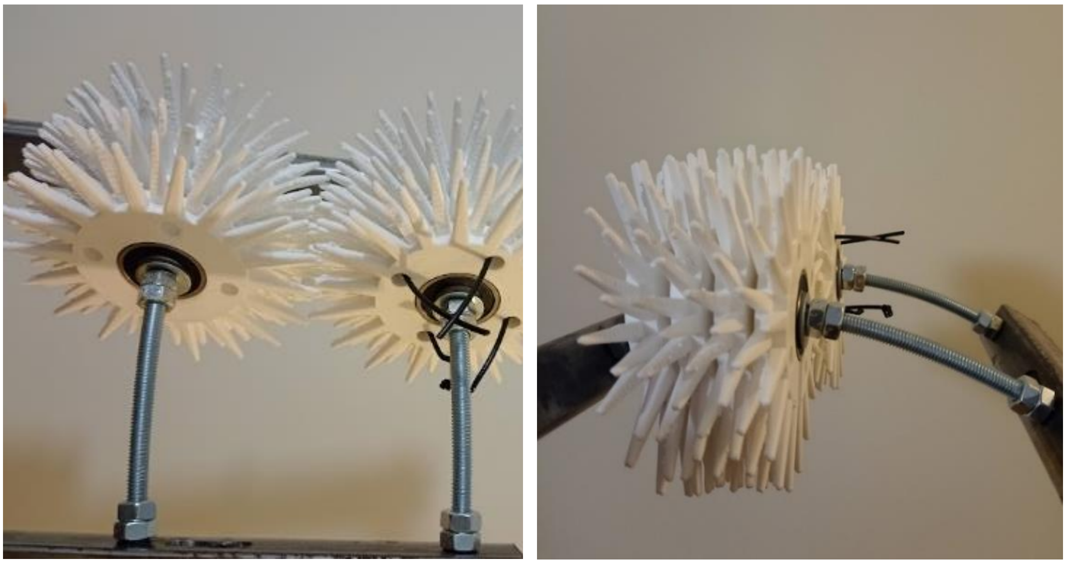


Figure 39. Spike rollers prototype. 3D-printed spiked rollers individually mounted with a bearing to a curved axis.

The lesson learned from this prototype was the difference between how the sheet material acts in the real world compared to the ‘ideal world’ inside the designers imagination. At first it seemed to be very clear that the material folds on the pre-cutted lines if just some force is applied to push the corner points from each side. However, the paperboard has recistance preventing to get folded. Instead of folding nicely, the spikes basically just punctured the paperboard (Figure 40). The result were so poor probably because the prototype was not tuned. Larger spike heads would certainly not pierce the material the same way and modifying the distance between the two axises would offer different folding angle possibilities.

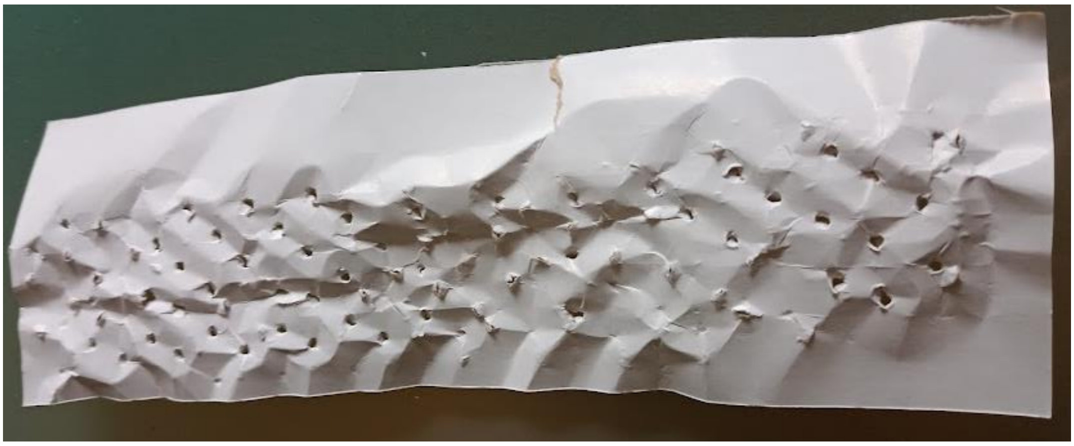


Figure 40. Punctured paperboard sample from spike rollers

This was a fast prototype which proved the dysfunctional concept of bare spikes. Instead of spikes which push just on the corner point, a wider structure has to be used which is able to push the whole valley and thus preventing the material from being punctured. The wider structure cannot be too rigid though, because then it would not allow the material to contract while being in between the rollers.

The first idea was to design a skeleton version of the prevous rollers, print it out of flexible but strong material and mount it to a curved axis as the spike rollers (Figure 41). The first problem came because a suitable material was not found which to print with and the second problem was realizing that single roller pairs would not provide enough contact area/time in between the rollers. As soon as the material exits the rollers’ press, it begins to unfold if a second stage is not applied immidietly.

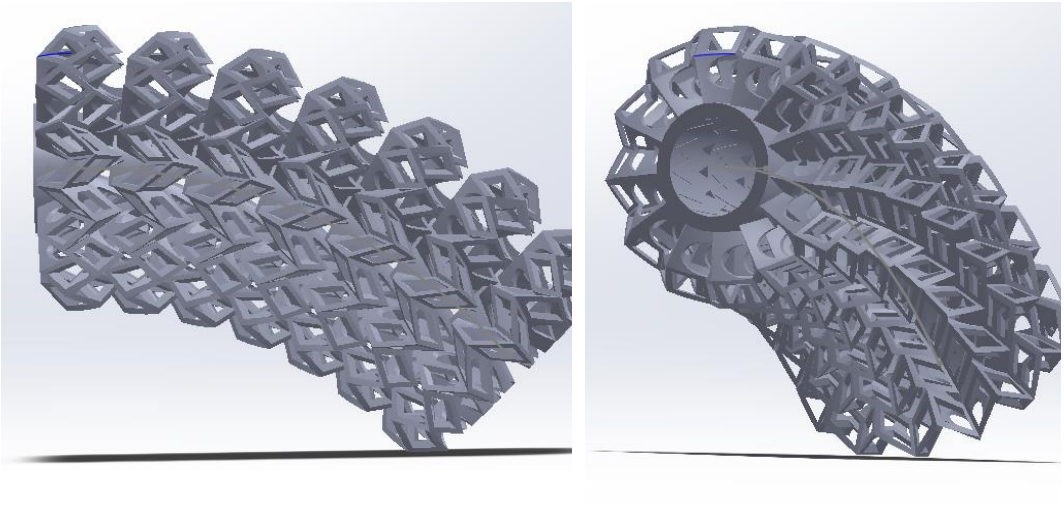


Figure 41. Draft of skeleton roller on a curved axis

After realizing that, another idea arose. Because the axis is curved, it means that the spikes move closer together when they rotate to the concave side of the axis. These kinds of spikes which come closer together in CD while being in contact with the sheet material could be used to make the folding procedure.

5.9 Spike belt folding machine 1

In this prototype the spikes must be able to move closer together in CD and at the same time they must have a ‘counter spikes’ which push the forming valleys from the other side of the sheet material. In this kind of machine, the spikes must be able to leave the rolling axis and travel in a straight line for some time and thus increasing the contact area/time between the material and the machine.

This sparked an idea of spiked belts which would be fastened between two pulleys. Then those pulleys would be mounted to a curved axis, enabling the group of spiked belts to take the sheet material in from a wider width and driving it to a narrow width (Figure 42). To prevent the spikes from piercing the material this time, a durable and foldable canvas could be glued on top of the spikes.

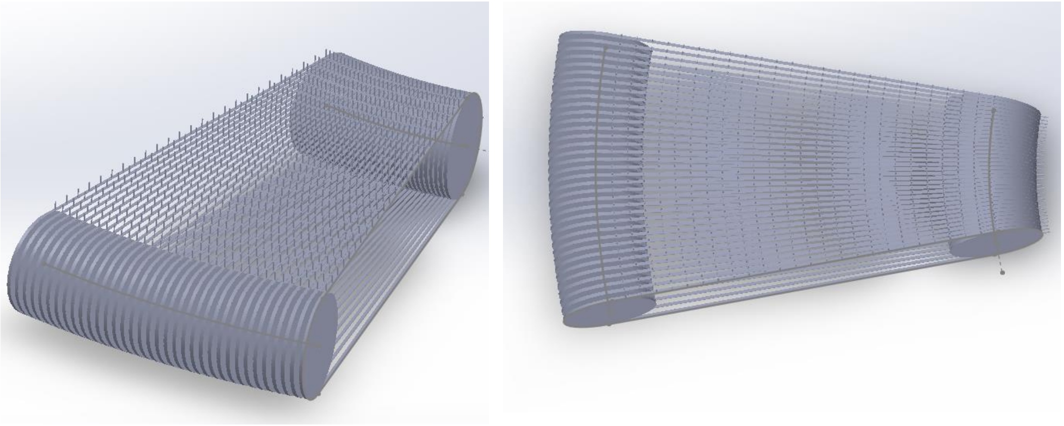


Figure 42. Concept of the spike belt folding machine. Another assembly just like this would be placed on top enabling the machine to push valleys from both sides.

Visualizing and designing the spike belt prototype was relatively easy but it was found to be rather difficult to actually build such a machine with relatively limited building options. The hardest part was to build belts with spikes on them, because those cannot be store bought. To test the concept fast and cheaply the belts were made by hand. Machine belts such as those used in car engines were not used because 5mm wide belts that could be obtained quickly could not be found with reasonable effort. If the concept would turn out to work well, then the best parts for machine building could be purchased. But in this prototype, it was decided to make the belts from strong fabric and duct tape. Those were easy to manufacture to proper width and the spikes, which are 25 mm long nails with 1.6 mm diameter, were easy to assemble to them as well (Figure 43a).

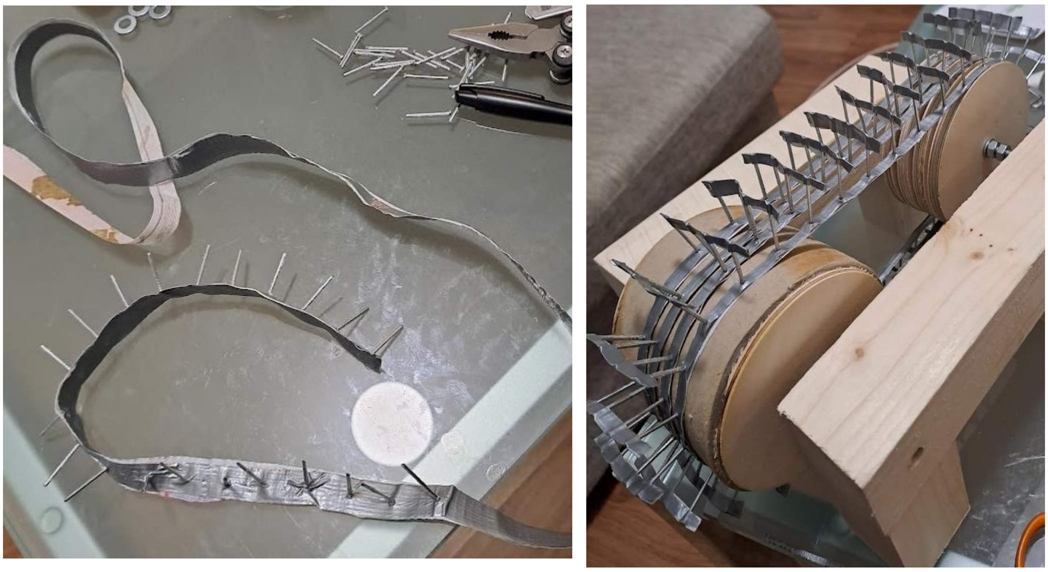


Figure 43. ***a)*** *Manufacturing of the spiked belts folding machine* ***b)*** *First iteration of spike belt*

The most obvious problem in this prototype was that the spike belts dropped from the pulleys as they were rotated. The reason in general was that the folding machine 1 was simply too poorly build and assembled for a small 10 mm Miura-ori pattern. All the little misalignments, poor manufacturing tolerances, axes clearances, inaccuracies made just a crappy machine (Figure 43b). although it would be suitable in a museum of modern art as well as the spike rollers in Figure 39.

5.10 Spike belt folding machine 2

Being still hopeful about this machine type, it was decided to scale the Miura-ori pattern up to 20 mm to make the assembly and manufacturing easier and to make the pattern forming easier for the machine. Folding 10 mm pattern requires a lot more force and durability from the belts and spikes than folding 20 mm pattern. Even larger patterns would be easier but those are quite easy to fold by hand as well so there would really be no need for such a machine.

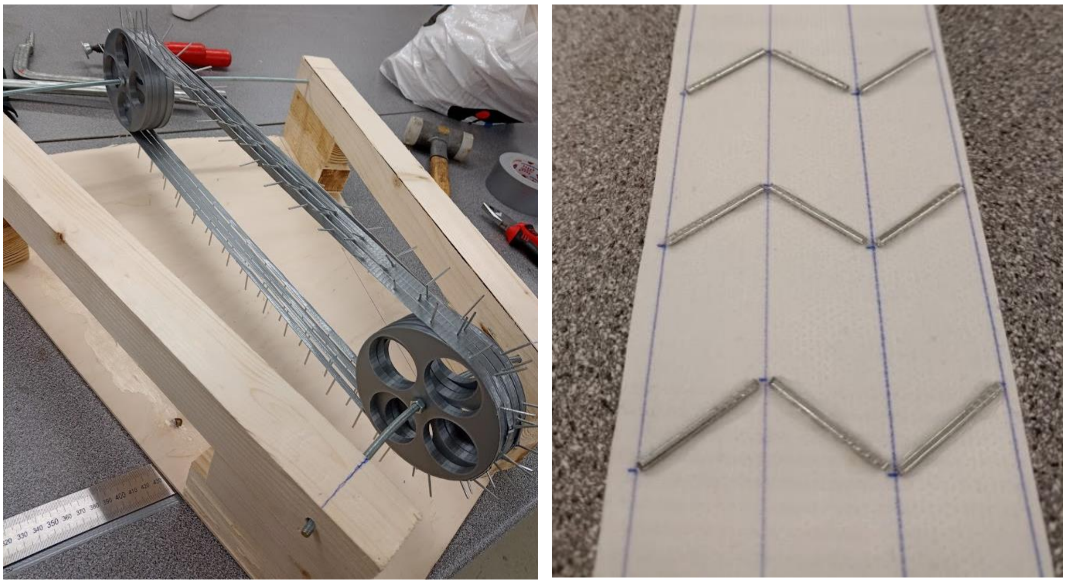


Figure 44. ***a)*** *Building of the second iteration of spike belt folding machine*
b) *Nail reinforcements glued to the canvas*

Building this prototype (Figure 44a) took a lot of time even though it was far from the full scale. It had only four spiked belts which are 140 cm long and has spikes every 4 cm. In total there were 35 spikes on each belt times 4 belts = 140 nails pushed through the belts. The belts were made very precisely 8 mm wide; the grooved pulleys were printed with small axel clearances to prevent the pulleys from wobbling and the belts from dropping again. Then the belts were tightened between the pulleys.

Figure 44a shows that the belts did not stay orientated right although at this point it did not matter that much because a canvas was to be attached on top of the spikes to keep them straight. Nevertheless, this indicates that there are some tensile forces which bend the belts, and they probably came from misaligning the fabric and the duct tape. Nails were glued to the canvas (Figure 44b) to reinforce the pushing of the valley and at the same time allowing the canvas to contract in the CD.

After laborious assembly, the canvas could be glued on top of the spikes (Figure 45a). In the plan, the canvas would complete the machine and provide enough structural strength to keep the spiked belts aligned straight. As the canvas was halfway glued in place (Figure 45b), it was realized that the belts and the pulleys were just too weak to even fold the canvas let alone much more resistant paperboard. To make a prototype work even in a proof-of-concept level, it would be needed to invest a lot of time and money to build a machine which could actually fold resistant material. By doing such a strong device would result that the spike belts would not have the freedom to contract in the MD as needed. And since the Miura-ori contracts in both MD and CD, the spike belt machine would be eventually useless. It was at this point that the once so brilliant idea was ready to be buried.

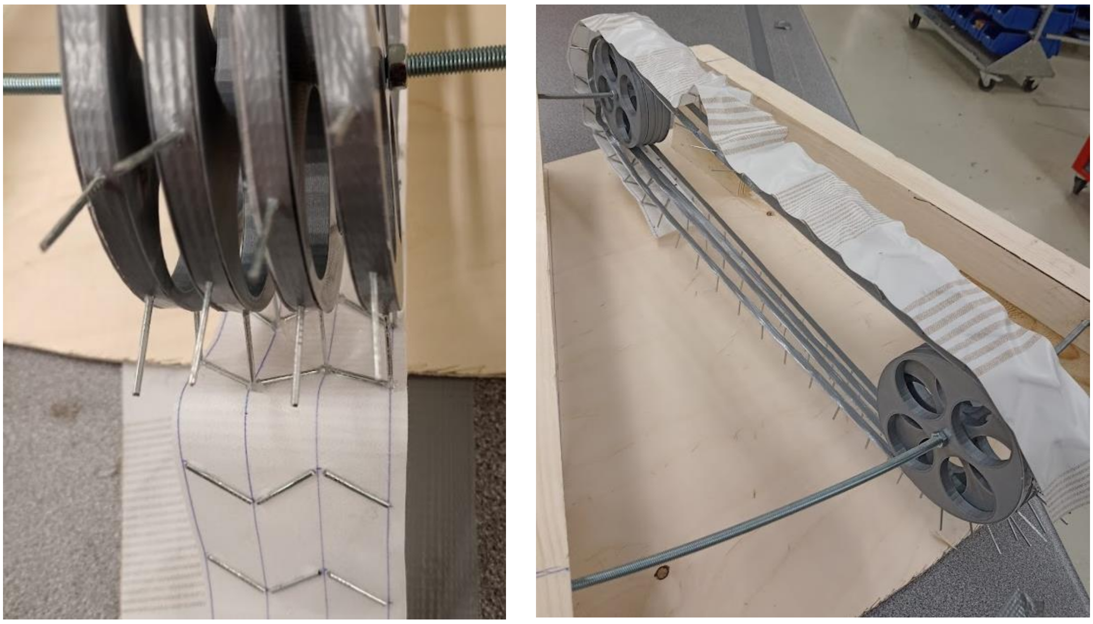


Figure 45. ***a)*** *Canvas glued to the spikes* ***b)*** *Second iteration to the point where I gave up*

5.11 Foldable structure from rigid material

The development process got new path as a place was found where laser-cutting machine could be used for a quick prototyping at Aalto university. Laser-cutting technique opens ways for quicker prototyping although the machines are much more expensive than 3D-printers.
First, enough 20 mm Miura-ori pattern parallelograms were cut from 2 mm thick plywood to make 2 x 4.5 cells Miura-ori structure which was taped together with duct tape. Then the mountains were cut open and the structure was folded (Figure 46a).

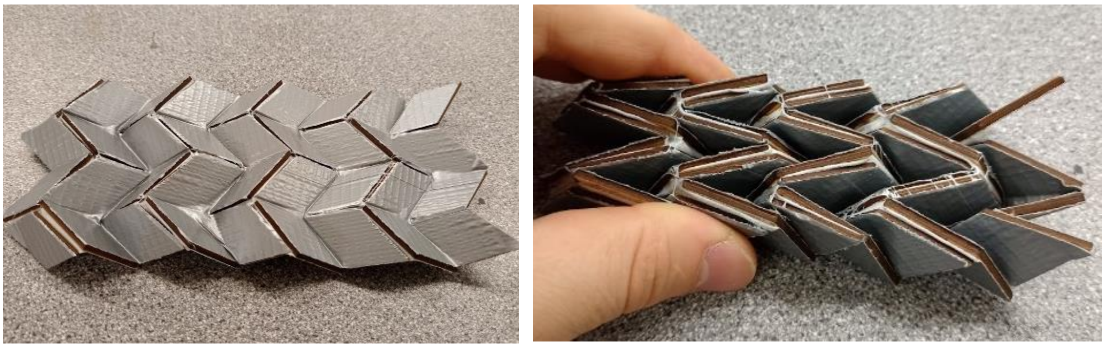


Figure 46. ***a)*** *Resting Miura-ori structure made from plywood*
b) *Same structure in its ultimate folding configuration*

The idea was to use this prototype as a foldable mould basically using two Miura-ori mats and fold the paperboard in between them. But as can be seen from the Figure 46b, the 2 mm plywood was too thick to make the structure fold enough. Also, the paperboard would be elongated way too much over the mountains. Therefore, the mats were made from the thinnest plywood available which was 0.8 mm thick.

Enough parallelograms were cut to make 4 x 11 cell Miura-ori mat which were picked them up from the laser-cutting bed with a blue vinyl tape (Figure 47a). The vinyl tape was brittle and not very stretchy, so it had to be cut open from the mountain side to make the structure foldable (Figure 47b). The bigger structure was harder to fold and required some origami folding skills even though it was only 4 x 11 cells.

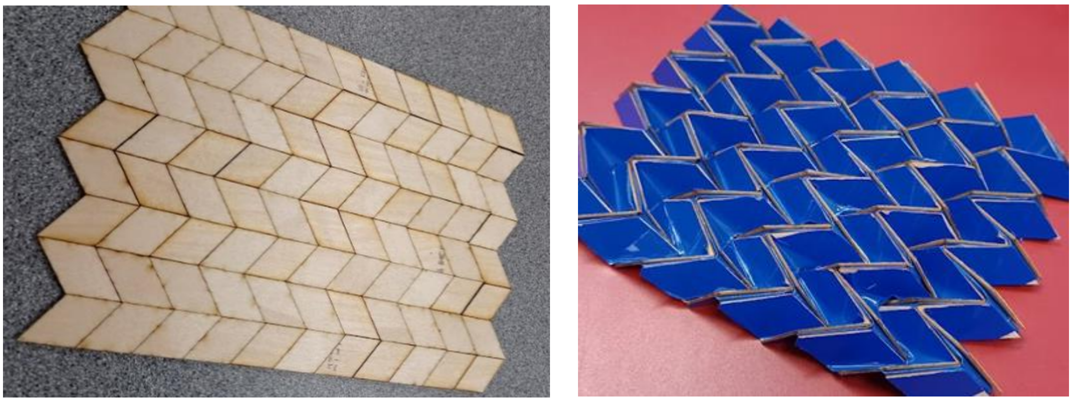


Figure 47. ***a)*** *0.8 mm plywood parallelograms attached to vinyl tape*
b) *Folded structure with cut open mountain folds*

The vinyl tape had too weak adhesive surface and it was very easily ripped so the mould was torn down and the plywood parallelograms were attached to a piece of duct tape. The stretchiness of the duct tape and the folding capability of the concept was tested with two 1.5 x 6 cell mats which turned out to be very promising (Figure 48a). The small-scale test validated to build bigger 6.5 x 6 cell assembly (Figure 48b). The parallelograms had to be placed precisely 1 mm away from each other to make the folding easier or even possible which was laborious.

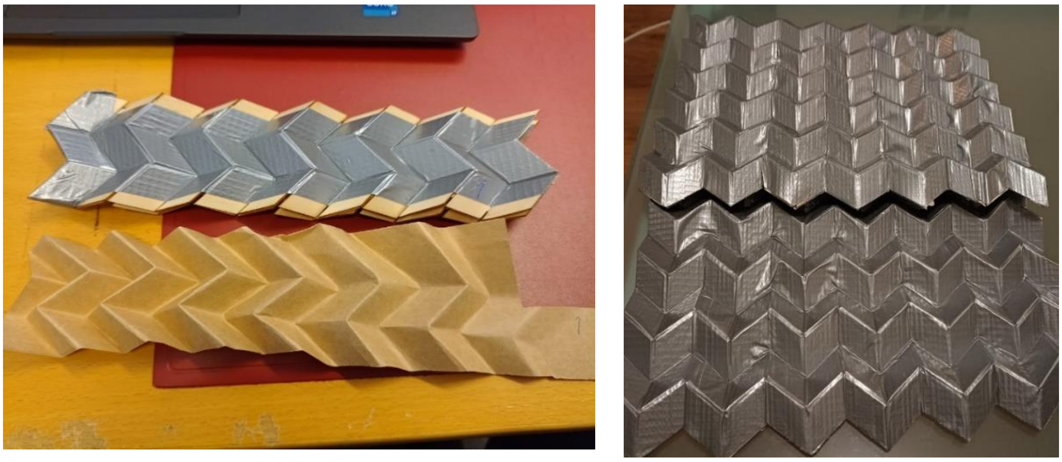


Figure 48. ***a)*** *0.8 mm plywood parallelograms attached to duct tape*
b) *Two Miura-ori mats made from plywood and duct tape*

The two mats made from duct tape turned out to be just the right size to be operated by two hands. At the same time, it had to be pushed together and squeezed from all around with 10 fingers. Softer materials such as paper towel and re-wetted paperboard were easy to fold with this prototype. Folding resistance of those materials were low and the weight of the mat kept them in place, so no extra force was required to push the mats together.

Normal printing paper was also easy to fold but it was more prone to tearing if the mats were pushed together too hard. Dry paperboard was so resistant material that it required actually some force to keep it in place between the mats but also gentle hands to make the folding without tearing the material. Closer look of the samples can be seen on Figure 49.

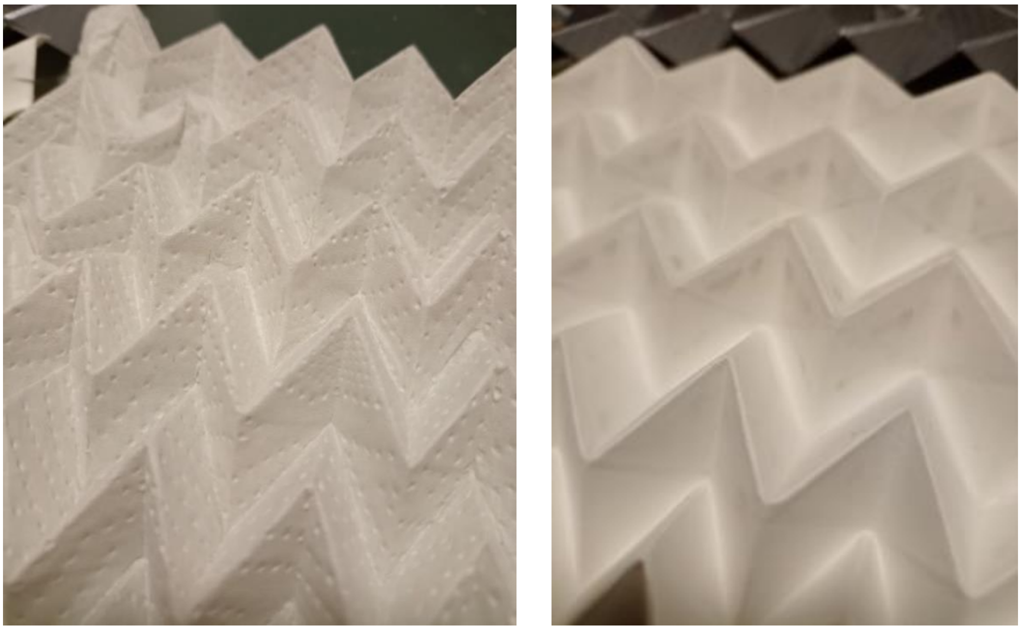
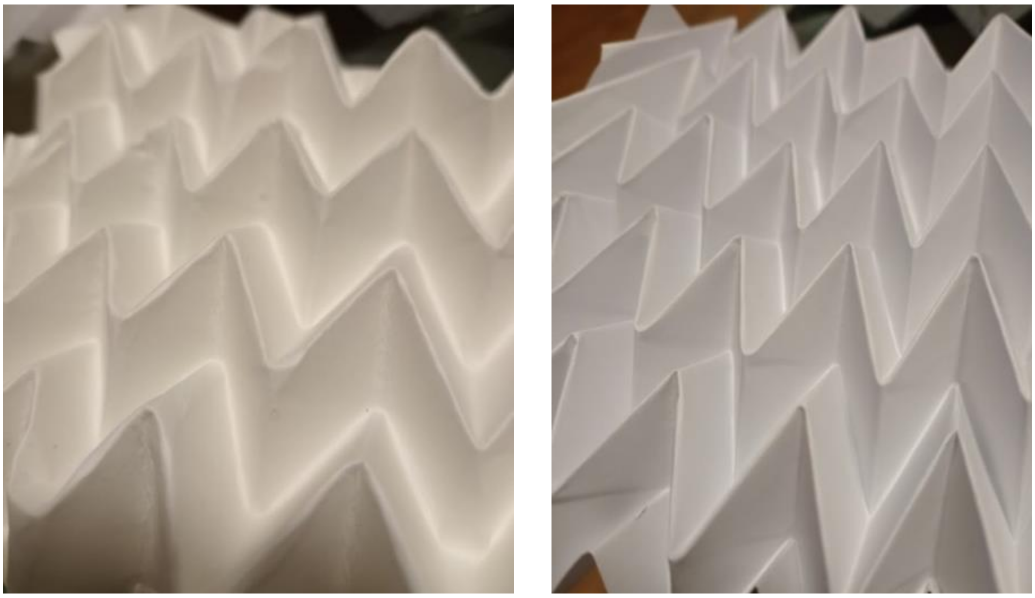


Figure 49. Folded Miura-ori made from ***a)*** *Paper towel* ***b)*** *Re-wetted paperboard*



c) *Dry paperboard* ***d)*** *Normal printing paper*

This was the best prototype so far and it was made relatively easily but it still required some folding skills to make a perfect sample. The next step was to find more efficient way to make the folding mats because placing the parallelograms one-by-one precisely 1 mm away from each other for a bigger prototype would take too much time.

The material was decided to be upgraded to steel because 0.5 mm steel is thinner, more durable and heavier. Usually, weight is a bad thing but here it actually helps to keep the sample in place. More durable and adhesive duct tape was also chosen for the next prototype. Duct tape is useful material for prototyping because of its strength, low cost and availability. It is really strong and durable material which can be easily applied to surfaces without additional adhesive such as glue. This makes it perfect material for rapid fixing and prototyping.

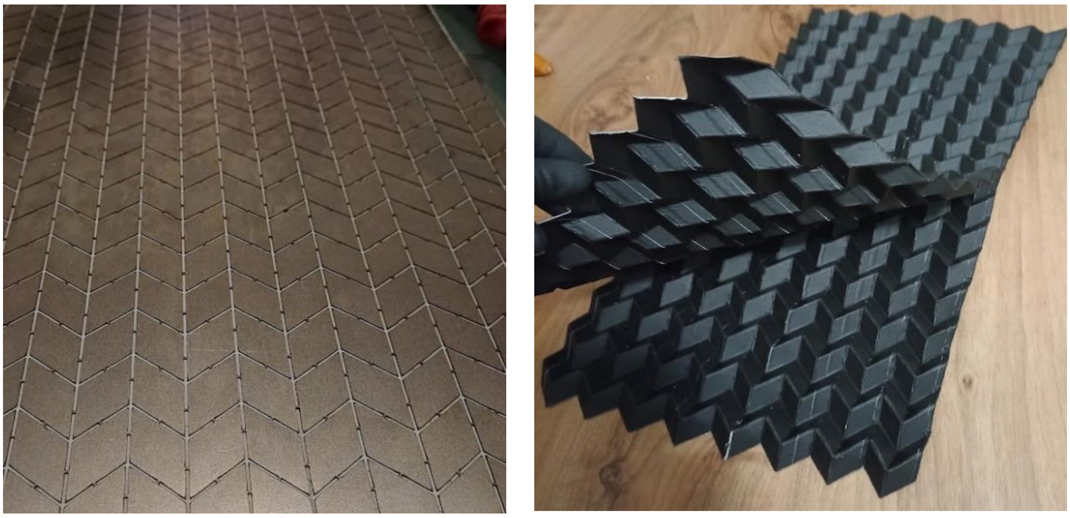


Figure 50. ***a)*** *Sheet of 0.5 mm thin laser cutted parallelograms*
b) *Two Miura-ori mats made from steel and duct tape*

The parallelograms were laser-cut from 0.5 mm steel sheet. To keep the parallelograms intact together and to ensure that the spacing of them is even, 1 mm thick and long bridges were designed in between the parallelograms (Figure 50a).

After the strong duct tape was applied, the structure could be folded. The 1 mm wide metal bridges helped in folding of the structure because unlike paperboard the bent bridges did not fold flat, instead they held their folded shape. This of course meant that the whole structure required lot of force to fold and unfold. But after few back and forth folds the bridges eventually fatigued leaving small burrs. Those burrs can be felt trough the duct tape, but they didn’t pierce it.

5.12 Ideas for material pre-treatment

These ideas are modifications to the whole process and not just the folding part, so they complicate the manufacturing process a bit, but they are very potential methods as well. I listed them separately unlike any other ideas during the development process because they can be implemented for all folding methods and not just some specific prototype.

5.12.1 Cuts on the critical corner

Since the greatest elongation of the material occurs at the corner point of the Miura-ori pattern, making it the point which would most likely rupture, it would seem logical to get rid of that part of the material. Basically, rupture is the same as a cut hole in the paperboard, but the difference is that cut can be clean and still offer great design features unlike uneven and unprecise rupture. In Figure 51 is a Miura-ori pattern which corner points have been cut off after the folding.

Figure 51.Miura-ori pattern with cut corner points

The holes would have to be cut to the sheet material before it undergoes the folding stage presumably with same kind of rollers that are used to make the mountain cuts. The challenge comes from synching all the process phases, so the corner points form to the cut area. If pre-cutting is used as a manufacturing method, it has to be synched anyways, so hole cutting phase doesn't add much complexity to the whole process in that sense. Although the waste management of the cut off corner points might do that.

Cutting the corner point open might also improve the malleability of the folded structure. The corner points are one of the first areas to break when the folded structure is curved over the limitations of the paperboard. Cutting the corners could allow the structure to bend more but they could also provide starting point for fractures to form.

Although, that is not necessarily a disadvantage because if the material is going to be teared up anyways, it might as well do it uniformly in predefined regions. To further develop this kind of planned rupturing, a much larger area could also be removed from the structure. For example, cutting open half of the folds would allow the folded structure to bend more easily over tight curves.

Cutting the corner points also offers more variability to the Miura-ori structure in the designing point-of-view.

5.12.2 Re-wetting the paperboard

While testing the roller nip prototypes, I also tested re-wetting the paperboard for better mouldability. Re-wetting the paperboard makes it softer and therefore it might not fracture so easily. It would mean that the process becomes more complex since the paperboard has to be re-wetted, processed and dried before packing. To test this idea, I quickly submerged a piece of paperboard to water and ran it between some of the roller nip prototypes to see how it reacts. The paperboard did indeed become softer and easier to force to take shape without rupturing it, so the re-wetting did impact on the critical elongation of the material.

Figure 52. Test of dry and wet paperboard samples ran through roller nip prototype 5

Best result I got with the roller nip prototype 5. In Figure 52 is a sample of dry paperboard on the left which is tore along the MD as expected but the wet paperboard on the right was not. The wet sample had also much clearer folding marks on it than the dry sample. All though the re-wetting helps, the structure was not able to fully fold just by pressing from the sides.

Even though the sample was not perfect, I think this experiment proved that re-wetting the paperboard improves it mouldability under some roller nips. Samples from failed experiments can be seen on Figure 53. The geometry of the rollers has to be optimized to not damage the re-wetted samples.

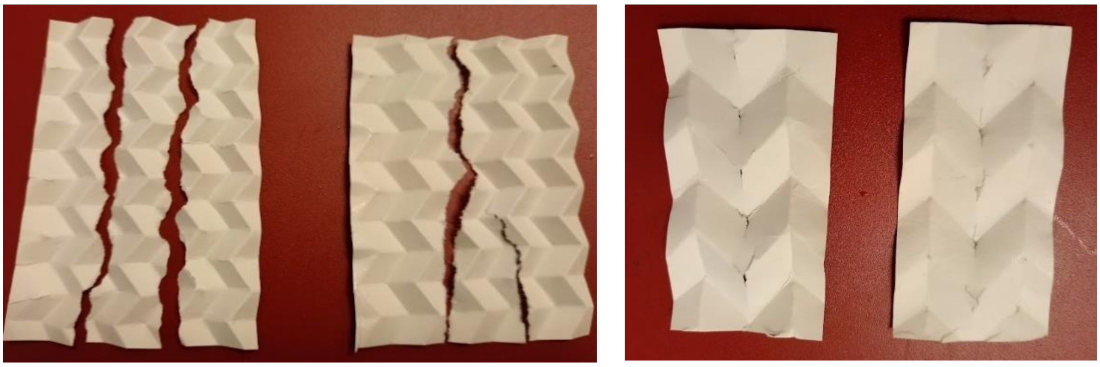


Figure 53. ***a)*** *Tests with roller nip prototype 2* ***b)*** *Tests with roller nip prototype 4*

I tested the method with second (shown in Figure 35) and fourth (shown in Figure 37) roller nip prototypes as well but those didn’t work as well as the fifth roller (shown in Figure 38). The second roller nip made brutal aftermath from both test samples and the fourth roller nip punctured both of the samples as well.

6 Results

In this section, the final conceptual design is presented. That is because any further developments for the needed mechanics will be new technology and therefore publishing them in this study would prevent the possibility to patent them later. I will also explain how to use the final design and review the samples it makes.

6.1 Folding device concept

The final version of the folding device consists of two mats which were made from laser-cut 0.5 mm thick steel sheet and black duct tape (Figure 50b). They can be though as foldable moulds and as far as known those have not been used to fold paper, paperboard nor any other more durable materials.

The concept isn't completely new because somewhat similar foldable moulds have been used to make patterns into textiles. It is called pleating, and in that method, the textile is places between folded moulds, which have been made from paperboard or similar material that can withstand steam. The textiles do not resist at all so the folding process is really easy. The moulds are fully folded and then steamed which makes the folding lines permanent to the textile (Nguyen, 2020).

Therefore, this technique cannot be said to be new technology although it is applied for new materials. However, addition and development of mechanical operation will create a unique machine. The material of the foldable moulds has to be significantly stronger than the folded material in order this method to work.

6.2 Operation of the folding device

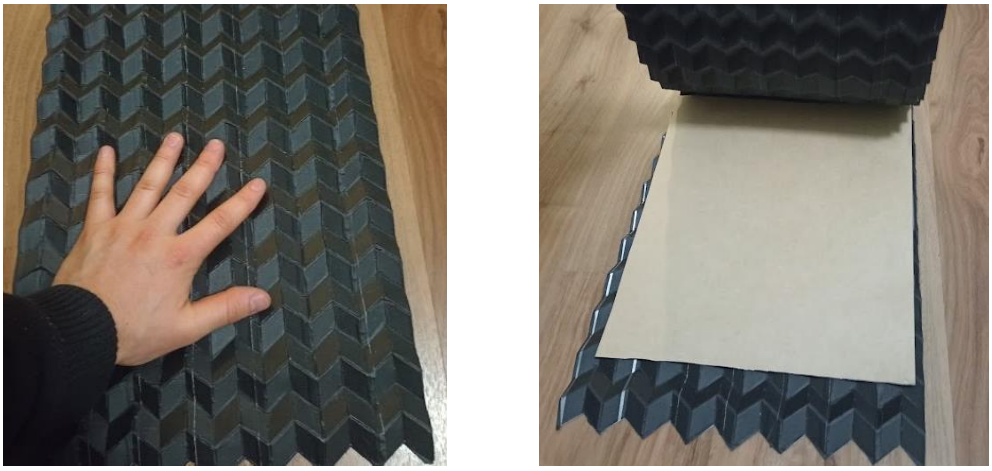


Figure 54. The foldable mats are spread as flat as possible. Then the material is placed between the mats.

The mats are spread flat to ease the material to take its place in the valleys. After that the material is placed between the mats (Figure 54). Tape can be used to keep the material still if needed. This is probably necessary if the mountain folds are pre-cut, and the material has to be a lined.

Figure 55. Fingers are used to push the valleys in from one end towards the other

After the first pushing (Figure 55) of the valleys was done, the material was bit more correctly aligned and possibly started to take some shape. The mats could be even stepped on to apply more force.

Figure 56.Fingers are used to push down the valleys from one end towards the other and at the same time the pattern is squeezed gradually

The folding had to be performed gradually (Figure 56). If other end of the mats was squeezed completely while the other end was left without pressing force, the mats separated, the material moved between the mats and ruptured. If more supporting hands were available, the valleys could be pushed down while one made the gradual squeezing. Small samples such as 15 cm x 15 cm can be done fairly easily with only 10 fingers but the bigger the sample the harder the folding process becomes.

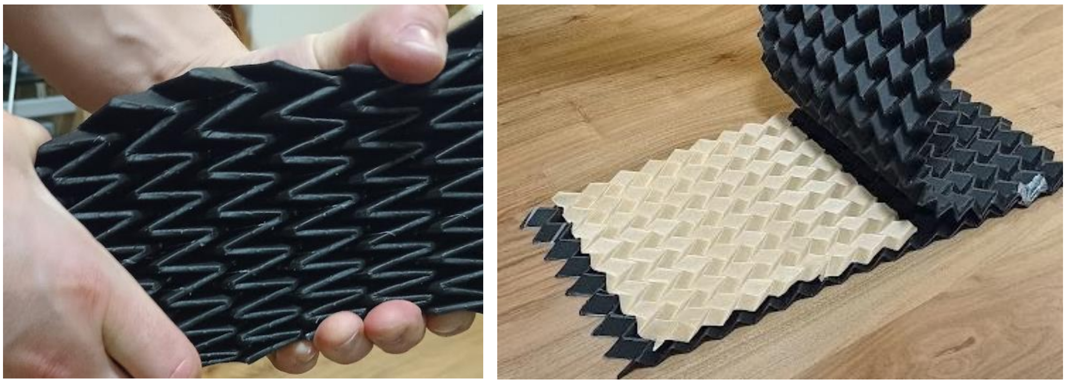


Figure 57. At the end, the mats are squeezed as hard as possible to the fully folded form

When material folding has begun and the user feels that pressing force is no longer needed, the mats are squeezed as hard as possible (Figure 57). After this process, the material was at stable Miura-ori pattern. The structure was post-processed by folding it to the fully folded form without the mats (Figure 58) to make the folds as sharp as possible.

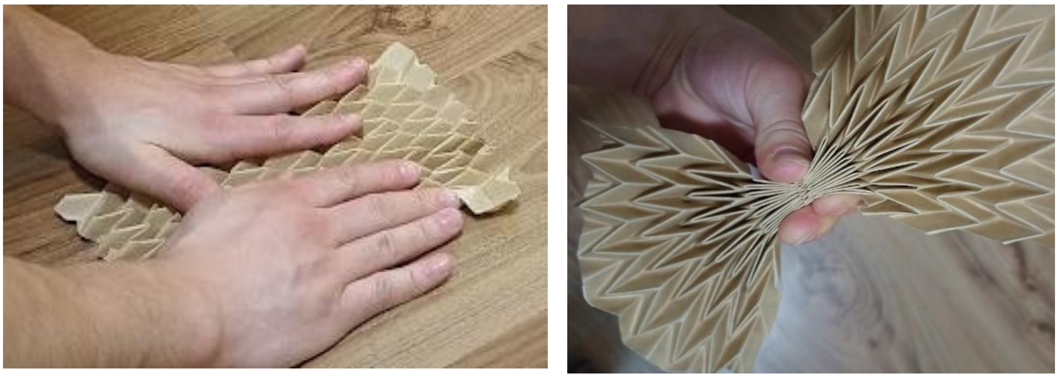


Figure 58. Final finish is folding the structure to the fully folded form without the mats

Automating and mechanising the presented folding phases makes the hand operated device into a machine. Those mechanical solutions are not presented in this study.

6.3 Samples made with the final design

The Miura-ori samples made with the final design were in overall successful. The folding process was fast compared to folding only by hands. Smaller samples such as 20 cm x 20 cm were easier and faster to fold than larger 20 cm x 50 cm samples, but all samples could be made in 1-2 minutes depending on the experience of using the folding mats. Successful samples require careful folding process, and the method is relatively easy to learn.

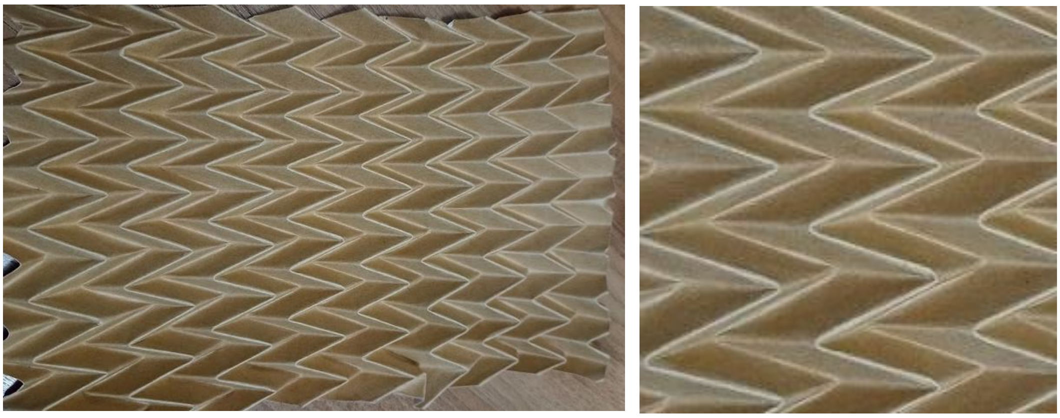


Figure 59. ***a)*** *Sample of 23 cm x 32 cm paperboard folded with the final design* ***b)*** *Close-up photo of the mountain folds which are 22-24 mm in length*

Figure 59a shows the results of the folded paperboard structure made with the final design. Folding was easy because the material was quite thin and did not resist the folding. After the structure is folded to the fully folded form without the mats, the folds became sharp. Some minor faults can be seen on the edges of the sample, but the result overall was quite good. The mountain folds are 22-24 mm long which may be visible from the Figure 59b so the geometry of the structure is not totally uniform but still adequate.

Figure 60. Three 20 cm x 20 cm samples made from 170 g/m^2 paperboard in transverse pattern orientation

Figure 60 presents three 20 cm x 20 cm samples made from 170 g/m^2 paperboard sheets which have been folded in TPO. All three samples were successful which indicated the repeatability of the process. In Figure 61 are similar samples made in LPO. The pattern orientation did not affect the foldability as much as expected but one of the samples folded in LPO did rupture on the corner point. The folding process for 170 g/m^2 paperboard was more difficult and required more pressing of the mats compared to the thinner material in Figure 59. However, the sample size was still quite small, so it did not cause too much trouble.

Figure 61.Three 20 cm x 20 cm samples made from 170 g/m^2 paperboard in longitudinal pattern orientation

Figure 62a presents the unsharp folds of the mountains of the 170 g/m^2 paperboard sample immediately after the folding process with the foldable mats. On Figure 62b can be seen the sharp folds after the sample has been folded to the fully folded form without the mats. The difference was quite clear so it can be stated that post-processing is necessary or at least preferable.

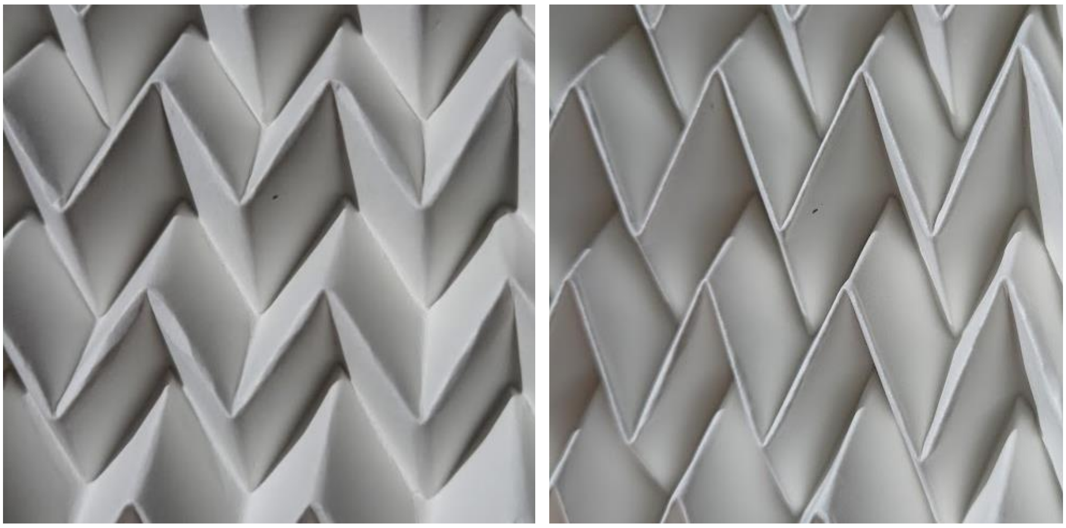


Figure 62.Close up photos of a 170 g/m^2 paperboard sample ***a)*** *right after the folding process with mats.* ***b)*** *after the fully folded form without mats*

Figure 63. Few defects of the previous samples ***a)*** *Unsharp folds at the edge of the sample* ***b)*** *Small rupture in the corner point* ***c)*** *Unsharp folds and uneven mountain lengths*

Figure 63 presents the defects that occurred in the 20 cm x 20 cm samples. The flaws were only cosmetical and did not probably affect the mechanical properties of the samples. Despite the final design was not suitable for finished product manufacturing nor was it the original 10 mm target size, it could be used to test the impact resistance of Miura-ori structures in laboratory.

Unsharp and uneven folds were found only in few Miura-ori cells, and they were usually located at the edges of the sample. The small rupture of the corner point in Figure 63b occurred only in one corner point of one sample which was folded in LPO. In LPO the corner point is more prone to rupture due to the smaller elongation of paperboard in MD than in CD. The flaws did not occur in all of the samples, and they were usually due to the impatient folding process.

Figure 64. 20 cm x 50 cm samples made from 170 g/m^2 paperboard. The two samples on the left were made using re-re-wetted paperboard and the sample on the right was made using dry paperboard.

In Figure 64 are larger samples made with the same 170 g/m^2 paperboard. The sample on the right is made with 20 cm x 50 cm dry paperboard, the one in the middle is 20 cm x 50 cm re-wetted paperboard and the one on the right is made from 30 cm x 50 cm re-wetted paperboard which is the largest sample that can be made with the final published design.

The re-wetted paperboard was a lot easier material to fold compared to the dry paperboard. The re-wetting was done by quickly running the sample under a faucet and shaking of the excess water. Even though the sample size was larger, the re-wetted paperboards were easier to fold than the 20 cm x 20 cm dry paperboard samples. The weight of the foldable mat provided enough force to push in the valleys and to keep the re-wetted paperboards in place so all effort of the folding process could be focused on the gradual folding of the mats and not to the pressing of them.

*Figure 65.Close up photos of folded **a)** dry paperboard **b)** re-wetted paperboard*

Figure 65a presents the mountain folds of fully folded dry paperboards sample. In Figure 65b can be seen the mountain folds of the re-wetted paperboard after it has been fully folded and dried. The difference may not be that clear to see from the figures but the folds in the re-wetted sample were sharper than in the dry sample.

7 Discussion

At the start of this thesis project, I thought that designing a machine to print out folded structures would be quite easy. The only design I had in mind was the roller nips and it seemed to be a no-brainer to make such a machine. Little did I know about the behaviour of the material the machine was supposed to handle. One important thing which I learned, again, during this thesis project was that rapid prototyping is really important when it comes to product designing. Only with rapid prototyping I was able to really figure out the nature of the material and how it actually behaves. All kinds of measures and tests can be done to test different materials, but a designer has to know how the material behaves and only measured numbers do not tell you that. Now it feels kind of silly to think about the idea of paperboard which I had in my mind in the beginning of the project. It was much more durable and elastic than it is in reality. As a designer it is important to get hands-on experiment of the material that you are dealing with and if it is cheap, destroy it as much as you can with different prototypes. Only by doing something wrong a dozen times you learn how to do it right.

The main object of this study was to develop a process to enable repeatable manufacturing of the Miura-ori pattern for laboratory testing quantities.
I think that the final published prototype of this study was able to fulfil this criterion because it could be used to make samples fast and with adequate repeatability. All though I would not call the final prototype a machine but rather a tool, because it requires some skills and user experience to operate.

In order to test the mechanical properties of the paperboard structure, the final prototype was sufficient enough. I still think that the development process needs to be continued to improve the visual appearance of the folded pattern and to enable the machine to finally produce smaller 10 mm Miura-ori structures as originally intended.

The idea of re-wetting the paperboard before the folding process proved to be very successful and I think it has a great potential to improve the foldability of any paperboard even though the re-wetting and drying procedure complicates the overall manufacturing process.

The final published design cannot be considered as new technology because similar synchronized methods have been used to make folds in textiles. However, if the tool is further developed and automized, the designed machine could be stated as new technology. I cannot address the features of such machine in this study even though I would like to explain the development process for that as well because I am quite proud of it.

Further development could be a kind of fusion of all the prototypes I have made so far, cherry picking the best properties of each prototype and leaving the disadvantageous properties out.

As the Fold project continues to research and develop packaging material from paperboard, in my opinion it would be more valuable for the partner customers and end customers if the focus is shifted to making more specially tailored origami structures. Miura-ori pattern sure is nice and certainly it has its value especially in the future when it can be mass produced, but the world of possibilities that open up if the pattern is varied just a bit is much larger. The origami patterns can be made so it can be wrapped around cylindrical or round objects such as wine glasses, plates, vases, crystal balls or whatever. Making foldable moulds for such complex patterns wouldn't require anything else than plywood and some duct tape even though the automation of different origami geometries might be a lot more difficult.

During this thesis project I learned lot about origamis in general, not just about Miura-ori. The possibilities that origami structures have is incredible. Origami is many times considered as birds folded from paper, but it is in fact much more. As a mechanical engineer, I can think of many applications where principles of origami folding can be used. Their speciality comes from the dynamics and the space saving foldability of the structure, not to forget about the design aesthetics. Could you imagine a whole concert venue which is one big dynamic structure made from steel, panels and hydraulic actuators?

8 Conclusions

The main object of this study was to develop a process to enable repeatable manufacturing of the Miura-ori pattern from paperboard for laboratory testing quantities. The study was done by researching patents and previous studies on folding machines that have been used to make similar origami patterns. After that, the methods in question were applied and tested for 170 g/m^2 paperboard and their suitability was evaluated, after which the process methods were modified to be more suitable for the paperboard through iterative product development.

The most important observations related to material were that the 170 g/m^2 paperboard strongly resists folding and at the same time is a material that tears easily. Because of this property, the methods used in the patents were largely not suitable for folding paperboard in the same way as they are suitable for folding metal sheets or composites. However, folding the paperboard could be made easier by cutting the tops of the folds open and softening the paperboard by moistening it. In this case, the folding resisting property of paperboard disappeared, and the paperboard became easier to mould.

Due to the easily rupturing material, methods like pressing mould and roller nips which used excessive pressing force to make the folding to the paperboard were not suitable. Those methods did not allow the material to fold freely but rather forced the material to take shape by elongating it eventually causing the material to break.

Synchronized folding method on the other hand proved to be very successful largely because it allowed the material to fold more freely. In synchronized folding, stresses which might strain the material, do not form because there are no unfolded and folded areas on the material at the same time.

With the synchronous folding tool developed in this study, the folding time Miura-ori samples reduced significantly. Folding of 20 cm x 30 cm sized sample by hand might take hours but with the folding tool it could be done within minutes. In addition to that, a sample without pre-cuts is almost impossible to fold by hand which the tool is able to make without problems. The folding process was also repeatable even though it requires some skills and user experience.

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