INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

INNOVATIVE DESIGN OF CULINARY MOULDS BASED ON CRUMPLED PAPERS

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Keywords: ecodesign, packaging, crumpling, food industry

1. Introduction

Paper is an inexhaustible source of innovations in a wide variety of industrial sectors. In the packaging domain, paper and paperboard are accounted as the largest share material with 38% of the market [WPO 2008]. Based on agro-resources, paper is biodegradable and recyclable, and paper making industries made many efforts to improve the environmental impacts of their technologies [Xu 2013]. In a global sustainable context, products based on paper can potentially be considered as environment-friendly products. The example of flexible packaging falls in this category. It uses the least amount of material compared to other forms of packaging, and adds little weight to the product. Based on these advantages, it is considered as the Perfect Fit in the Flexible Packaging Europe report [FPE 2011].
From writing support to packaging, many technical features have been conferred to paper to achieve basic or complex services. In the food industry for example, new properties have been developed to adapt the material to foodstuff contact. A paper can be greaseproof, a barrier to heat, a barrier to water, increase the shelf life of foodstuffs or simply aims at transporting food. Depending on the industrial context, packaging can be subdivided into three categories: primary, secondary and tertiary. Primary packaging is the term used to designate the layer of packaging in immediate contact with the product, and flexible packaging accounts for over half of the volume share of the primary packaging in the global packaged food market. Secondary packaging designates the packaging used to group various pre-packaged products together, it is intended to protect not only the product, but also the primary packaging. For mass market products, the secondary packaging is the one that is most visible to the consumer in retail displays. Tertiary packaging is a transit container designed to facilitate handling secondary packaging and prevent them from transport damage. Paper and its derivatives (paperboard) constitute the most common shared materials to achieve primary, secondary and tertiary packaging ie containing, portioning and transporting functions. However, the potential of paper has not been fully explored. It remains niches particularly in the field of origami to design powerful packaging with new functionalities. The origami techniques have especially been explored for artistic purposes but the power of folding contains much more possibilities by relying on its basics through crumpling actions. This paper argues that a structured crumpling process aims at the design of dynamic flexible structures with innovative applications in the packaging domain.
An answer to innovative packaging is proposed in this paper by exploring the potential of crumpled structures in the food industry. The pastry sector is chosen to create a new generation of moulds. The design process begins with the functional modelling of pastry moulds. Then, a functional comparison between existing moulds defines the sphere of actions to address non-existent or poorly performed functions. Some propositions of crumpled baking paper moulds (CBPM) are proposed to fulfil these functions. They are described with experimental tests to prove their operational efficiency. Finally, a discussion defines the limits of CBPM in terms of environmental and industrial view points, and a

conclusion identifies complementary studies for a better understanding of crumpled structures in the packaging domain.

2. Folding vs crumpling

2.1 Folded structures

In the everyday life, everyone has experienced the folding of a letter to fit in an envelope. The mechanical principle consists in superposing faces of a flexible sheet in order to reduce its surface footprint. Based on this concept, automated machines have been designed to manipulate paper at a very high speed, allowing the design of folded objects for mass market products. The way to fold a flexible sheet can be extended to create three-dimensional structures. The design of packaging falls in this category. From a flat layout, an ordered sequence of folding actions allows the design of structured 3D packaging [Mullineux 2010]. For example, the paper cupcake shown in Figure 1is the result of a forming process of a sheet between two fluted matrixes (Figure 2) where the folding sequences are performed at the same time. The process is automated and fast, it perfectly meets mass market products requirements. However, some might consider disadvantages due to the obligation to create each fold, which could be considered as a brake on innovation.

Figure 1. Paper cupcake

Figure 2. Industrial fluted matrixes

2.2 Crumpled structures

2.2.1 Crumpling principle

Crumpling is a common action experienced by everyone when someone wants to create a crumpled paper ball. By confining a paper sheet between his hands, the flat sheet becomes a three-dimensional structure (Figure 3). This process confers mechanical properties which can be extended and used by the packaging industry for cushioning applications. The principle consists in confining a flat paper sheet between two mechanical rolls, the resulting object is a three-dimensional structures with elasticity properties to protect a product in a package during its transportation (Figure 4). By comparison to a folding process, crumpling has the advantage to produce random creases considered as unique, but this property is not consistent with mass market products.

Figure 3. Crumpled paper ball

Figure 4. Cushioning application

2.2.2 Structured crumpled structures (SCS)

A structured crumpling process offers a solution to reproduce ordered crease patterns which are consistent with mass market products. Inspired by Paul Jackson's definition of basic crumpling methods [Jackson 2011], crumpling is derived of the origami folding techniques [Yoshizawa 1954]. It consists in a systematic self-generation of folds organized in a structured network. This technique has been using and developing since over fifteen years by the CRIMP research team for artistic purposes (figure 5). All those crumpled objects have been created with no glue. CRIMP creates organized crease patterns very similar to those observed in nature [Floderer 2007], [Floderer 2008], [Mérat

2010], the resulting biomimetic models are flexible and dynamic, they consequently can open new alternatives for packaging applications.

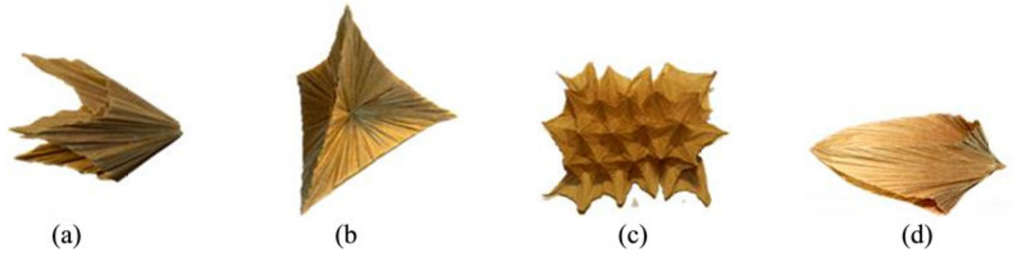


Figure 5. Structured crumpled paper sheets, CRIMP © 2013

Preliminary studies [Rohmer 2013], [Rohmer 2014] highlight some fundamental crumpling tasks in the design process of structured 3D crumpled objects. Concentric pressure and reversal of surface constitute the two basic actions which are operated in an iterative manner to confer elasticity in the structure. The resulting object is dynamic and robust as for example the tetrahedron respectively shown in Figures5a and 5b in its folded configuration and in its operational configuration. Those photos express the ability of a crumpled object to be folded in a minimum of space in order to reduce its transport cost before to be used. Figure 5c is a regular network of radial crease pattern, its configuration could be used as a tray to separate products, moreover its elasticity can fit different sizes of products, it can be considered as a standard adaptable tray. The last example shown in Figure 5d represents an inflatable object made of a unique square paper sheet, without cutting or gluing processes, it could be used as a primary flexible packaging.

Due to the complexity of the food industry, a restricted area must be chosen to explore the potential of SCS. Based on the feedback experiences of CRIMP members, some requirements can be listed. First, SCS are created by hand, the industrial sector should concern handworkers. Second, SCS are inspired by nature, their shapes should be related to the product for which there are associated. Third and last, SCS should be made of food contact materials [UE 2004].

The bakery sector meets all the requisites. It is a traditional area where the most part of companies are bakers and pastry cooks artisans. The foodstuffs are based on agro-resources (fruits, cereals, etc.) which are perfect models for biomimetic objects. Finally, paper is often used in bakery such as kraft alios paper, wax paper, baking paper, greaseproof paper.

3. Crumpled structures for the food Industry

3.1 Context and objectives

3.1.1 Bakery sector

The bakery sector is chosen to test the potential of SCS. The objective is formalized as follows: identify the strengths and weaknesses of structured crumpled structures (SCS) in the bakery sector by comparison to existing food contact packaging.

Based on this objective, a restriction can be stated on the panel of packaging. The study will focus on products used for the baking process and the delivery of the pastry to the customer. The generic term of "mould" will serve at their identification.

The use of moulds is a common practice to cook a product in conventional or microwave oven as well as in freezer. Depending on the context (industrial or household use), a mould can mutualize several functions at the same time (contain, protect, etc.) or be used for only one of them. Different categories of moulds can be listed: cookie cutter (Figures 6a, 6c), cookie stamper (Figures 6a, 6b), container (Figures 6d, 6e).The professional rotary mould shown in Figure 6a mutualizes the cutting and stamping functions, and the moulds for household use shown in Figures 6d and 6e (aluminium square, silicone) mutualize the containing and molding functions.

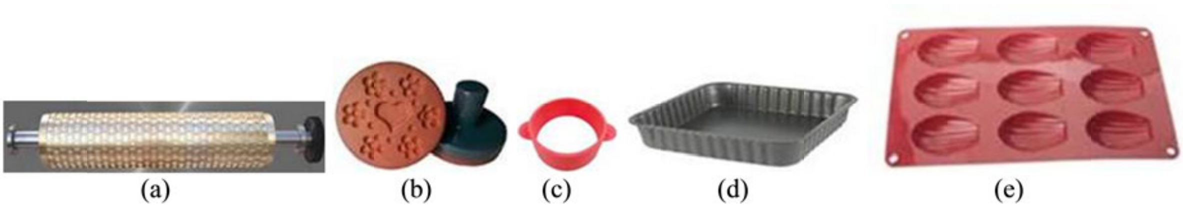


Figure 6. Moulds

The materials of the moulds are chosen depending on the context of their use (professional or household) and on the way they will be subjected to cooking constraints (temperature, pressure, water, etc.). Based on our previous arguments, silicone moulds are flexible and fall in our requirements, it serves as a referent packaging to compare our proposition made of crumpled culinary paper moulds.

3.1.2 Silicone moulds

Flexible moulds made of silicone are widely appreciated because of their ability to be reusable up to 1600 bakings and more, and their ability to unmold a large variety of foodstuffs. They are advertised as non-toxic, chemically inert, resistant to UV and supporting temperature up to 250°C. Silicone is produced from a polymerisation process which needs catalysts to accelerate the chemical reaction. The migration of chemicals is consequently possible and has been proved [Halling 2012], [Elskens 2012]. Based on the Directives 93/8/CEE, 97/48/CEE, the overall migration limit (OML) from silicone must be less than 10mg/dm² or less than 60mg/kg of foodstuff. Recommendations to limit volatile organic compounds (VOC) are also defined and are limited to 0.5%.In terms of recyclability, silicone could be recycled, but due to the lack of appropriate collecting and recycling channels, they must be disposed of with household waste.

3.1.3 Culinary papers

A recent work (will be next published) proves that culinary papers have the ability to be crumpled. Experimental tests performed on kraft alios paper, baking paper, wax paper and greaseproof paper show that the crumpability (ie ability to be crumpled) is defined by a triple Cr(Shi, Cpi, Sri), where Shi is the ability of the material i to create a 3D shape, Cpi is the ability of the material i to contain a permanent structured crease pattern, and Sri is the ability of the material i to recover its shape after being stretched. Mei, Cpi, and Sri can independently take the qualitative value G, M or B respectively Good, Medium, Bad depending on respective thresholds. The final scores of the crumpability for each material are: Cr_{alios}(G,G,M), Cr_{baking}(G,B,G), Cr_{wax}(M,M, B) and $Cr_{greaseproof}$(M,M,M).
By matching our requirement for the bakery sector (ability to be heated), only baking paper could achieve the functions of silicone moulds. It is chosen as our referent material to create crumpled moulds.
Note that there are some existing moulds made of baking paper. A company [Bio Food Pack] produces for example circular and rectangular baking paper moulds with the following specifications: biodegradable mono-material, resistance to humidity, resistance to high temperature (up to +200°C), greaseproof, freezable, resistance to shocks, no odor before and during baking, respecting flavour of the food (Figure 7). These moulds are considered by the manufacturer as the moulds substitution in aluminium cooking.


Figure 7. Circular and rectangular baking paper moulds

As illustrated in Figure 7, the shapes of the moulds are conventional. They have the advantage to be used for a large variety of recipes, they have been designed to carry out two functionalities: baking mould as well as tray for a presentation on the dining table.
Based on the existence of baking paper in the food industry, and because it is a material with a good crumpling ability, our assumption is that baking paper can create complex crumpled baking paper moulds (CBPM) to compete silicone moulds.

3.2 Design of crumpled baking paper moulds (CBPM)

3.2.1 Methodology

Our objective is first to prove that CBPM can achieve the same service as silicone moulds and existing baking paper moulds, and second to prove that CBPM brings innovative added value by comparison to other moulds.
In this context, all the conditions are present to apply value analysis as a design method [Heng 2010]. The functions of a CBPM are defined depending its life cycle and depending on the relationships with its environment. The life cycle of a mould and its functions are:

- Transportation: contain foodstuff, maintain foodstuff's form, transport foodstuff, is foldable, is extendable, resist to shocks,
- Use
    - Preparation: contain foodstuff,
    - Baking: confer form/shape/mark to foodstuff, resists to heat/cold, transfer heat/cold to foodstuff, doesn't allow migration, doesn't emit VOC, doesn't emit odors,is a barrier to grease, is a barrier to water, is a barrier to heat/cold, resist to shocks,
    - Unmolding: easily unmold the foodstuff, resist to shocks,
    - Presentation: is aesthetical for customer (presentation at dining table, for sale),
- Maintenance: can be washed, resists to dishwasher, resist to shocks,
- Recycling: is reusable, is recyclable
- Disposal: is biodegradable.

The above functions are listed in Table 1 in order to describe the services (or constraints) achieved by silicone moulds and existing moulds.

3.2.2 Comparative analysis

Table 1 describes the technical solutions to achieve the functions of a mould. Examples of silicone and baking paper moulds are illustrated.
Silicone offers the advantage to be more flexible than circular or rectangular baking paper moulds. This property allows a rapid access to the foodstuff, and allows the creation of concave three-dimensional objects. Another advantage is that they can be reused up to 1600 times, while baking paper can only be reused maximum 10 times.
Based on the differences between silicone and baking paper, CBPM could find an opportunity to innovate. The two principal functions a CBPM could achieve are: contain foodstuffs with multiple capacity and create convex 3D shape. The first function allows CBPM to give the same service as silicone for multiple capacity. The second is a new functionality that are not achieved by both silicone and existing baking paper moulds.

Table 1. Functional comparison: silicone moulds vs baking paper moulds

Functions	Criteria	Silicone moulds	Existing baking paper moulds
contain foodstuff	unique capacity		

	multiple capacity		no
confer form/shape/mark to foodstuff	concave 2D Form	 cookie cutter	
	convexe 2D form	 cookie cutter	
	concave 3D shape		 only for cupcake / cake
	convex 3D Shape	no	no
	Mark	 cookie stamper	 fluting
maintain foodstuff form	yes/no	yes	depends on the food
transport foodstuff (resist to the pressure of the foodstuff)	resistance	yes	depends on the weight of the foodstuff
resists to heat/cold	temperature	min =- 20°C max = 200°C	min =-20°C max =200°C
transfer heat/cold to foodstuff	thermal conductivity (W/m.K)	transfer	important transfer
doesn't allow migration	OML limit	OML < 0,5%	no migration
doesn't emit VOC	% of VOC	<0,5	doesn't emit VOC
doesn't emit odors	odors panel	depends on 1rst use	doesn't smell
Is a barrier to grease	yes/no	yes	yes
Is a barrier to water	yes/no	yes	yes
Is a barrier to heat/cold	yes/no	no	no
easily unmold the foodstuff	flexibility	possible reversal of surface	possible reversal of surface
is aesthetical for customer (presentation at dining table, for sale)	yes/no	no	
can be washed	washing quantity	1600 times	<10 times
resists to dishwasher	yes/no	yes	yes but cautiously
can be reusable	quantity of reusability	1600	maximum 10
can be extended	% extension	no	only for cupcakes
resist to shocks	yes/no	yes	not evaluated
is recyclable	% recyclability	0%	100%

3.2.3 Creative CBPM

A large variety of silicone moulds inspired by nature can be found (Figure 8) but their form/shape are rudimentary. One creative idea has been proposed by the world champion pastry Christophe Michalak in his recipe untitled "chocolate egg in its cabbage leaf". It is based on the moulding process of a chocolate paste (Figure 9a) between two cabbage leaves (Figure 9b). The resulting pastry looks like a real leaf (Figure 9c), but some disadvantages can be listed. It is impossible to have cabbage leaves in all seasons, the availability of the pastry is then limited. The creativity of the pastry is conditioned by the size of the leaf and the structure of the pastry is limited to the real form or shape of the vegetable, preventing to design attractive objects in a competitive market.

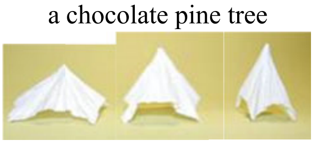
Figure 8.Moulds with vegetal forms

(a) (b) (c)

Figure 9. Vegetal mould

Opposite to those previous examples, CRIMP designers are able to create 3D structures inspired from nature (Figure 5) and can achieve at the same time industrial requirements. As defined in Table1, crumpled structures can contain, portion, confer form/shape/mark. The following CBPM are simple experimental moulds used to cook chocolate and dough for cakes.

Table 2. Creative CBPM

Types	Functions	CBPM		Resulting foodstuffs
		Description	Usage	
mono mould	confer form/mark	a radial crease pattern (from a square baking paper sheet) to create a crumpled chocolate cup	 chocolate on mould	 Fruits in chocolate cup
		 radial crease pattern	 mould in a cup	 cake
	contain, confer complex 3D shape	3 sizes of a radial pattern (from the same square paper) to create a chocolate pine tree 	 chocolate in mould	 chocolate pine trees
multiple mould	contain, group confer form/shape/ mark	4 regular radial patterns to create a chocolate multi-cups  folded unfolded	 chocolate on mould	 fruits in the chocolate multi-cups
		 16 regular radial patterns to create cookies	 before cooking	 16 cookies

3.2.4 Qualitative analysis

The tests have been performed with popular foodstuffs: chocolate and dough for cakes (mixing flour, eggs, sugar, etc.). They have the advantages to be available everywhere and packaged in various forms at different prices, allowing a suitable choice for professional or household use. The tests can be reproduced and performed with simple equipments (pan, spoon, cooker), the recipes are elementary. For chocolate recipes, the CBPM doesn't need to be heated, it acts as a container and maintains chocolate during cooling. The ability of the baking paper to be heated is only used for the cakes.
The first feedbacks of the experiments give both advantages and disadvantages. First, Figure 10 shows a mould vertically maintained by a glass during the cooling of the chocolate. The glass acts as an additional equipment to maintain the mould, unlike a multiple mould is stable due to its multiple contacts with a support (plate, table, …). The unmolding process is also a disadvantage, it must be meticulous to not damage the chocolate, and pieces of chocolate can stack in some creases of the mould, preventing its reuse. However, if the mould is washed (Figure 11), it can be reused. In the case of dough for cakes, the cake can also get stuck in the mould if it has not been previously oiled.
The main advantage of CBPM is its ability to create new forms and shapes. The examples of chocolate cups (unique or multiple capacity) and chocolate pine tree shown in Table 2 are three of them. The chocolate tree uses the ability of a CBPM to be flexible. Three different parts have been done with the same mould, and their assembly represents a pine tree. The chocolate cup shown in Figure 12 illustrates the ability of CBPM to create biomimetic shapes like leafs or vegetal hulls.

Figure 10. Additional equipment

Figure 11. Dirty mould, washed mould

Figure 12. Creases

Note that the experiments have been performed by non-professional cooks, and the moulds are made of basic radial crease patterns. Those examples prove the usability of crumpled structures and can be improved by changing their shapes and the way to use them with other foodstuffs.

4. Discussion

The CBPM presented in this paper prove the feasibility of crumpled structures applied in the bakery sector. Nevertheless, convex CBPM has not been fully proved, the pine tree example results from three moulds, new propositions must be made to respect product based on single component to simplify the process. Even if the operational feasibility is proved, the technical usage of CBPM must be thorough by defining a protocol to test various foodstuffs (sugar, caramel, …). A proposal will be next engaged with a training center for apprentices (CFA) in the bakey sector and cuisine. The moulds will be developed based on the CFA needs and feedback will serve at a better characterisation for industrial implementations. Note that new opportunities can be open by exploring the use of edible sheets subjected to crumpling procedure. The competitiveness of CBPM should also be considered by comparison to other technologies. 3D printing is one of them, this technology offers the opportunity to design 3D objects and could print complex flexible moulds or foodstuffs, unfortunately the technology is not yet available. On the other hand, the main advantage brought by CBPM is that designers do not need additional resources or automated processes. Culinary papers are already used by professionals and the handcraft process doesn't need technical means, while 3D printing needs machines, compatible 3D software and 3D models. The resulting investment is too important for artisans and can be considered as incompatible with artisan principles.

5. Conclusion

The development of flexible packaging is an important purpose for the culinary sector. To accompany this trend, a new folding process is presented in order to design experimental flexible moulds (CBPM). The resulting structures can compete with available moulds on the market, but some restrictions can be expressed in terms of technology transfer. At the current level of development, only artisan production can be considered. The handcraft process used to create CBPM is viewed as an added value for luxury production, but is a lock for mass production. For this purpose, new investigations are already undertaken and will be next proposed, they concern the crumpling ability of materials and the development of automated crumpling machines. Based on these information, complementary projects on the environmental performances of CBPM will be conducted. The environmental studies will assess the environmental impacts by comparison to existing moulds. The French academic EcoSD network (Ecodesign systems for Sustainable Development) supports the researches on this topic.

Acknowledgement

Thank you to Alain Giacomini who gave his authorization for the publication of his origami models shown in Figures 5a, 5b and 5d.

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