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Crumpling feasibility of flexible paper sheets. Application to packaging in the food industry

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Abstract Flexible packages are considered as the most-reduced form of packaging in terms of environmental performances. In order to contribute to their development, this paper proposes to explore some mechanical properties brought by a new folding process that confers elasticity to flexible materials and consequently new environmental advantages. The innovative folding process consists in sequences of crumpling actions transforming a 2D sheet into a dynamic 3D flexible structure, without cutting or gluing actions. In order to prove the efficiency of the crumpling process, a methodology is proposed to evaluate the ability of a material to be crumpled. The procedure is then applied on different types of papers used in the food industry, and a study case of a crumpled packaging highlights new innovative functionalities as well as its potential environmental gain.

1. Introduction

Sustainability is gradually becoming a worldwide challenge for companies, they are conscious of the growing importance of taking into account environmental considerations in their development strategies. The directives and certification schemes adopted by public authorities [1-3] oblige industries and the packaging sector in particular to face the environmental challenge by developing new strategies and new products. Some propose their own certification to demonstrate their commitment to sustainable packaging. United Parcel Service company (UPS) proposes for example its own certification in its Eco Responsible Packaging Program for business customers [4]. Other companies choose to question the technical design of their packaging in order to achieve environmental criteria (biodegradability, recyclability, etc.). This strategy is based on some generic environmental principles: the least possible amount of materials/energy, use of renewable resources, maximizing recycled contents, increase of the potential for reuse [5][6]. The development of flexible packaging falls into this strategy. Indeed, a flexible packaging is considered as the most source-reduced form of packaging by comparison to those that are rigid. Its shape can be readily changed providing a simple and adaptable answer to portioning, preservation and convenience demand. It uses the least possible amount of material compared to other forms of packaging. A flexible packaging adds little weight to the product and leaves little to discard when it is empty; it is considered as the Perfect Fit in the report of Flexible Packaging Europe (FPE) [7].

The manufacturing of flexible packaging is quite recent. Flexible paper bags were first manufactured by hand and commercialized by E&S Robinson for grocery stores in Bristol in 1844 [8]. Later, in 1852, Francis Wolle invented an automated machine for making paper bags. The technology consists in a blade which pushes a flat paper sheet in a slot, then the paper is seized between a pair of cylinders which revolve continuously. The resulting object is a half folded flexible paper. Nowadays, this type of machine is designed as knife folder. A second principle consists in feeding the paper between rollers, it is then stacked in a pocket, the reaction of the paper is to buckle, then high friction rollers grip the paper and pull it through, folding the paper, which is squeezed between the rollers. The resulting flexibility is limited but defines basis for flexible packaging. A derivative way to create flexible packaging is the crumpling process. Crumpling consists in confining a material (usually a thin sheet) in a restricted volume up to its deformation in an irreversible way. When the material is confined, and because of its non-homogeneity, the stresses focus on certain points where the energy given by the confinement is dissipated [9]. Depending on their location, some points are connected and become folds which are generally simplified to a line [10]. A simple crumpling process can be illustrated by a paper ball confined in the hands. The resulting structure contains a unique non ordered set of folds called crease pattern [11]. A direct consequence of the deformation caused by the confinement is the emergence of elasticity properties in the resulting structure. Unfortunately, this property is only used for cushioning applications [12] crumpling is viewed as a poor added value in terms of mechanical performances conferred to flexible sheets.

To accompany the trend in designing flexible packaging, this paper presents new performances by exploring the potential of structured crumpled structures. As previously defined, crumpling is only used for cushioning applications, but by comparison to conventional folded structures (rigid boxes), they contain a creative potential that lies in the self generation of their crease patterns. Structured crumpling processes could generate new structured three-dimensional shapes with elastic properties for flexible packaging. For this purpose, the paper first investigates crumpling principles. Then, a scheme is proposed to measure the ability of a paper to be crumpled considering mechanical criteria. An application in the food sector illustrates the feasibility of structured crumpled structures and their potential environmental gain. In the last section, a discussion highlights the advantages and the limits of the methodology and gives margins for improvements for future work.

2. Crumpling

2.1. Context and objectives

Inspired by Paul Jackson's definition of basic crumpling methods [13], crumpling is a method derived of the origami folding techniques [14]. It consists in a systematic self generation of folds from a single paper sheet in order to create three dimensional structures without cutting or gluing processes. This technique has been used and developed on a wide range of paper sheets for over fifteen years by members of the CRIMP research team for artistic purposes [15][16]. This technique creates organized crease patterns very similar to those observed in nature, allowing the design of biomimetic models (Figure 1). A crumpled structure is the result of successive sequences of folding and crumpling actions. The key idea is the creation of relationships among ordered crumpled crease patterns to get new functionalities based on the resulting elasticity and plasticity. The expected environmental performances are made possible by eliminating cutting and gluing processes, as well the use of a single raw material for a simplified recycling.

(a) *(b)* *(c)* *(d)*

Figure 1 Structured crumpled papers

In order to prove that structured crumpled papers could offer new opportunities for packaging, a preliminary study on the crumpling characterization is proposed. The aim of the study is to prove the crumpling feasibility of different types of papers used in the food industry based on CRIMP crumpling experiences. The expertise of the CRIMP members in the packaging domain may be legitimately considered, knowing that the largest share of packaging is accounted for paper and paperboard with 38% of the market [17]. The establishment of behaviour laws of materials subjected to the crumpling process is not included in this paper.

2.2 Methodology

The crumpling ability of a material has not been specified before, therefore the understanding of the mechanical behavior of materials under crumpling processes is required. It will complete previous researches on the modelling of structured crumpled structures [18-20] for industrial purposes. The following methodology is proposed:

- comparison with existing folding/wrinkling measures,
- definition of a referent crumpling sequence and referent specimen,
- definition of a metric to measure the ability of a material to be crumpled,
- definition of a qualitative approach to test materials.

a) Existing measures

Crumpling is an extended usage of folding, therefore its characterization can be inspired from the foldability criterion. Two existing standards related to foldability can be used as basis to measure the crumpling ability. First, NF ISO 5626 defines folding endurance as the logarithm of the number of double folds required to cause rupture of the test piece when tested under applied standard stress conditions (Figure 2). The principle of the method is to fold backwards and forwards a narrow strip of paper under a longitudinal stress in a standardized way, until it breaks. Second, ISO 9867 defines the evaluation of the wrinkle recovery of fabrics. A test specimen is wrinkled in a wrinkling device (Figure 3) under a predetermined load for a prescribed period of time. The specimen is then reconditioned in the standard atmosphere and evaluated for appearance by comparison with three-dimensional reference standards. A qualitative number between 0 and 5 is finally associated to the wrinkle recovery capacity.

Figure 2 Folding endurance tester

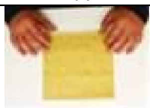
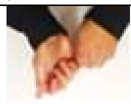
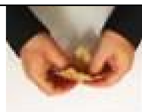
Figure 3 Wrinkle tester

The wrinkle recovery test could be defined as the opposite evaluation of the crumpling ability. Indeed, the more the recovery is important, the less the material is able to be crumpled. However, the wrinkle tester doesn't express the ability of a material to be crumpled several times. Knowing that radial creases are created from an iterative sequence of a crumpling action coupled with a reversal of surface, a modified wrinkle tester should operate alternatively to simulate the reversal of surface. At his time, due to the non existence of normalized tester to evaluate the crumpling ability of materials, a simplified process based on a manual test is proposed.

b) Referent crumpling sequence and specimen

By regards to the CRIMP experiences, an appropriate crumpling sequence which confers elasticity property to a paper sheet has been defined [18]. It consists in a repetitive sequence of a concentric pressure and a reversal of surface applied on a pre-folded paper into a cone shape (Table 1). Feedback on alios paper shows that eight repetitive actions of concentric pressure/unfolding/reversal of surface give a good understanding of the crumpling ability. This process will be considered as our referent crumpling sequence.

Table1. Referent crumpling sequence

Step	1	2	3	4	5
Definition	square paper on a support	pre-folding	concentric pressure	unfolding	reversal of surface
Image					
Conferred attributes	location	conical shape	Radial creases	spreading of the borders	reverse direction of the surfaces

As explained in section 2.2a, the standards ISO 5626 and ISO 9867 are not in adequacy with the referent crumpling actions and cannot support the crumpling procedure. Therefore, the evaluation of the crumpling ability will be manually performed by an operator. Our assumption is that a professional origami folder is able to reproduce the same crumpling actions within the same conditions. Due to the uncertainties derived from the human factor, a discussion is engaged in section 5 to suggest mechanical principles aiming at the design of normalized crumpling testers.

Some requirements can be listed to define the geometric features of the specimen. Most of existing packaging is based on the transformation of a square or rectangular sheet, the square form will be adopted for the specimen. From a practical point of view, the handling of the specimen must be ergonomic, it should consider the hands size and should minimize the amplitude of the movements of the operator's arms. Consequently, the feature of the specimen is a square sheet of 20 cm side.

c) <u>Metric to evaluate the crumpling ability</u>
Prior to the definition of a metric, the following terms and their definition are suggested:
Crumpability or crumpling ability - the capacity of a material in a particular form to be crumpled, ie to have the wanted geometry and mechanical properties after a crumpling sequence,
Crumpled creases – structured and oriented set of crease pattern providing from a crumpling sequence.
The term *Crumpability* will be adopted for the rest of the paper.

The complexity of the crumpability is related to the quantity of criteria involved in its evaluation. Three criteria are considered as relevant:

- the ability of a sheet to create a 3D shape,
- the ability of a sheet to generate a permanent structured crease pattern,
- the ability of a sheet to recover its shape after being stretched.

Due to the non-existence of norms or standards, a scheme is proposed for a progressive evaluation of crumpability. The progression is viewed as the growing understanding depending on the technological means employed. Table 2 expresses a list of possible measures depending on the qualitative or quantitative evaluation modes.

Table 2. Evaluation modes of the crumpability

Ability	Qualitative evaluation	Quantitative evaluation
Shape creation	Subjective comparison with a referent shape	2D digital data acquisition 3D digital data acquisition
Generation of permanent structured crease pattern	Subjective evaluation of the crease quantity	2D digital data acquisition 3D digital data acquisition
Elasticity	Subjective evaluation of the elasticity	2D sensors 3D sensors

In this paper, only the qualitative evaluation is presented, a discussion on the quantitative evaluation is proposed in section 4.

d) <u>Qualitative evaluation</u>

The qualitative evaluation first considers the 3D shape creation. The idea is to verify that the crumpled specimen has a conical shape made of a peak with a curved or linear section when it is deployed. By comparison with a referent shape, three levels are defined: Good, Medium, Bad. Good means the existence of a sharp peak with a curved or linear section; Medium means that the peak is smooth, Bad means no peak or a cross section with several inflection points.

The second consideration concerns the existence of a permanent radial crease pattern. It can be simply evaluated by counting the creases. To simplify the counting, a referent mask with partitions (Figure 4) is applied on the crumpled object. Three levels are defined: Good, Medium, Bad. Good means that the distribution of the creases is located in the smallest partition i.e. the quantity of crease is enough. Medium means that the creases are in the intermediate partition, and finally Bad when the creases are in the largest partition (small quantity of creases). For this evaluation, using the specimen after the first crumpling sequence is better, it causes the first significant mechanical response.

The third consideration is about the shape/form recovery related to the elasticity property. Without the use of sensors, a simple evaluation can be made by stretching the crumpled specimen during an interval of time (10 s), then the specimen is released and the measurement of its retraction rate relative to its initial footprint is evaluated. Three levels are proposed: Good, Medium, Bad. A retraction rate more than 50% is considered as Good, Medium if more than 35% and Bad if less than 35%. Figure 5 shows the retraction of the wax paper. Its footprint is 263mm² after being stretched, the resulting retraction rate is 34.1% and obtains the score M.

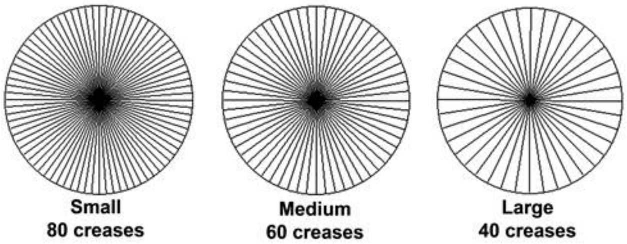


Figure 4 Referent creases

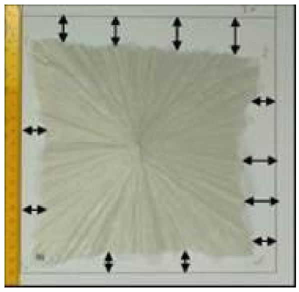


Figure 5 Retraction

Definition: the *crumpability Cr* of a material i is a structure (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.

Based on this definition, twenty seven qualitative configurations of the crumpability are possible, from (G, G, G) to (B, B, B). Depending of the functionalities required for a packaging, materials will be chosen regarding their abilities. For example, a packaging required to group and store different sizes of products will be chosen with at least the abilities (M, B, G). In this case, elasticity is the most important consideration, the crease pattern can be Bad, and the 3D shape can be Medium.

3. Application

The crumpability test is applied on papers used in the food industry. They are chosen among those available in professional stores, they are: alios paper, baking paper, wax paper, greaseproof paper. By applying the crumpling procedure, Table 3 presents the measures for each material. The final crumpability notation can be summarized as follows: Cr_{alios}(G,G,M), Cr_{baking}(G,B,G), Cr_{wax}(M,M, B) and $Cr_{greaseproof}$(M,M,M).

Table 3 Crumpability measures

Crumpability measure		Abilities					
		3D shape		Crease pattern		Elasticity	
		peak section	*level*	*sector*	*level*	*footprint mm^2* / *Retraction%*	*Level*
Alios paper		sharp / curved	G	small	G	248mm^2 / 38.0%	M
Baking paper		sharp / curved	G	large	B	185mm^2 / 53.7%	G
Wax paper		sharp / line	M	medium	M	263mm^2 / 34.1%	B
Greaseproof paper		sharp / line	M	medium	M	229mm^2 / 42.0%	M

3.1 Analysis

A first qualitative evaluation can be made by the crumpling operator. His/her sorting of the best papers for their elasticity is: baking paper, alios paper, greaseproof paper and wax paper. By comparison to Table 3, the qualitative evaluation gives the following sorting: baking paper, greaseproof paper, alios paper, wax paper. The difference comes from the tactile sensation on the greaseproof paper which is considered by the operator as more difficult to be manipulated than alios paper.

The measures show that alios and baking papers have the best performance to create 3D shapes. The best performance for the crease pattern criterion is associated with alios paper and the best elasticity is allocated to baking paper. Alios paper seems to have a better quality, but a paper must be chosen depending on the functional and environmental requirements. Greaseproof paper could be chosen for its ability to create crease pattern (M) instead of wax paper, assuming that it has a better environmental performance.

3.2. Implementation for pastry

The previous results show that baking paper has an interesting crumpability. Because it also has the ability to be heated, a crumpled baking paper could propose new functionalities for the cuisine other than just prevent food from sticking to its support. A brainstorming session was held with professional and non-professional cooks for the emergence of new applications. Among the ideas generated, one of the most recurrent propositions is an extensible mold for pastry baker.

a) <u>Crumpled molds</u>

CRIMP members created crumpled molds made of different shapes inspired by nature. The products have been given to a pastry baker with the instruction to use them with the utmost creativity. An illustration of molds and resulting candies are given in Figure 6 and 7.

leaf mold ***multi cones mold***

Figure 6 Crumpled molds

chocolate leaf ***chocolate hill***

Figure 7 Crumpled chocolate candies

These photos are from the first tests, they just prove the technical feasibility of extensible crumpled molds. The feedback of the pastry baker is that crumpled baking papers can easily replace silicone molds. The mechanical strength is sufficient to maintain different types of food. Their complex forms offer new possibilities to create biomimetic food used for example as edible containers (shell, etc.) or food itself (chocolate candy, etc.). A culinary protocol is currently engaged to precisely define the conditions under which the extensible molds could be exploited in an economic and creative way.

b) <u>Environmental interests</u>

Section 2.1 hypothesizes that crumpled papers aim at the eco-design of dynamic flexible packages. In the case of extensible molds made of baking paper, some prior appraisals can be set:

- they can advantageously replace molds made of silicone or aluminium: the product prevents from using fossil resources and mineral resources.
- they can mutualize several functions (contain, prevent from sticking): reduction of materials.
- they are extensible and can be used for the cooking of different sizes of food: reduction of materials.
- they do not need to be cleaned after using: water gain, only valid for the replacement of a classic mold containing a flat baking paper.
- they do not need to be cut or glued: operational simplification, reduction of energy and consumable.

Those propositions do not valid the environmental gain but give a roadmap for a procedure based on comparative Life Cycle Analysis (ISO series 14040).

4. Discussion

Some limits on the qualitative evaluation can be set. First, depending on the industrial sector, the qualitative scale based on three levels (Good, Medium, Bad) can be adapted. An advice is that the more the quantity is important, the more the experts could disagree. Second, the technical means to quantify the creases can evolve but a comparison has to be engaged to prove which one will be the most reliable. Third, in terms of human factors, the crumpling procedure is performed by hand, consequently some uncertainties on the pressure applied on the specimens can be discussed. Please note that the procedure has been applied by a professional origami operator who has been specialized in crumpled papers for fifteen years. A next step will be to create a crumpling machine to perform the tests, and its mechanical principle could be used for the design of machines for industrial purposes.

This paper presents a qualitative approach, but the scheme is to go further with quantitative considerations. An experiment has already been engaged to capture geometric and topological information by digitizing crumpled objects (3D laser scanner). The resulting information will be used for computer aided design purposes as for example the simulation of crumpled objects subjected to mechanical constraints. The quantitative consideration can also be understood from the environmental point of view. A complementary environmental study will measure the energetic expenditure to manufacture crumpled materials. A life cycle analysis will offer the opportunity to validate the expected environmental gain.

Concerning the adequacy of crumpled papers with the packaging industry, new investigations must be done to create relationships between the functions of a packaging (maintain, distribute, contain, transport, etc.) and the criteria of crumpability. The resulting matrix will serve as a guideline for designers.

5. Conclusion

This paper proposes a progressive approach to evaluate the ability of materials to be crumpled. It consists in the measurement of three relevant criteria: ability to create a 3D shape, ability to generate a permanent crease pattern, and elasticity ability after being crumpled. The approach is then applied on some papers used in the food industry and proves its operational feasibility. Based on those results, a study case is presented to create new functionalities in the culinary sector by the use of a crumpled baking paper. The results are promising but not sufficient. The quantitative evaluation of the crumpling ability will be next performed by exploring 2D digital data acquisition. For the industrial implementation, a workforce of culinary professionals (pastry, bakery, butchery) from a culinary institute was established to carry out new experiments. The resulting information will be integrated to improve the technical validation of crumpled molds, and will enrich the knowledge on the production, recycling and disposal of the molds for their environmental evaluation.

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