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FOLD MECHANICS OF NATURAL AND SYNTHETIC ORIGAMI PAPERS

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ABSTRACT

To realize engineered materials and structures via origami methods and other folding construction techniques, fundamental understanding of paper folding mechanics and their dependency on paper micro/nano-structure is needed. Using selected papers commonly used in origami designs, we establish the relationship between the mechanical properties of fibrous paper and their corresponding ability to form and retain simple creases and mountain/valley folds. Using natural fiber paper (abaca), synthetic fiber paper (Tyvek), and a metal-fiber laminate paper, we studied how the fold radius depends on the load applied using a controlled rolling apparatus. After folding, we examined the resultant micro- and nanoscale deformation using electron microscopy. In general we found that the fold radius follows a power law, decreasing with the applied rolling force. At a critical strain, each paper exhibits a transition between elastic and plastic behavior, after which the trend asymptotically approaches the minimum fold radius with increased applied force. Finally, we present examples of centimeter-scale two-dimensionally "mountain fold" patterns and relate the folding characteristics observed in these designs to the mechanical properties of the papers in folding.

INTRODUCTION

For centuries, the art of origami has led to the realization of beautiful and complex sculptures using simple sheets of paper. Increasingly, novel engineering structures from the nano to macro scales are being inspired and realized by origami designs [1], [2], including large-scale morphing surfaces and collapsible shelters, and miniature optics and containers [3]. At the macroscale, mechanical actuators and bearings are used to establish folding; while at smaller scales, folding is often achieved by patterning of active materials, or using active paper and sheet materials themselves [4]. A variety of materials and mechanisms of fold creation have been explored down to the nanoscale, including folding of metal films [5], graphene [6], DNA [7] and polymer sheets [8], [9]. A common challenge in all origami inspired folding is creation of localized strain that induces folding at a desired location. Additionally, fundamental understanding of the role of paper morphology in the realization of robust folded structures is necessary to select and manufacture suitable origami sheet materials at all scales.

The attributes of good origami paper, arguably for any scale of application, include the magnitude of force required to fold the paper, its strength and endurance [10] when (re-) folded, and its ability to elastically recover after the folding force is removed. Most papers have fibrous microstructures, often embedded in a polymeric matrix, which lead to the superior mechanical behavior of these papers in contrast to thin solid sheets. The intrinsic properties of the fibers, their density and organization, as well as the matrix properties govern the paper elasticity and determine the onset of plasticity during folding [11], [12]. In addition to their mechanical properties, most papers are made from natural fibers and are recyclable therefore promoting environmental sustainability.

Using selected construction papers typically used in origami and folding art, we present an experimental analysis of the effect of paper morphology on its minimum fold radius and the stability of its folds. We quantify the relationship between folding radius and force applied at the fold and qualitatively discuss further insights about folding gained from centimeter scale origami designs. This paves the way for understanding the favorable structural characteristics of paper that should be combined in engineered papers for creating origami-inspired surfaces and structures.

METHODS

We selected four common origami papers in order to investigate the effect of the paper micro/nanostructure on folding mechanics. Scanning electron microscopy (SEM) images of each paper are shown in **Fig. 1**, and each paper is briefly described below. The SEM images were taken using a Philips XL30-FEG.

- **Abaca,** a naturally derived paper made by a pressing process which results in random fiber orientations (**Fig. 1a**). It is made by hand at the Center for Book and Paper Arts, Columbia College, Chicago. Abaca paper of medium weight, having a nominal thickness of 93µm, was used in this study. As a result of its manufacturing process, Abaca paper tends to have a high degree of variability in fiber orientation and density between samples.
- **Aluminum foil paper** consists of two layers of thin aluminum foil laminated on both sides of a sheet of fibrous paper (**Fig. 1b**). It is sold as "Aluminum Folding Squares" by Folia Paper, Germany. The samples used in our experiment were 67µm thick.
- The 100 lb tex-weight **Corronado** paper has the highest fiber density and SEM images reveal local alignment of fibers (**Fig. 1c**). Commercially, it is referred to by its trade name, "Fox River Corronado" and is distributed by Neenah Papers, USA. The thickness, as tested, was 161µm
- Finally, we selected black **Tyvek**, a paper made of synthetic fibers (**Fig. 1d**). It has the lowest fiber density of the four papers, but due to its elasticity, it is most resistant to tearing. We measured a thickness of 143µm for our samples. Tyvek is supplied by Material Concepts, and the product is a registered trademark of DuPont.

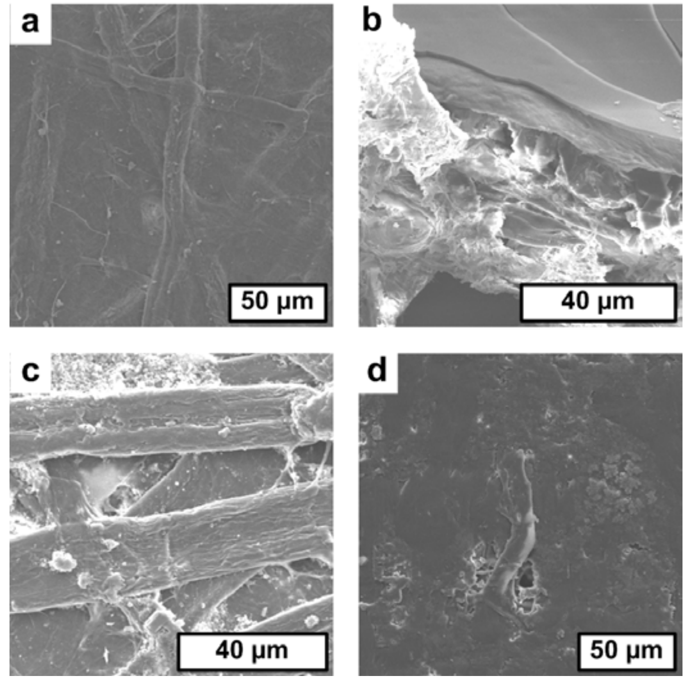

Figure 1: SEM images of selected origami papers: (a) Abaca; (b) Aluminum-coated paper (side view); (c) Corronado; (d) Tyvek

A rolling experiment was used to controllably fold small strips of each paper placed on an inclined plane (**Fig. 2**). A video camera (60 frames/sec) was used to measure the minimum fold radius as the roller passed over the fold. Before rolling, the two ends of the paper strip were laminated and taped to the inclined plane as shown in **Fig. 2a**. We controlled the rolling force via the width of the strip (in-plane and parallel to the ramp); in this study, the width ranged from 0.5cm to 6cm, resulting in a force per unit length along the fold between 58N and 2030N As the roller travelled over the paper, the fold radius decreased and the location of the crease moved by a small amount along the curve of the fold as shown in **Fig. 2b** [11]. The frame in which the roller is about to roll past the fold apex was selected, and the minimum fold radius (r) was measured as shown using ImageJ software. As the roller travelled past the paper, the fold radius partially recovered as shown in **Fig. 2c**. For each paper, a series of tests was performed using strips cut to a range of widths, therefore changing the force per unit length acting along the fold. After the rolling experiment, selected samples were cut 1cm from the fold. The width between the cut ends of the paper was referred to as the recovered radius.

In an additional set of experiments, we folded a sample of each paper between two planes held by a binder clip, for approximately one hour. This applied a very large static force, and thereby enabled identification of the minimum fold radius that can be achieved, which is then determined by the structure and thickness of the paper. In order to visualize the folds in SEM, the paper samples were held in binder clips away from the fold location. Optionally the papers were coated with gold using a sputtering machine before SEM imaging.

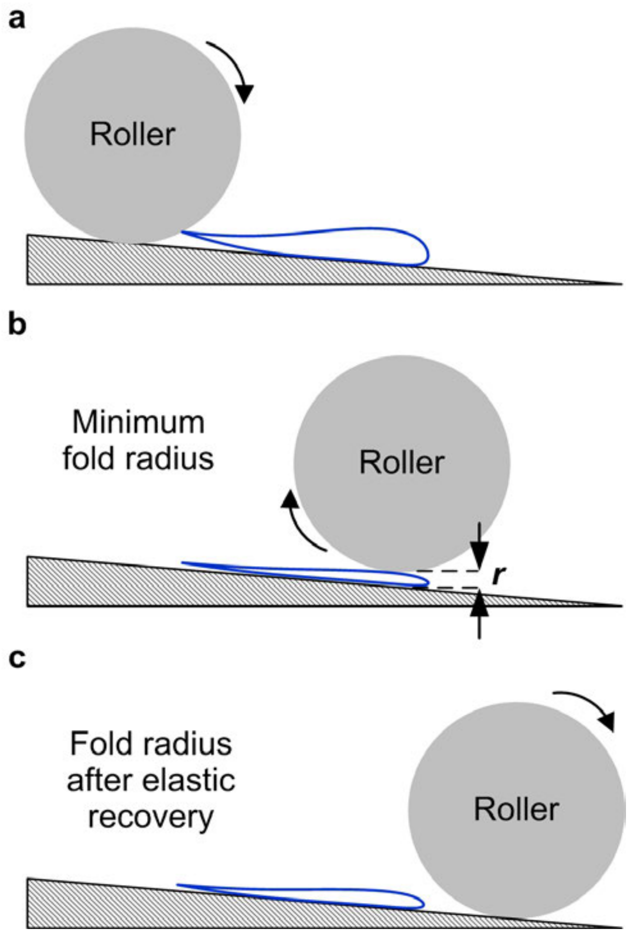

Figure 2: Schematic of rolling experiment used to determine relationship between applied force and folding radius.

RESULTS AND DISCUSSION

In **Fig. 3**, we plot the strain (equal to the paper thickness *t* divided by the fold radius r) obtained by varying the force per unit length applied by the roller (determined by the paper strip width)**.** When the fold radius equals the paper thickness, the surface strain equals ε=1. Although these experiments were performed on all four selected papers, for brevity and clarity only results from Aluminum foil and Tyvek are discussed in this section.

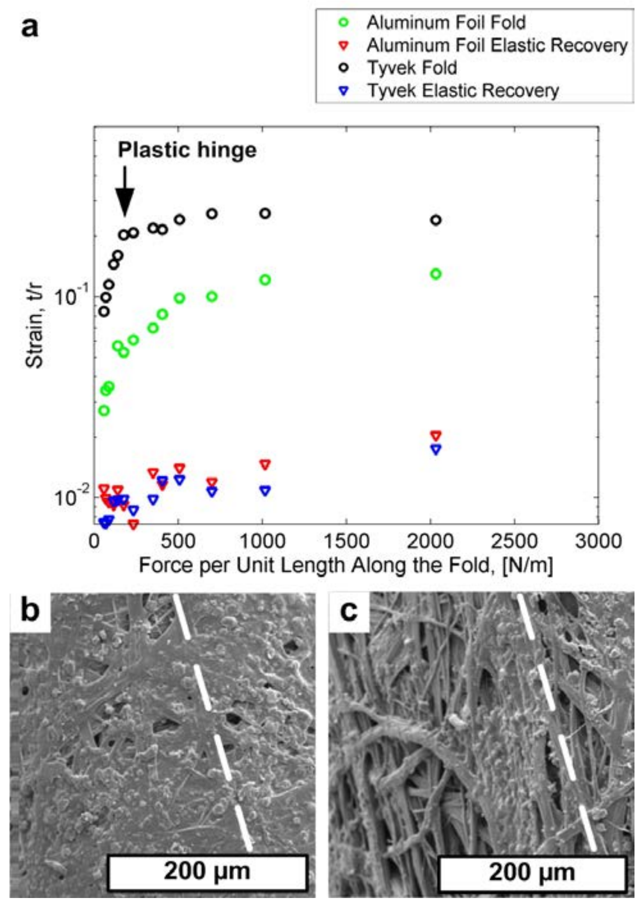

Figure 3: (a) Relationship between fold strain and applied load; Tyvek microstructure at the fold (b) before and (c) after the plastic hinge. The dashed line shows the apex of the fold.

For Tyvek, the trend of the minimum fold curvature (strain) attained for each of the applied forces shows two regions. The initial stage follows a power law increase of strain, evident for plastic deformation (i.e., partially recoverable kinking at the fold location) until reaching an inflection point marking the onset of the formation of a plastic hinge. A plastic hinge is defined as a discontinuity in the geometry at the crease. Subsequent increases in the applied force result in a different power law of higher order, and eventually lead to smaller changes in the fold radius. Previous work by Wang shows that for a thin sheet that is either perfectly elastic or perfectly plastic, the power laws governing the fold radius have exponents equal to -0.5 and -2.0 for before and after the formation of the plastic hinge, respectively. Wang also shows that the physical location of the crease changes by 2% during the travel of the roller over the fold [6]. In our case the inflection point for the Tyvek is seen at 400 N/m (**Fig.**

3a). For Tyvek, the exponent we observed in the elastic regime was -0.77.

SEM imaging of the Tyvek paper after folding (**Fig. 3b,c)** reveals the condition of the microstructure of the paper due to plastic deformation. As described above, the paper was held in a binder clip for an hour, which led to a minimum fold radius of 0.14 mm (ε=0.4). We observe that the matrix pulls away from the fibers in the area of high strain, while it is difficult to assess if any of the fibers have broken or pulled out from the matrix.

For the aluminum-coated paper, we also observe a power law relationship until 500 N/m, indicating the occurrence of plastic deformation. The mechanics of deformation of the aluminum coated paper is more complex at strain ε > 0.1. We find this is due to the laminated structure and failure mechanism of the aluminum-coated paper. SEM images (**Fig. 4**) show delamination and the buckling of the bottom aluminum layer due to compression.

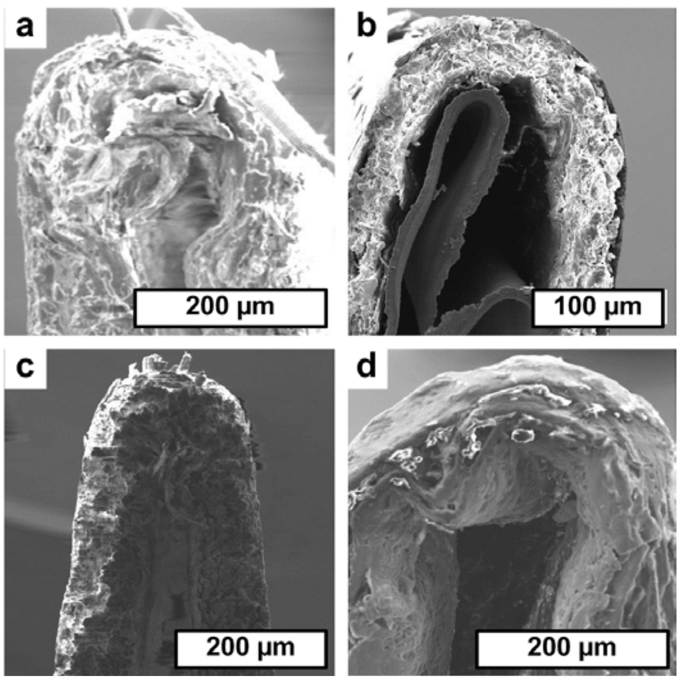

Figure 4: Minimum folding radius of construction papers showing types of plastic deformation in (a) Abaca; (b) Aluminum Foil; (c) Corronado; (d) Tyvek.

We next study the amount of elastic recovery measured from the cut paper folds after the rolling experiments. This gives insights on the reversibility of folding for dynamic structures and surfaces. **Fig. 3** shows that at least 90% of the maximum strain is recovered in both cases. The Aluminum paper is both stiffer (less total strain per applied force) and more plastic (larger percent of residual strain). This is also attributed to delamination of the aluminum during folding at high forces.

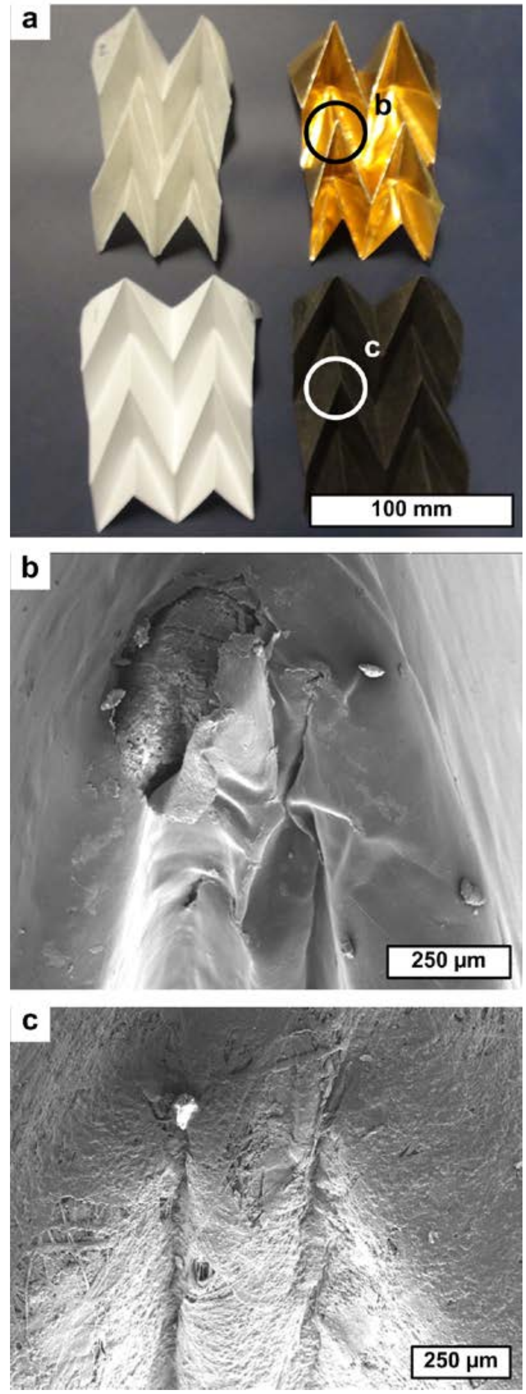

Figure 5: Centimeter scale corrugated surface designs with mountain and valley folds: (a) Clockwise from top left Abaca, Aluminum foil, Tyvek and Corronado; Sharp mountain fold in (b) Aluminum foil and (c) Tyvek.

ANALYSIS OF SHEET FOLDING PATTERNS

Last, we briefly examine the folding of more complex patterns in the same selected papers. Transformation of simple folds into corrugated sheets can potentially realize novel structural and functional properties such as high stiffness energy absorption at low density. Further, engineered optical and thermal response could be achieved when folds are created at smaller scales. As a design study, the papers were cut into 100 x 100 mm squares, and then folded into sculptures with alternating "mountain" and "valley" folds (**Fig. 5**). The fold pattern is similar to the Miura-Ori but with more acute angles [13]. It is commonly referred to as a basic 45 degree pleated or corrugated form.

We summarize our observations during the manipulation of these types of paper for manually folding the origami shown in Figure 5. While each paper is folded with the same pattern and initial sheet size, the sculptures have different sizes after folding due to variation in the recovered radii, which as shown before depends on the paper thickness and structure. The bending resilience of the Abaca sheet is higher than the other papers in this study, and therefore folding it into the required shape consumes the highest amount of mechanical work. However, it retains its folded geometry with high fidelity. Owing to its laminated structure, the aluminum foil paper is prone to cracking and misfolding, and hence fractures easily when sharp folds are desired. This makes it unsuitable for applications where the origami needs to be actuated or reversed. The aluminum origami structure also has the lowest stiffness due to the presence of cracks after folding. For Tyvek, the combination of high resilience and its smooth surface represents a challenge to the precise manipulation of the paper during folding, therefore often leading to inaccurate folding geometry. Also, due to its relatively high stiffness, Tyvek is only suitable for single fold origami (i.e., as shown in Figure 5) as it becomes increasingly stiffer and hence more difficult to form multiple folds in close proximity..

These folded patterns provide important insights for further work on actuated folding of paper-like materials. For instance, a highly elastic material like Tyvek requires a significantly larger force in order to induce the plastic strain required for sharp folds. Another possibility is laminating a desired material on paper, where regular paper like the ones described in this study can function as "carrier" for a functional thin film. We envision that this technique would be particularly useful for folding very thin materials, because direct manipulation is challenging at thicknesses below 1 μm. Based on the observation of aluminum foil paper, it is important to consider possible delamination of layers beyond the elastic limit. This places a practical bound on the minimum fold radius possible while folding layered papers.

CONCLUSION

With the increased interest in engineering applications of origami designs, it is necessary to understand how to design paper materials by controlling their micro- and nanoscale constituents. More specifically, the precisely controlled folding of paper relies on the understanding the mechanics of simple creases. We showed how desktop rolling experiments could be used to measure the non-linear folding mechanics of origami papers, and revealed their behavior in the plastic deformation regime. We revealed challenges in using laminated and multi-layered papers for origami designs, such as Aluminum coated paper, which delaminate and buckle during folding. We related these experimental observations to the simple exercise of folding corrugated mountain-valley pattern from the preselected paper. The resilience and surface roughness of paper are essential to control of the fold geometries and location. The insights obtained here can be applied to the engineering of highly resilient papers, and thinner papers, for realizing origami designs at multiple scales.

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