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Simple equations that governs the deformation physics of Kirigami promising for engineering applications and regenerative medicine

Summary

Professor Ko Okumura (Ochanomizu University) with a student, Midori Isobe, discovered simple equations that governs the physics of deformation of Kirigami, a form of Japanese traditional art to realize three-dimensional structure using a sheet with a certain cut pattern. They uncovered that the high stretchability of Kirigami originates from the transition from in-plane (two-dimensional) to out-of-plane (three-dimensional) deformation, and showed that this transition is precisely determined by remarkably simple laws of physics. Kirigami ("Kiri" and "Gami" are Japanese words standing for "cut" and "paper," respectively) has received rapidly increasing attention as a key structure for various engineering applications such as flexible electrodes or solar batteries. The simplicity of the equations thus established allows us to provide simple guiding principles for the development of applications, e.g., for cell sheets in regenerative medicine, by designing the Kirigami structure.

Background

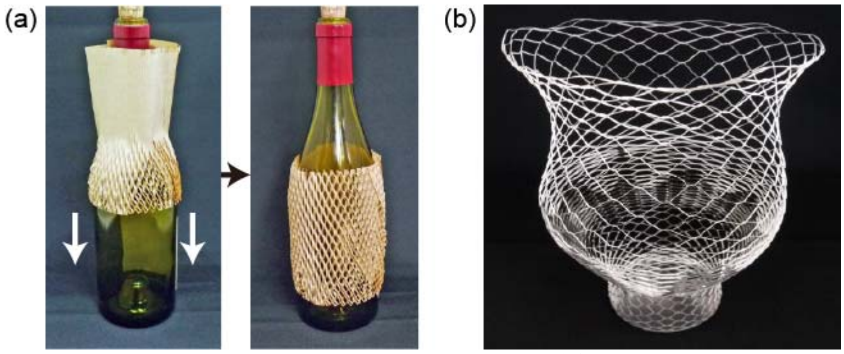


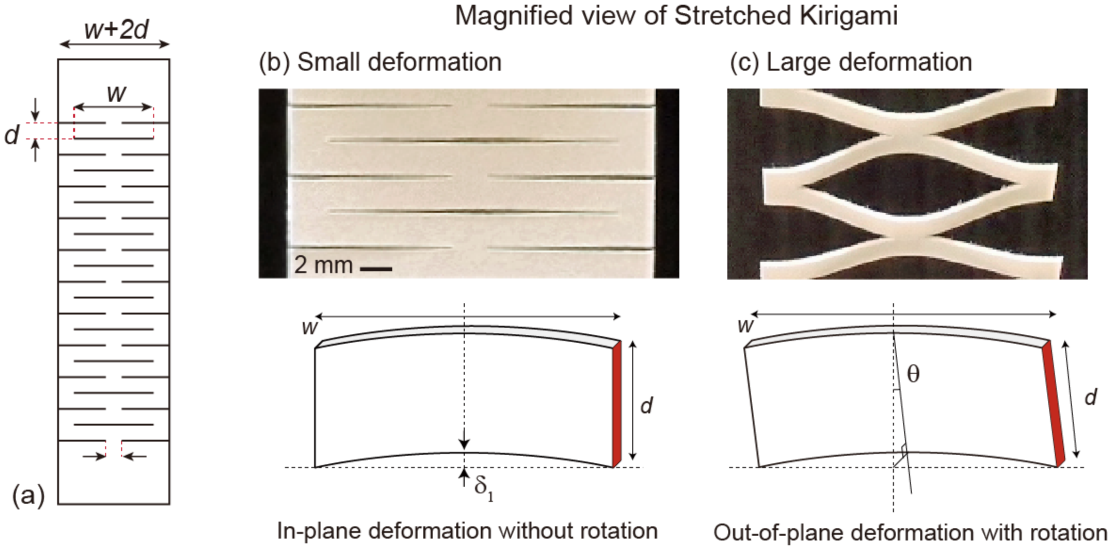
Figure 1 : Examples of Kirigami for daily use in Japan. (a) Shock absorbing Kirigami sheet for protecting a bottle of wine. (b) "Airvase" (Toraf Architect, Japan) sold worldwide in museum shops. Photographs are from the article, Sci Rep, 2016. http://www.nature.com/articles/srep24758. （CC BY 4.0）

The group of Okumura has investigated fundamental issues concerning the toughness of polymer materials in Prof. Ito's project*, with his research background on tough biological materials such as spider webs. It is a prerequisite for future automobiles to toughen and thin down porous sheets of polymers integrated in Lithium-ion batteries. In nature, there are biological materials that are reinforced by introducing many pores in the structure, which include the soft bone of sea cucumbers. Okumura thus started a project on the mechanical properties of Kirigami in Ito's project. In fact, inspired by daily examples of Kirigami (see Fig.1), Okumura initiated a preliminary project with a student, Midori Isobe, who joined Okumura's Group about two and half years ago.

Quite recently, there has been a surge of engineering utilizations of the Kirigami structure [1-4]. Examples include flexible electrodes or solar batteries, and applications using graphene: softened Kirigami graphene can be an element for ultra-micro actuators. However, no studies have been performed to clarify the physical principles of the deformation.

Content of the study

Okumura and Isobe performed a systematic experiments and theoretical investigation using a simplified pattern (see Fig. 2 (a)). As a result, they noticed that the high stretchability of Kirigami originates from the transition from in-plane (two-dimensional) deformation to out-of-plane (three-dimensional) deformation (see Fig. 2 (b)). On the basis of this observation, they developed a theoretical framework that describes the transition. As a result, they derived two equations (1) and (2) that determine the rigidity (elasticity) of the Kirigami sheet for small and large deformations (corresponding to in-plane and out-of-plane deformation, respectively). In addition, they derived another equation (3) that describes the condition of the crossover between the two regimes of small and soft deformation. Furthermore, they showed that the three equations are consistent with the data. In particular, it is shown that the equations for the in-plane deformation (1) and for the transition (3) hold with remarkable precision. The three equations expressing the laws of physics are quite simple (see Fig. 3) so that they could be useful as guiding principles for the development of various applications.


Magnified view of Stretched Kirigami

(b) Small deformation

(c) Large deformation

In-plane deformation without rotation

Out-of-plane deformation with rotation

Figure 2：(a) Kirigami pattern used in the present study, which is simplified without losing the physical essence. (b) Kirigami under a small tension (top) and illustration for the in-plane deformation without rotation (bottom). (c) Kirigami under a large tension (top) and illustration for the out-of-plane deformation with rotation.

（1）Elasticity for in-plane deformation $E_{in} = \alpha(d/w)^4 E$

（2）Elasticity for out-of-plane deformation $E_{out} = \beta(hd/w^2)^2 E$

（3）Strain at the transition $\varepsilon_c = \gamma(h/d)^2$

Figure 3 : Three simple equations describing the physical essence of the high stretchability of Kirigami established in the present study. “Elasticity” is a measure of flexibility and “strain” corresponds to the elongation. The parameters, d, h, and w, are the ones specified in Fig. 2(a), whereas the parameter E is the elasticity of the original material, such as paper (α, β, and γ are numerical coefficients).

Perspectives

This study is being developed into a physics-engineering collaboration to seek more possibilities of applications of the present study. This project has been performed in the physics group of Okumura. Recently, Atsushi Takei (Ochanomizu University) has joined the group with his research background in engineering. As a result, they started a more application-oriented project, confirming that the equations are universally valid for polymer materials such as rubber and plastics, as well as paper, and have applied for a Japanese patent.

Example of applications include the utilization of the Kirigami structure for cell sheets promising for regenerative medicine. One may increase the possibility of the success of regenerative surgery by adjusting the elasticity of the cell sheet to that of the plant region of the patient. Applications in cylindrical geometry (see Fig. 1(a)) may include personally customizable elastic supporter for medicine and sport. The in-plane to out-of-plane transition can be easily detected because the transition is from two-dimensional to three-dimensional deformation, which can be exploited for the detection of force (force sensor). The Kirigami force sensor could be suitable for detecting and measuring extremely small force if, for example, the sensor is made of graphene.

* This research was performed in the research project led by the program manager, Professor Kohzo Ito (The University of Tokyo), funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan). Prof. Ito’s Project aims at developing various kinds of “Shinayaka” polymers (“Shinayaka” is a Japanese word meaning, tough and flexible). The research group of Prof. Okumura in Ito’s project has investigated fundamental issues for toughening polymers, which include porous thin polymers for Lithium-ion batteries indispensable for future automobiles to obtain the present results.

References

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Original paper
Name of the journal: Scientific Reports (Nature PG)
Title of the paper: Initial rigid response and softening transition of highly stretchable kirigami sheet materials
The Authors of the paper: Midori Isobe and Ko Okumura　(Graduate School of Ochanomizu University, Ochanomizu University)

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