Temperature-Induced Rotation in Liquid Crystal Elastomer Toroids

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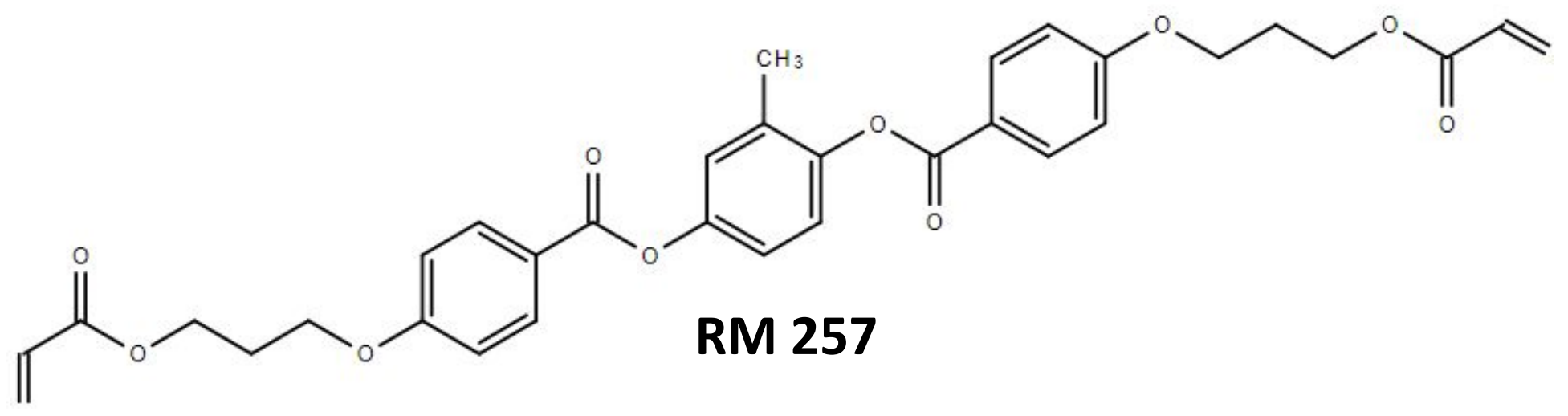
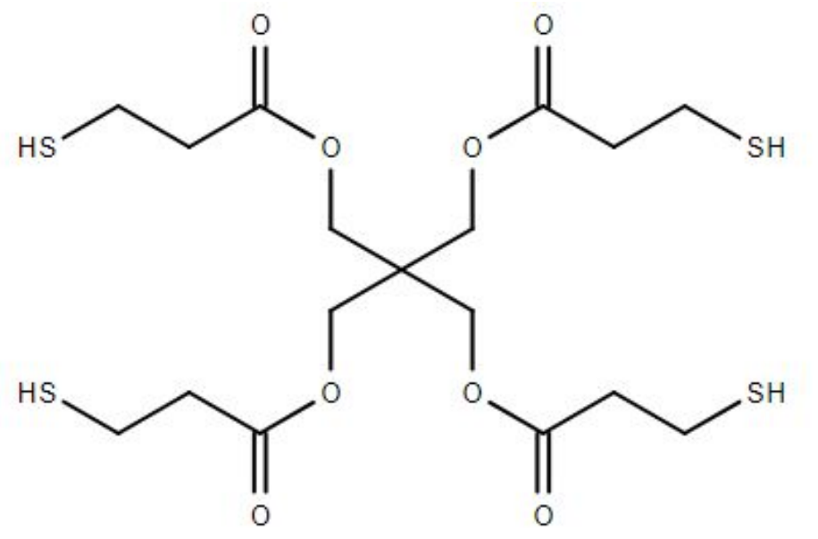
Abstract

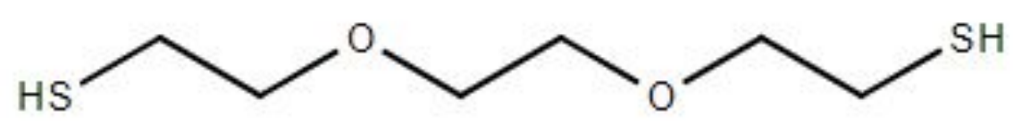
Liquid crystal elastomers (LCEs) are soft materials exhibiting both the macro-organizational properties of liquid crystals and the elastic properties of elastomers. This material is gaining attention for its planar contraction, shape retention, and self-healing regarding single-dimensional applications. This study explores one application of their contraction in two dimensions: toroidal LCEs exhibit a continuous rolling phenomenon when placed on a heat source. Heating causes the LCE molecules to lose their nematic organization and enter the isotropic phase, causing them to contract. A thermal gradient is created, causing the heated portion to contract, putting thermal stress on the torus, and subsequently generating torque. We focused on the effects of temperature, torus diameter, and cross-sectional radius on the rolling behavior. The toruses are found to increase in rotational velocity with increasing temperature and ring size, and to decrease with increasing cross-sectional ring radius. The contraction of the LCE's in two-dimensional shapes and the resulting rolling phenomenon have limitless applications that are yet to be explored.

Background

Liquid crystal elastomers are a polymer network exhibiting the macroscopic physical properties of an elastomer and the mesogenic macro-organization of a liquid crystal network. They can exhibit reversible changes in optical and mechanical functions.


RM 257


PETMP


EDDET

In our work, LCEs are formed using a two-stage crosslinking reaction involving a thiol-acrylate Michael addition reaction and radical polymerization. For our LCEs, RM 257 provides the diacrylate liquid crystal mesogens, EDDET is a flexible spacer, and PETMP is a crosslinker. In Stage 1, the solutions are mixed with the Michael-addition catalyst, poured into tubular molds, and cooled, resulting in the opaque and unorganized polydomain stage. The tubes are then stretched to temporarily align the liquid crystal mesogens in one direction, resulting in a clear elastomer in the monodomain stage. Then, a photopolymerization reaction is used to photo-crosslink the excess acrylate groups into a single stable LCE. This second cross-linking step ensures that the LCEs' contraction properties are reversible, as shown in Fig. 1b.

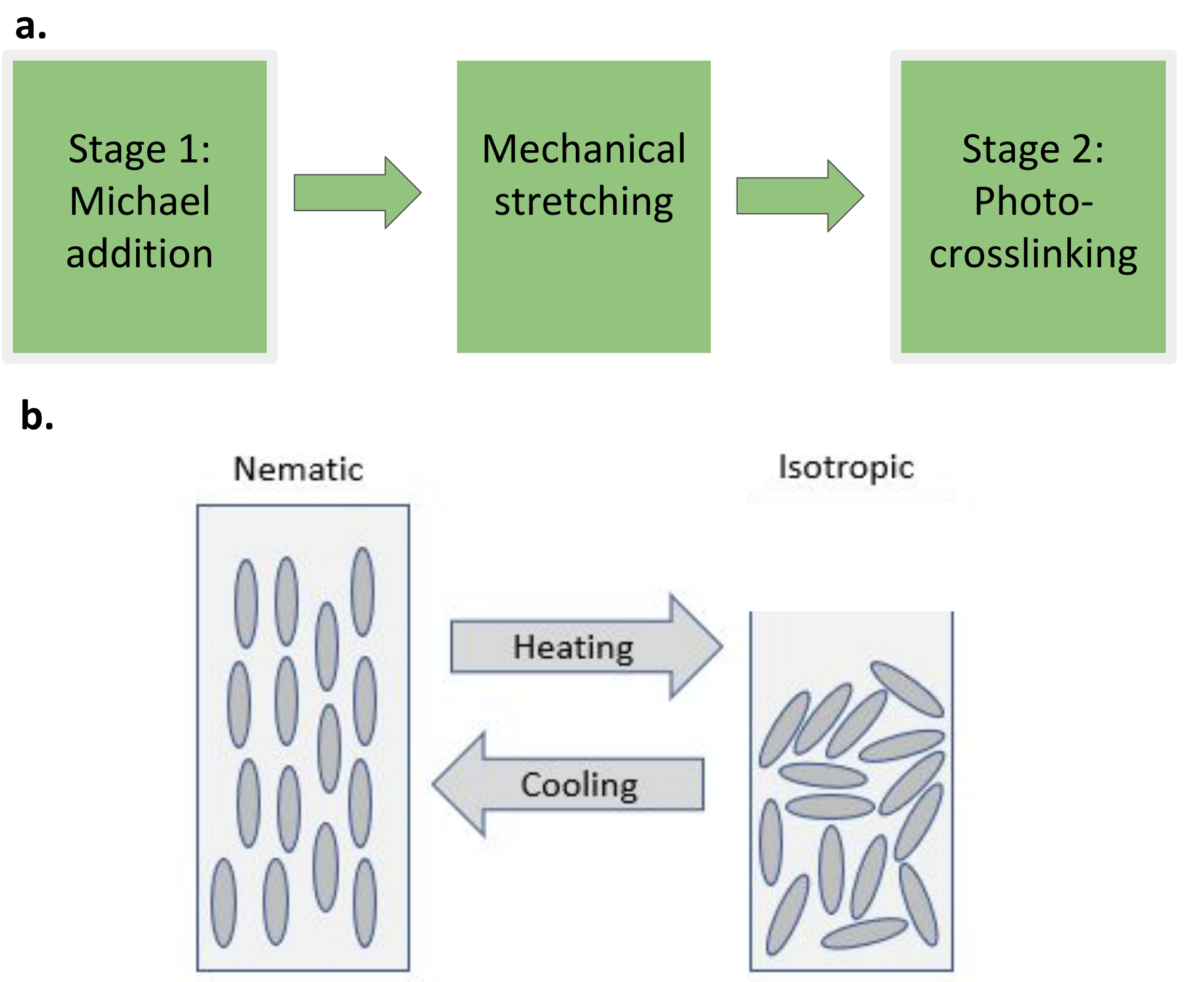


Figure 1| **a.** Synthesis process for LCE. **b.** Reversible contraction of LCEs, enabled by Stage 2

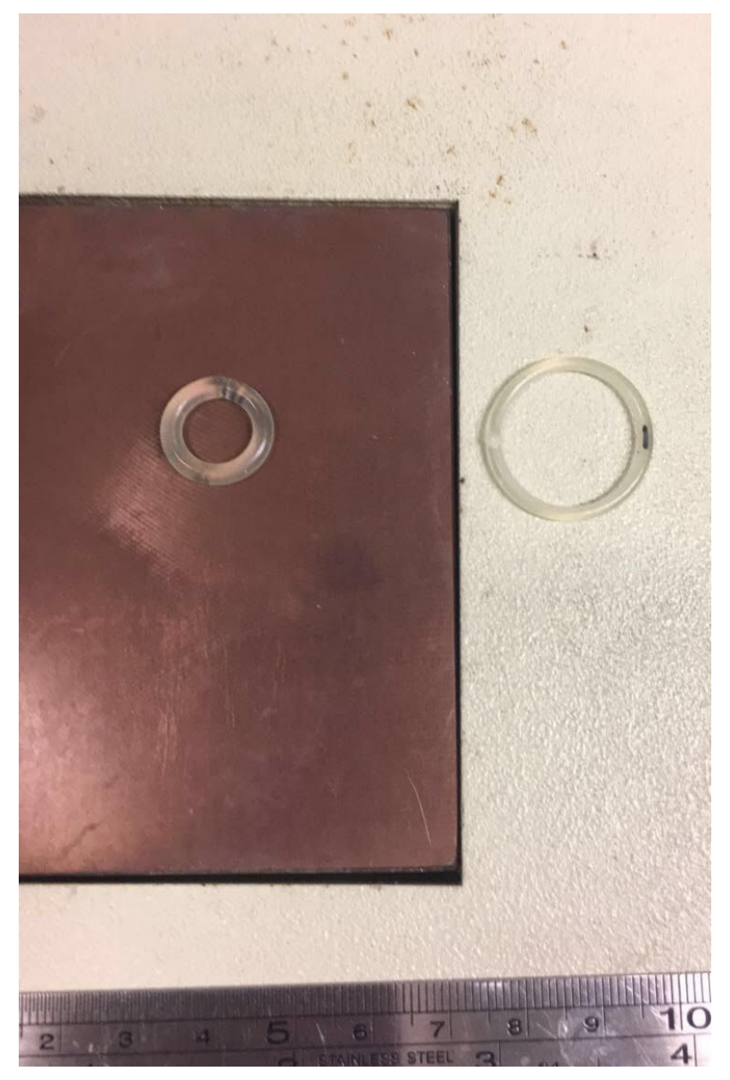


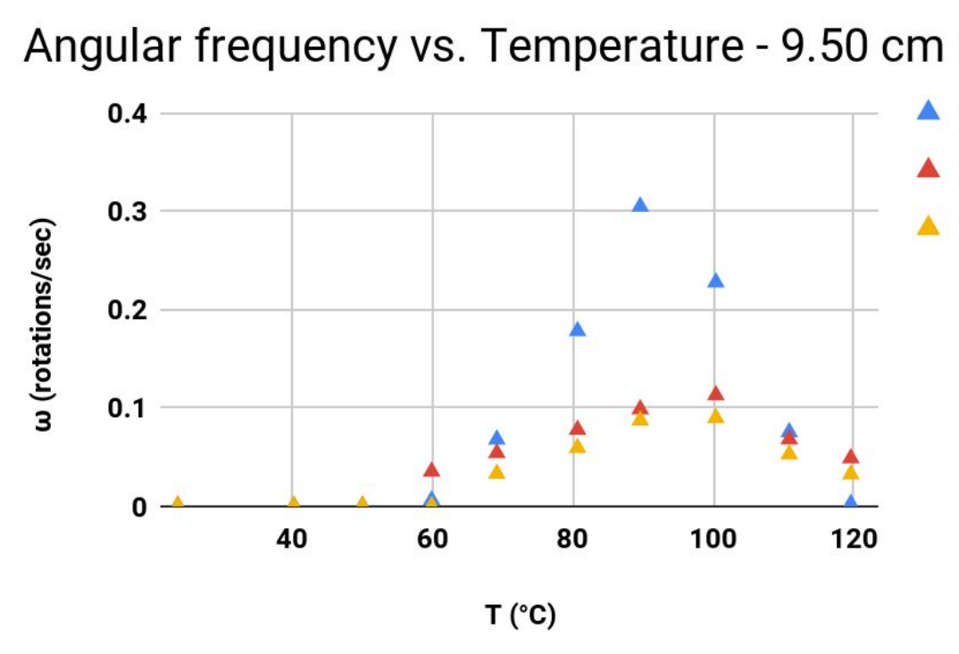
Figure 2| Experiment set-up. Torus on left is heated to 120°C. Torus on right is unheated.

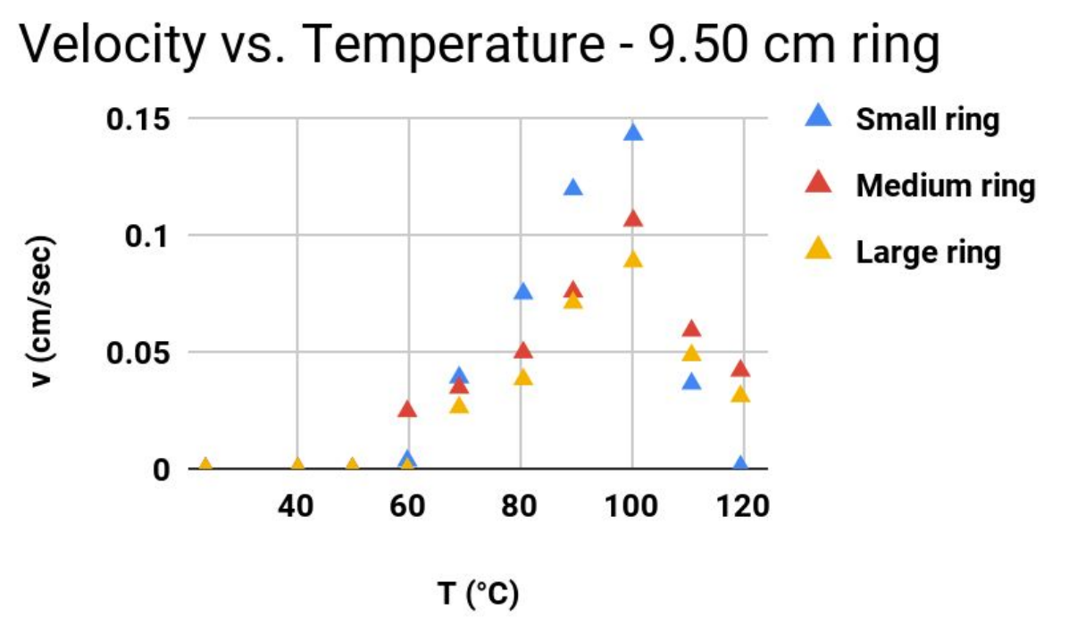
Methods

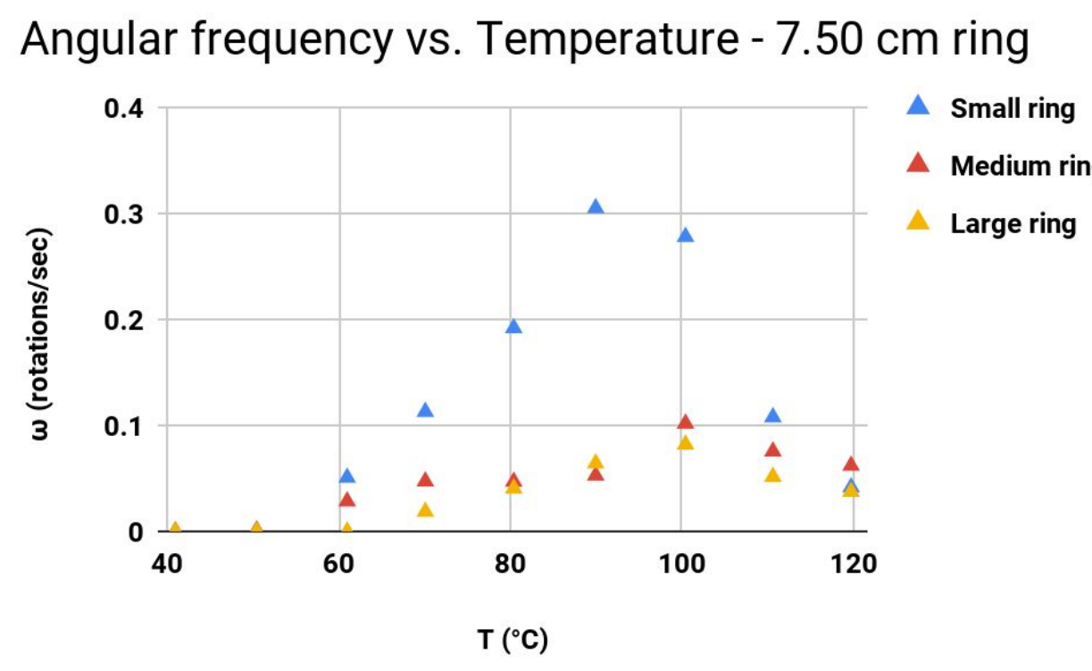
For testing the rolling phenomenon, LCE tubes of three different thicknesses - referred to as "small", "medium", and "large" - were prepared by Dr. Zhijian Wang. The tubes were heated in the oven to 85°C to remove deformities, cooled, and then cut. We first recorded the contraction of 6.50 cm tubes in 5°C intervals from 30°C to 120°C before testing the rings, identifying the temperatures where peak contraction occurred. The two ends of the tubes were aligned to minimize twisting or deformities and then glued together. We also marked the torus to aid with counting rotations, and recorded their inner and outer diameters. The samples were allowed to sit on a heat block and reach thermodynamic equilibrium before we recorded the number of rotations over 120 seconds. We also noted the temperature and inner and outer diameters of the torus. Data points were collected at 10°C intervals from 30°C to 120°C. Each ring sample underwent five trials, three of which were recorded by video. Samples were allowed to cool between trials.

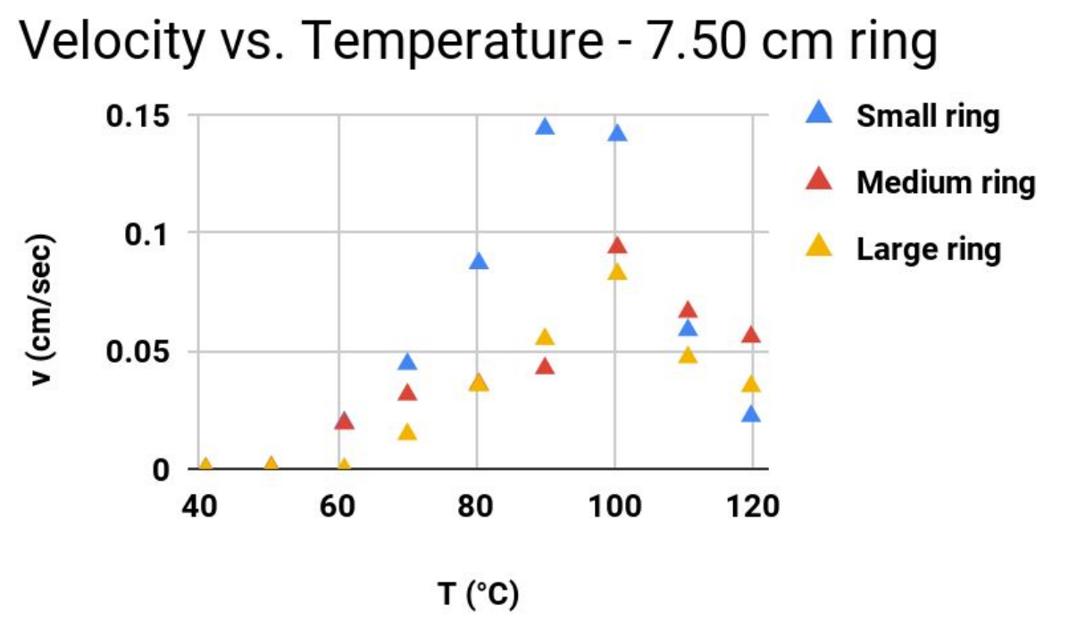
We used the flat bottom surface of a FISHER dry bath as our heat source, as a standard heat plate provided inconsistent heating. We also used a metal ruler heated to the temperature of the sample to minimize any heat loss during measurement.

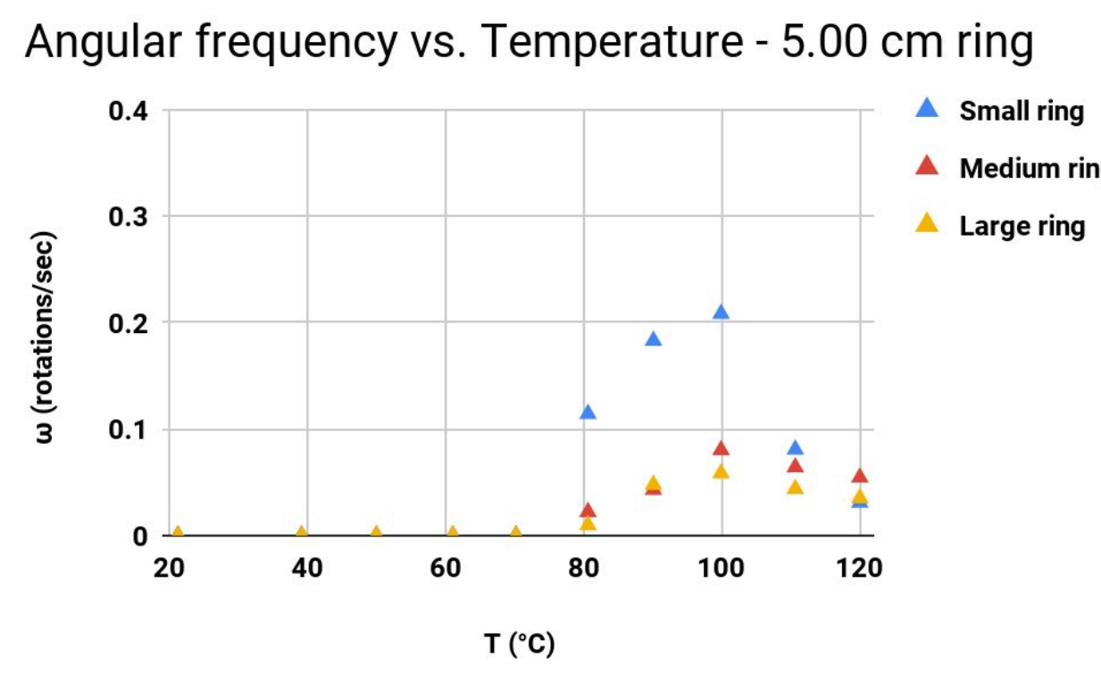
Results

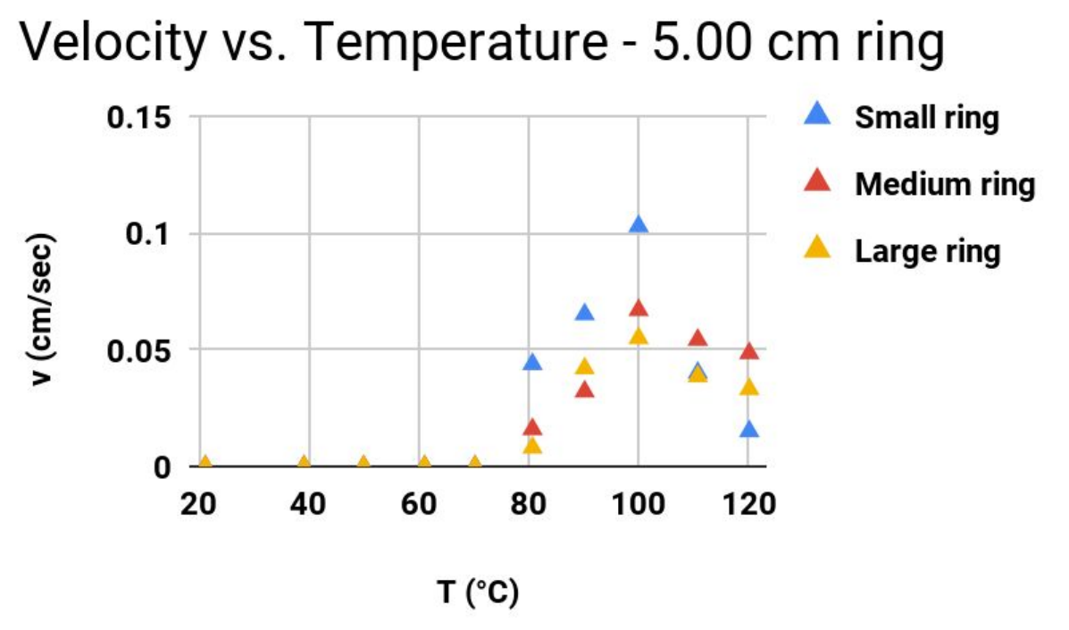


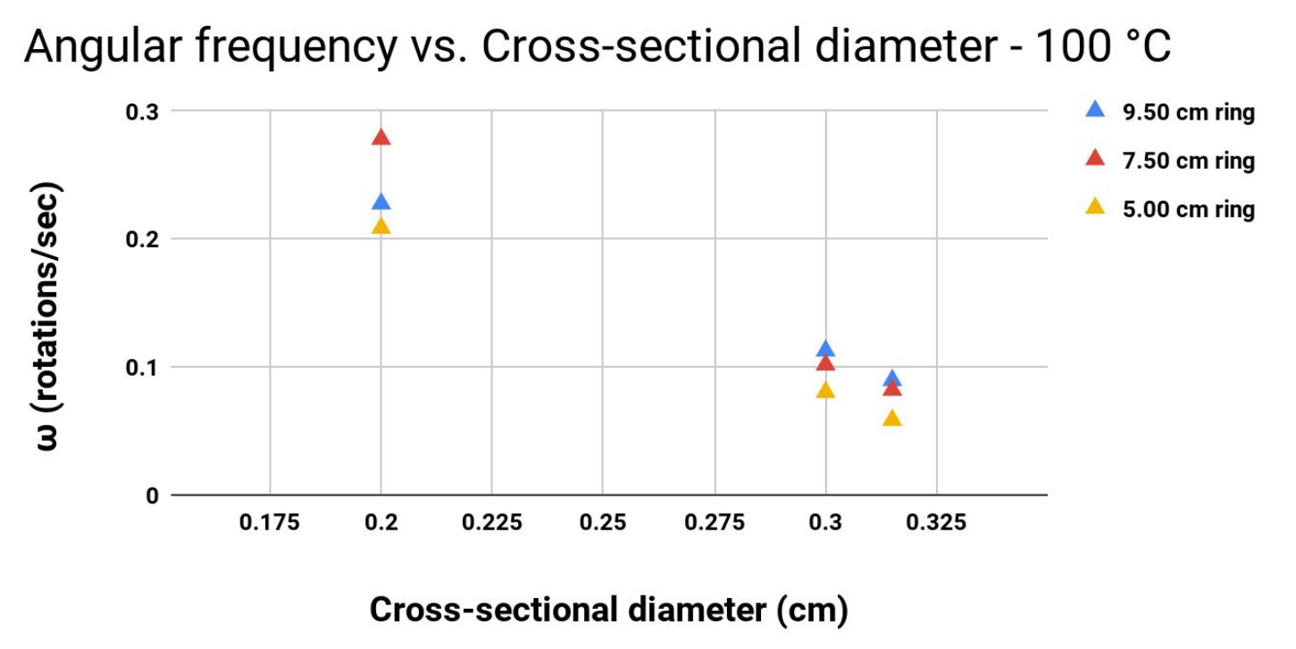


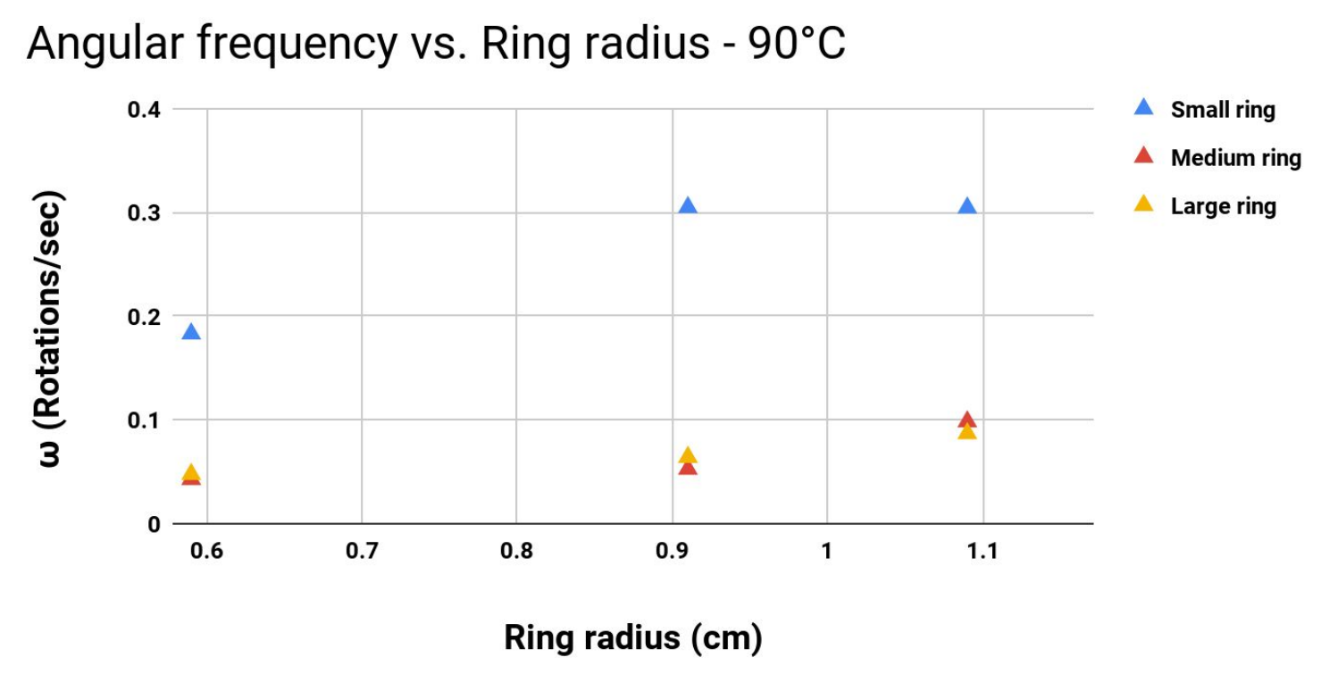












Analysis/Conclusion

Rotational velocity (ω) increases with temperature (up to 90°C to 100°C) as higher temperatures intensify the temperature gradient that drives rotation. At very high temperatures, though (starting at 110°C), the heat source is so strong that the overall gradient is actually weaker, weakening the torque and inhibiting rotation.

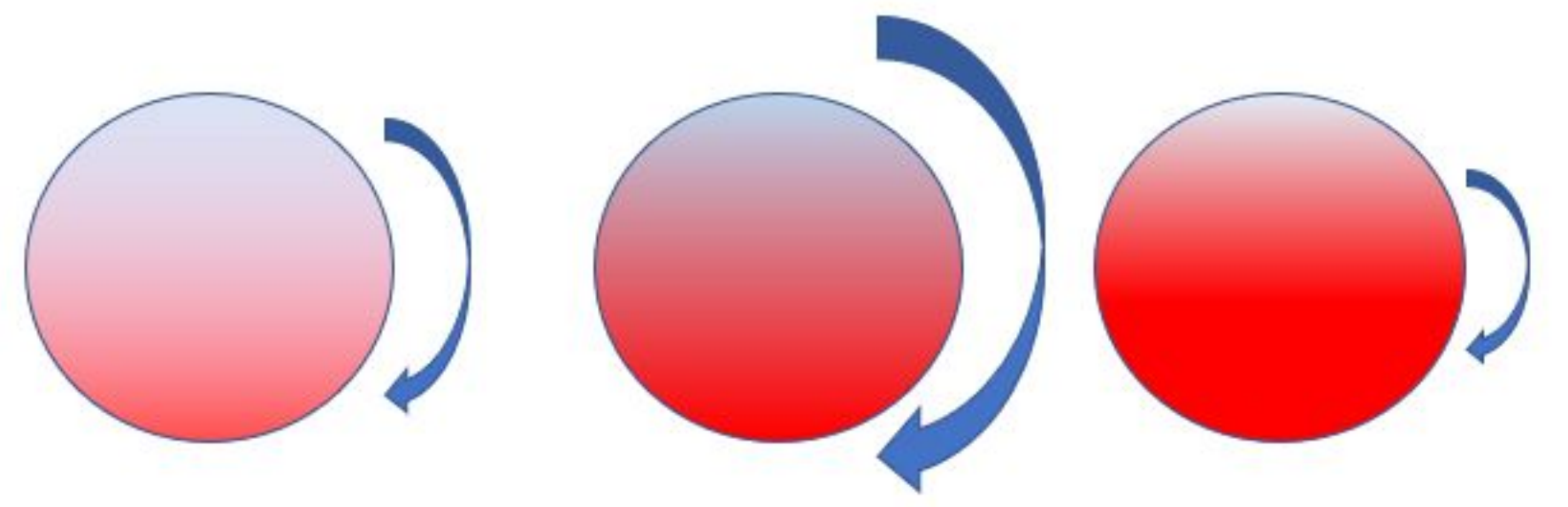


Figure 3 | Cross-section of toroids at increasing temperatures, depicting the strength and orientation of the temperature gradient. Red and blue indicate high and low temperature regions respectively.

Rolling velocity also increases as ring radius does. This is because the local curvature of the ring decreases as radius increases. This means there is less tension for the temperature-induced torque to overcome. Specifically, greater local curvature inhibits rotation, thus reducing curvature aids rotation.

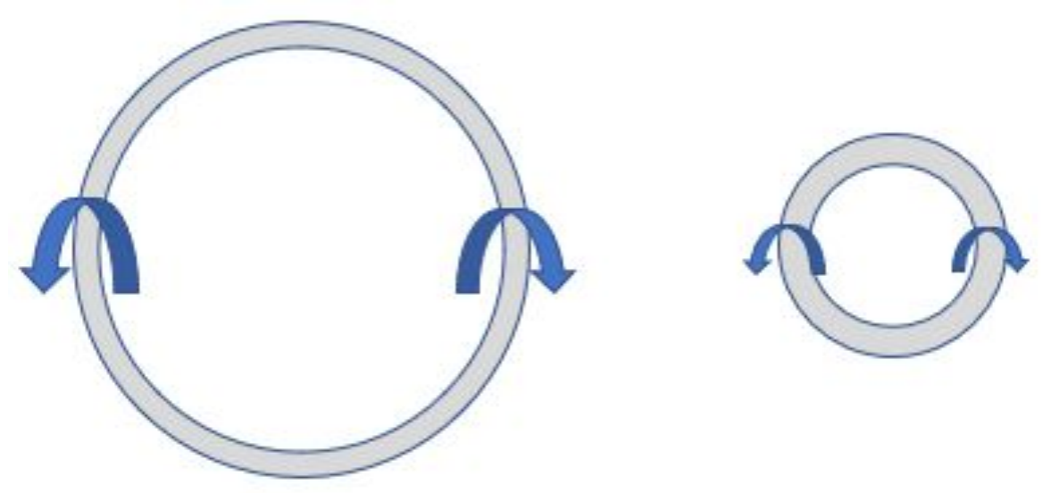


Figure 4 | Two rings with different radii and curvatures. Ring on left is larger, rotating more readily.

Conversely, rolling velocity decreases as the cross-sectional size (diameter) of the rings increases. This again is a result of the temperature gradient. If two rings of different cross-sectional thicknesses are heated to the same temperature, the thicker ring will have a weaker temperature gradient and thus have less torque.

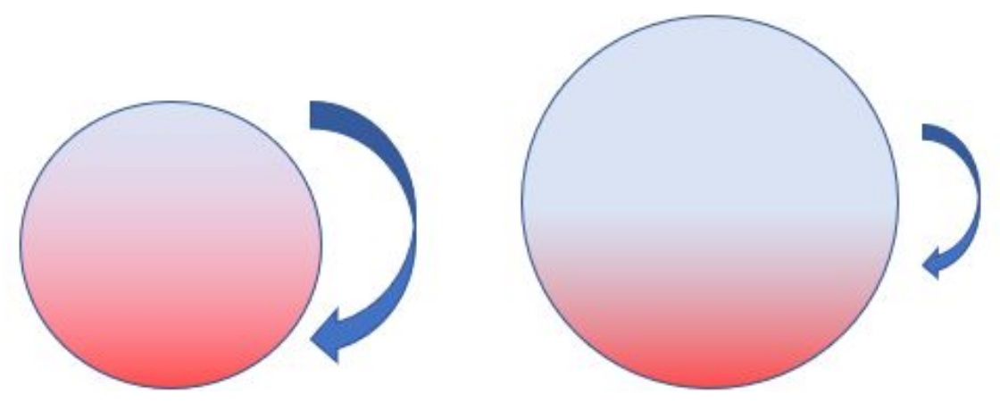


Figure 5 | Cross-section with temperature gradient of two rings with different thicknesses. Ring on right is thicker, rotating less readily.

Though these variables individually have relationships with rotational velocity, the entirety is more complex. Due to the contractive properties of LCEs, a temperature change also induces change in ring radius and cross-sectional diameter, which in turn have their own effects on rotational velocity. The research of LCE rings has many potential applications. This study can serve as a bridge into more complicated two- and three-dimensional applications of LCEs. The next step in this research is to form LCEs into other shapes and explore new applications of their motion. The rolling phenomenon can be used to explore rings that "swim" in heated water. Applications of three-dimensional contraction include objects that retain the energy when heated and release it in the form of kinetic energy. We are confident that the information gained in this study will be useful in future engineering projects, including artificial muscles, rotational spiral motors, and the myriad of yet-unexplored uses of LCEs.

References

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