論文内容の要旨

In recent years, with the miniaturization of mechanical devices and objects, micromanipulators capable of high-precise control of micro to nanoscale objects have been required for the biomedical applications and MEMS. In respond to this demand, research on the development of various micromanipulator and microactuator systems have been actively conducted. A micromanipulator is defined as a mechanical system capable of transporting small objects from one location to another and it is indispensable for observing and handling them without a microscopic observation instrument. However, in conventional micromanipulator systems, its mainstream is to utilize a needle-like metal probe at the tip of a robotic arm to manipulate the microscopic object, which can damage the microscopic object with direct contact. In addition, this micromanipulator system can become enlarged in size and complicated since a high-precision control mechanism is required.

Focusing on the phase interface existing at the boundary between the isotropic and liquid crystal phases, West et al. proposed a micromanipulator system that takes advantage of the phase interface and physical characteristics of a nematic liquid crystal material. This micromanipulator can create a phase interface between the nematic liquid crystal and isotropic phases through temperature distribution, in which the phase interface of the nematic liquid crystals can capture and drag microscale particles from one place to another. The liquid crystal micromanipulator system is characterized by its simple structure and small number of components in the system, mainly because it consists of a liquid crystal material, a container to encapsulate liquid crystals and a heat source to control the temperature of the liquid crystal. In addition, this process can reduce the size of the system itself and use of a phase interface created between the isotropic and liquid crystal phases that can allow the soft manipulation of microscale objects without damaging the objects.

When the particles are on the phase interface, they are subjected to a force whose direction is perpendicular to the phase interface and toward the isotropic phase region. Then, the interfacial force arises from the disturbance of the molecular orientational field inside the nematic liquid crystal phase, and the nematic phase region acts to exclude the microscale objects into the isotropic phase region. That is, it is possible to develop a micromanipulator system capable of controlling the position of objects by utilizing the interfacial force generated at the phase interface as a driving source in thermotropic liquid crystals, such as the nematic liquid crystals. Therefore, is a mechanical device that can be carried out as thermal and kinetic energy through the phase change in thermotropic liquid crystals. Previously, Tsuji and Chono proposed a manipulator system to measure the nematic-isotropic phase interfacial force of a 4-cyano-4'-pentylbiphenly liquid crystal (where the phase interface of the nematic liquid crystals drags a polystyrene particle with diameter of 30μm and density of 1.19 g/cm^3), and they found that the force is about 1.4nN. Also, they reported that the microscale particles prefer the state existing in the isotropic phase rather than the liquid crystal phase, and the interfacial force does not depend on particle size.

To further explain, thermotropic liquid crystals are the only material that possess two distinctive fluid phases, where the spatial coexistence of two fluid phases (liquid crystal and isotropic phases) depends on the temperature distribution. It is noted that both the liquid crystal and isotropic phases are capable of infinite deformation, and the volume change and heat transition associated with the phase change is relatively unchanged. In the physics perspective, the nematic liquid crystals exhibit a high degree of long-range orientational order of the molecules in the molecular orientation field, such that the rod-like (or disk-like) molecules have orientational order, but no translational order. However, in the isotropic phase of thermotropic liquid crystals (i.e. nematic liquid crystals), the molecular configuration lacks both orientational and translational order. In other words, the order of the molecular configuration differs between the nematic and isotropic phase, where the molecules are orientationally ordered only in the nematic phase. On the other hand, the molecular configuration of smectic liquid crystals exhibits the layer structure (i.e., possess translational order) in addition to the orientational order, and the deviation of the orientational order and the layered structure from their equilibrium state may cause the greater phase interfacial force than that for the nematic liquid crystal materials.

In this work, we have chosen three distinctive thermotropic liquid crystal materials, which are the 5CB 4-cyano-4'-pentylbiphenyl, 8CB 4-cyano-4'-octylbiphenyl and 12CB 4-cyano-4'-dodecybiphenyl liquid crystals. The 5CB liquid crystal provides the phase interface between the nematic and isotropic phases at T = 35.2 ℃. The 8CB liquid crystal possess phases of nematic and isotropic phases, and nematic and smectic phases. The 8CB liquid crystal provides the phase interface between the nematic and isotropic phases at T = 40.5 ℃ and the phase interface between the nematic and smectic phases at T = 33.5 ℃. Lastly, the 12CB liquid crystal, having a higher layered structure of molecules in the molecular orientation field, provides a phase interface between the smectic and isotropic phases at T = 58.8 ℃. The liquid crystal materials are individually enclosed between two rectangular glass plates treated with a homeotropic alignment treatment. When a temperature distribution is applied through the ends of the liquid crystal cell, two phases appears in which are separated by a phase interface. Therefore, the stable phase interfaces are created by controlling the temperature distribution of the encapsulated liquid crystal material, and the interfacial force is evaluated by trapping microscale particles, which fall from a higher temperature phase into a lower temperature phase between the liquid crystal and isotropic phase interface. The interfacial force is calculated based on the force acting on the particle and the phase interface. Therefore, the interfacial force between the liquid crystal and isotropic phases is estimated through the evaluation of forces acting on the particle based on experimental results. The forces acting on the particle are the gravitational acceleration force, the buoyancy force, the fluid resistance force, and the phase interfacial force, respectively. We have found that the 12CB liquid crystal provides the highest interfacial force when trapping a tungsten carbide particle of density of 15.63 g/cm^3 and diameter of 100μm. This interfacial force was estimated to be 99.3nN, which is about 70 times stronger than the previous calculated nematic-isotropic phase interfacial force. From these results, the application of a greater interfacial force can be achieved by utilizing the phase interface in smectic liquid crystals for better micromanipulator systems. In addition, it is reported that the liquid crystal interfacial forces depend on the size of a spherical particle. A theoretical discussion on the stress acting on the surfaces of spherical particles is considered for generalizing our results. Specifically, the energy densities due to the disturbance of the molecular alignment fields, which are commonly represented by a director field are described by the Frank's energy theory, is used. Therefore, the energy associated with the equilibrium condition of the thermotropic liquid crystals is considered. It is observed based on the analytical experimentation that the direction of the stresses acting on the particle's surface is normal to the surface, and it can be assumed to be uniformly aligned. The DSC techniques for various thermotropic liquid crystals is considered and the phase transition temperatures, and energies of 5CB, 6CB, 7CB, 8CB, 9CB, 11CB and 12CB are described. The thermotropic liquid crystal materials are enclosed in a aluminum standard 40μl crucible and it is heated up to a heating scan rate of 1 K/min. From the DSC technique, the transition temperature appears from the liquid crystal phase to the isotropic phase, or the liquid crystal phase to liquid crystal phase, respectively. Diagrams of the activated phase transitions of various thermotropic liquid crystals are shown in the last section. From DSC experiments, a correlation between the energies and forces of the interfacial forces of the thermotropic liquid crystals will be attempted.

To summarize the first part of the thesis, we aimed to develop the soft microactuator device that allows manipulating microscale objects by the interfacial force between the liquid crystal and isotropic phases. In previous work, the interfacial force between the nematic and isotropic phases is 1.4nN. To extend the application of the device, we focus on the interfacial force between the smectic and isotropic phases, and the smectic and nematic phases, respectively. From the experiments, the smectic-isotropic interfacial force is found to be more than 70 times stronger than the nematic-isotropic phase interfacial force. The results show that potential usage of this microactuator device that enables the manipulation of biological cells without damage, or the manipulation of microbeads for industrial applications.

Secondly, another liquid crystal mechanical device was proposed by utilizing the elasticity of the molecular orientation field of nematic liquid crystals. In nematic liquid crystals, when there is a spatial distortion in the director field of the molecules, the preferred local average direction of the rod-like molecules, the local energy density follows by the Frank elastic energy density. Some of the factors to create a distorted director field may consist of orientation anchoring at the solid boundary of a container, electric or magnetic fields, and flow. By using the energy when the molecular orientation field of a nematic liquid crystal filled between two small circular glass plates is distorted by an anchoring condition, the rotation of an upper glass plate is achieved. Our experimental results confirm that an upper glass plates rotates 90º counterclockwise with the relaxation of the director field, so the development of unique mechanical elements can be expected for future liquid crystal applications. A postulated theoretical approach was attempted through the use of the Frank's energy theory and Leslie-Ericksen elasticity theory to quantify a physical description between the difference of the anchoring condition directions from a lower and upper glass plates, which is defined as the rotational angle ϴ. To summarize the second part of the thesis, we developed mechanical elements utilizing the elasticity of the molecular field of the nematic liquid crystals. By utilizing the energy when the molecular orientation field of the liquid crystals filled between two circular glass plates is distorted by anchoring condition, the rotation of the upper glass plate is attempted. Our experimental results confirm that the object rotates with the relaxation of the distortion energy.