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Capillary oscillations and instabilities of discotic liquid crystal threads (*)

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Résumé. — Des expériences mécaniques sur des fils fins de cristal liquide discotique sont décrites. La résonance des fils sous l'effet d'un champ électrique oscillant permet de mesurer la tension de surface. Des instabilités de flambage sont observées sous compression mécanique ainsi que sous champ magnétique. Tous ces effets, contrôlés par la tension de surface après relaxation plastique, sont caractéristiques de l'ordre discotique qui assure la stabilité des fils.

Abstract. — Mechanical experiments on thin threads in discotic liquid crystal are described. Thread resonance under oscillating electric field excitation allows the measurement of the surface tension. Buckling instabilities are observed under mechanical compression and also under magnetic field. All these effects, dominated by surface tension after plastic relaxation, are characteristic of the discotic ordering which ensures the thread stability.

Disk-shaped molecules can exhibit discotic liquid crystal phases with a two-dimensional network of molecular columns. Such a structure presents anisotropic mechanical properties. The discotic liquid crystal should appear as a solid body under compression or dilation either parallel or normal to the columns. One however expects that the columns may easily glide one along the other : the column curvature elastic constant should then have a value of the same order of magnitude as that of a nematic liquid crystal ; for the same reason, the apparent shear elastic constant, in a direction normal to the columns, should be small, and depending on the specimen thickness, since it would correspond to a weak curvature of the columns.

In practice, some of the mechanical properties of discotic liquid crystals were previously analyzed. The compression elastic constant (along the columns) and the apparent shear elastic constant (normal to the columns) have been measured [1]. These experiments were performed on bulk specimens, oriented between two glass plates. The shear elastic constant (~ 10⁶ c.g.s.) appears to be abnormally large and thickness independent. Through obser-

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vations of mechanical instabilities [2, 3] a value of the column curvature elastic constant has been obtained and found six orders of magnitude larger than expected. This large $K$ value, as mentioned before is probably due to the influence of defects [2]: in the presence of defects, the discotic columns cannot glide along each other, and the system tends to behave as a normal solid. Recently, J. Prost has proposed that these defects may be thermally excited point defects, intrinsic of the discotic phase: the column length would present a finite characteristic size [4]. N. A. Clark has shown that it is possible to obtain freely suspended strands (or threads) [5, 6] with a good crystallographic quality, by stretching discotic liquid crystals. It is thus interesting to study the mechanical properties of these discotic strands. As shown later, a new problem is that, with very thin specimens, the surface tension energy becomes the dominant part, compared to the column curvature energy, when the thread is bent.

In this paper, we describe mechanical experiments on discotic threads. After a discussion of the role played by the surface tension according to the sample dimensions (part 1), we describe the discotic threads (part 2). We have made observations of thread vibrations under sinusoidal electric forces. These vibrations are controlled by the surface tension energy and are assimilable to capillary waves; the surface tension is deduced from thread resonances (part 3). We have also observed a buckling instability due to volume elastic energy transfer to surface elastic energy under compression (part 4), a magnetic buckling instability on a clamped thread under longitudinal magnetic field and finally magneto-plasticity on a half-thread with a free end (Part 5).

1. Role of the surface tension energy.

Up to now, the surface energy was not considered when discussing mechanical properties of discotic materials. The problem now, for threads with a relatively large external surface, is to compare the surface tension energy and the column curvature energy in presence of bend. Let us consider a cylindrical sample with columns aligned along the cylinder axis. We call $L$ the cylinder length and $d$ its diameter, $\gamma$ the surface tension and $K$ the column curvature elastic constant. We imagine (Fig. 1a) that the cylinder is curved and makes an angle $\theta$ with its initial positions at both ends. The change in the surface energy is

$$W_s \sim 2 \pi d L \gamma \left( 1 - \cos \theta \right) \sim \pi d L \gamma \theta^2.$$

Calling $q = \pi / L$ the wavevector of the bent cylinder, the curvature energy density is $1/2 K q^2 \theta^2$, so that the total curvature energy is

$$W_c \sim \frac{1}{2} K \frac{\pi d^2}{4} \frac{\pi^2}{L^2} \theta^2 \sim K \pi \frac{d^2}{L} \theta^2.$$

![Fig. 1. — Buckling diagram of a discotic liquid crystal under compression strain along the columns: a) for a thread, b) for a bulk specimen.](image-url)
The surface energy becomes preponderant if \( W_s > W_c \), giving

\[
d \approx \frac{\gamma L^2}{K}.
\]  

The limit value of \( d \) depends on \( L \) and \( K \), so that the effect depends on the geometry of the experiment.

We can first discuss the buckling of a columnar discotic liquid crystal under a compression applied along the columns. The first evaluation of the buckling threshold was presented by Kleman and Oswald [7], for a bulk specimen between two glass plates (Fig. 1b). Writing that the curvature energy balances the compression energy at the threshold, they found the displacement threshold \( \delta \sim \pi^2 K / LB \), where \( L \) is the specimen length in the column direction and \( B \) the bulk compressional constant. Using the usual values for liquid crystal elastic constants \( B \sim k_B T / m^3 \) and \( K \sim k_B T / m \), where \( m \) is a molecular length, \( k_B \) the Boltzmann constant and \( T \) the absolute temperature, this result gives \( \delta_c \sim \pi^2 m^2 / L \), which is much smaller than a molecular length, even for a very thin sample. We can then remark that, for this low \( K \) value and with \( \gamma \sim k_B T / m^2 \), the relationship (1) becomes \( d \approx L^2 / m \) and is always verified in practice. For example, if we consider a sample of thickness \( L \sim 200 \mu m \), the surface tension energy is preponderant when \( d < 10^3 \text{ cm} \). Thus, the buckling threshold should be evaluated by balancing the compression energy by the surface energy and not the curvature energy as it was assumed in reference [7]. To do this new evaluation, we consider a specimen bent under a displacement \( \delta \) so that the columns make an angle \( \theta \) at their ends. The compression energy is \( \delta d^2 L (\delta / L - \theta^2 / 2)^2 \). The change in the surface energy is \( dL \gamma \theta^2 \). The threshold \( \delta_c \) corresponds to the \( \theta^2 \) terms equality: \( B d^2 \delta_c \theta^2 = dL \gamma \theta^2 \) and \( \delta_c = (\gamma / B) (L / d) \sim (mL / d) \). This new threshold is of the order of \( m / 100 \), larger than the preceding evaluation of reference [7], but too small to be experimentally measured.

In fact, the buckling experiment on a bulk specimen has already been performed [2]. A buckling threshold \( \delta_c \sim 10 \AA \) has been found, depending on the column length as \( 1 / L \). Using a model where the instability results from energy transfer between compression down to curvature energy, it has been deduced that \( K \sim 0.1 \text{ cgs} \) is six orders of magnitude larger than in usual liquid crystal and that \( \delta_c \) depends on \( L \) as \( 1 / L \). This model was appropriate to the sample geometry: with this large value of \( K \) and for \( L \sim 50 \mu m \) and \( \gamma \sim 100 \text{ cgs} \), the relationship (1) is verified when \( d < 25 \mu m \); the sample diameter used in reference [2] (some mm) was much larger, i.e. the surface energy was really negligible in this previous experiment.

Consider now a discotic thread with a diameter of a few microns. Using the same large \( K \) value, the relationship (1) is then fulfilled; we can thus predict, in general for threads, a new kind of mechanical behaviour, controlled by the surface tension and not by the curvature: a thin discotic thread should present a capillary behaviour. This property is specific of discotic liquid crystals: for a thread made from a tridimensional crystal, \( K \sim BL^2 \) and \( \gamma \sim Bm \), so that relationship (1) is only verified when \( d \sim m \), never realized. For a liquid or a nematic liquid crystal thread, the surface tension is preponderant but the surface energy can be relaxed by a growth of the section, since there is no positional ordering in the bulk. These threads are unstable and the capillary regime can only be observed on drops and not on threads. For a discotic thread the section cannot vary because of the 2D ordering of the columns: the threads are stable and can present a capillary behaviour. Smectic thin films, with clamped edges, should also present a capillary behaviour, although this has never been observed. Discotic threads are then the only stable threads which could present a capillary behaviour. In the following, we show some specific examples: thread vibrations and mechanical buckling instabilities.
2. Preparation of threads.

2.1 PREPARATION. — We used a discotic liquid crystal synthetized by C. Destrade [8]: the Hexa-n-pentyloxytriphenylene (C₃HET). This compound presents a discotic columnar phase with a hexagonal column network and with a molecular ordered distribution along a column (Dₜ₀ phase) in the following temperature range:

C₃ HET : K $\xrightarrow{69 \, ^\circ \text{C}}$ Dₜ₀ $\xrightarrow{122 \, ^\circ \text{C}}$ I.

We prepared the discotic threads with the same procedure as in reference [5]: the liquid crystal is melted between two glass plates of thickness 100 µm, and the temperature is lowered to the discotic phase temperature $T = 80 \, ^\circ \text{C}$. When the plates are slowly taken away from one another, a discotic drop is formed which will give rise to a thread. The motion of the plate is frequently interrupted, with a ten minutes annealing between each displacement. We obtain quasi-cylindrical threads attached to the glass plates by larger parts, called « bases » in what follows. We can make threads with diameter from 1 µm to 20 µm and length from 100 µm to 1 mm. We have verified that, for the thickest threads (> 10 µm), the optical axis is oriented along the thread axis, this corresponds to the direction of columns. On the other hand, the base is a highly distorted region with a mean column orientation along the thread axis. When the thread is obtained, it is possible to slightly change its length during the experiments, by moving the glass plates (and then the bases) with a micrometer. We do not know the exact thread temperature during the experiments, but only the base temperature maintained at 80 °C; we are nevertheless sure that the strand remains in the discotic phase ($T > 69 \, ^\circ \text{C}$), since, when freezing it, we observe a strong light scattering from the now crystalline thread.

2.2 STRIATIONS. — When we begin to make a thread, we first obtain a discotic film which partially breaks and then a large strand with longitudinal grooves. Accordingly, we observe transversal, apparently periodic, striations on the base (Fig. 2). The base thickness compares the previous film thickness determined by interferometric method, with the Newton scale colours, in the range of 10 to 20 µm. When observing the grooves, the thread seems to be

Fig. 2. — Drawing from a microphotograph of a thread end during thread formation.
composed with several thinner strands placed side by side. Moving the glass plates further away, the thread becomes thinner and finally we obtain a thin thread without any visible groove.

The transverse striations observed in the base remain visible all the time during thread formation and even about 1 hour after the thread is obtained; the striations are normal to the thread axis and their distance depends on the base thickness. For two base thicknesses $d = 10 \mu m$ and $d = 14 \mu m$, the striation wavelength is equal to $4 \mu m$ and $6 \mu m$ respectively. To explain these results, it could be tempting to simply transpose them in the frame of a previously published model [3] about the column undulation instability observed on a bulk specimen under dilation normal to the columns. In this work, writing that the dilation elastic energy is balanced by the column curvature energy, we established the relationship between the undulation wavelength, $\lambda$ and the sample thickness $d$: $\lambda^2 = 4 \pi d \sqrt{K/B}$. This model is valid for the base striations if the base is thick enough so that the surface tension does not play any role. Using relationship (1) with a base length $L \sim 30 \mu m$, we obtain that the thickness or the width must be $d > 10 \mu m$, which is approximately the base thickness. Note that the relation was established in reference [3] for a sample between two glass plates, giving a maximum transverse lateral dilation for the discotic columns at the sample middle. Here the upper and lower surfaces are free and correspond to the maximum dilation, but in both cases the conditions define the same transverse wavevector equal to $\pi/d$. The same relationship can thus be used in the present geometry. For the two base thicknesses, the new $\lambda$ and $d$ measurements are reported in figure 3, which is the same figure as the corresponding one in reference [3]. These results are consistent with the previous graph, giving two points for small values of $d$. We can thus suppose that these striations are due to a base dilation during the thread formation: when stretching the liquid crystal, there is a flow of matter from the base to the thread and the pressure decreases in the base, this is equivalent to a dilation normal to the columns in the base. This dilation is larger than the undulation threshold so that the columns are broken and the striations are permanent after the deformation relaxation.

![Figure 3](image)

Fig. 3. — Square of the undulation wavelength versus the sample thickness $d$. Crosses: previous results of reference [3] on bulk specimen. Stars: new results on thread bases.
3. Thread vibrations.

We induce transverse vibrations on the discotic thread with the following experimental set up. The liquid crystal is kept at the ground potential. A thin metallic wire, placed at about 20 μm from the thread center is set at a sinusoidal potential with a 40 V r.m.s. amplitude and frequency ν in the kHz range. Under the applied electric field, the thread is submitted to two forces which correspond to two terms in the liquid crystal polarization. Polarization results from the molecular induced dipoles and from the free ion dipoles. The first force $f$ is due to the action of the field gradient on the induced molecular dipoles. The second force $f'$ comes from the Coulomb force acting on the free charges and exists only if the field period is larger than the charge relaxation time. The force acting on the thread contains then a DC component and an oscillating component proportional to the square of the applied field, and thus at a frequency $2ν$. The DC component creates a permanent thread attraction towards the wire (which is discussed later) and the AC component excites transverse resonances of thread when the frequency $2ν$ coincides with the frequency of one of the normal modes of thread vibrations. As the wire is close to the thread center, we expect the selective excitation of odd modes of wave number $n(\pi/L)$, with $n = 1, 3,$ etc... An example is shown in figure 4: a thread of length ~ 300 μm and thickness ~ 8 μm undergoes a thread vibration, corresponding to the mode $n = 1$, of amplitude ~ 10 μm, at $ν = 4.6$ kHz.

Fig. 4. — Optical microscope picture of a thread vibration at the resonance frequency : $x$ is the thread axis and $y$ is the direction normal to the thread axis. The thread length is 300 μm.

To calculate the resonance frequency of the thread, we propose the following model : we assume that the thread is a cylinder. It is submitted to two restoring forces from volume and surface tensions. We neglect the volume contribution due to the column curvature, from the discussion of part I. There remains a volume tension due to the forces created by the anchoring of thread ends; assumed to be a rigid edge anchoring, the thread is submitted to an initial elongation $δ_0$ and the volume force is $T = B(πd^2/4)(δ_0/L)$. On the other hand, if the thread is free to glide at the ends, $T = 0$. The surface term is due to surface tension and the resulting tension is $T' = πdγ$.

To compare these two forces, we use the same relationships of $B$ and $γ$ versus $m$ as in part I: to obtain $T < T'$ we must satisfy the condition $δ_0 < 4 mL/d$. For the thread
dimensions described above and with $m \sim 10 \text{ Å}$ we obtain $\delta_0 \approx 1.5 \mu m$. This condition is probably satisfied during annealing of the sample from plastic flow at the thread ends: for a complete plastic relaxation, the ultimate value of $\delta_0$ would be a molecular size $m$, much smaller than the estimated limit $\sim 1.5 \mu m$, and $T'$ is negligible compared to $T'$. In practice, we do not know the exact boundary conditions on the thread but we can reasonably expect plastic relaxation to result in $\delta_0 \sim$ a fraction of the thickness, i.e. lower than the 1.5 $\mu m$ limit, resulting again in a negligible volume tension compared to surface tension.

Assuming a perfect plastic relaxation of the thread, the transverse vibration equation, with a thread displacement $y$ normal to the thread axis $x$ (see Fig. 4), is written

$$\frac{\partial^2 y}{\partial t^2} = \frac{4 \gamma}{\rho d} \frac{\partial^2 y}{\partial x^2}$$

(2)

where $\rho = 1.1 \text{ g/cm}^3$ is the volumic mass. The solution of (2), with a force of frequency $2 \nu$ is $y = y_0 \sin 2 \pi (2 \nu t - x/\lambda)$. For the fundamental resonance mode $n = 1$, the thread resonance frequency is given by $4 \nu_R^2 = \gamma / \rho d L^2$. The corresponding field frequency is $\nu_R$, so that the surface tension energy is obtained from the relationship $\gamma = 4 \rho d L^2 \nu_R^2$.

Experimentally, when a resonance is obtained, we take the precaution to relax any residual bulk tension $T$ of the thread, by moving closer the glass plates on a few $\mu m$ and repeating this procedure several times: the resonance frequency decreases by 30% and finally becomes stable. We can consider that the bulk tension is then totally relaxed and that the only restoring force is due to the surface tension. Figure 5 shows the observed $\nu_R^2$ vs. $1/4 \rho d L^2$, where $L$ is the length of the vibrating part of the thread; this length $L$, as well as the thread diameter $d$ (assuming the thread to be a cylinder) are measured on pictures made through an optical microscope. The experimental points of figure 5 arise from several samples with vibrating lengths from 200 to 500 $\mu m$ and diameters from 4 to 12 $\mu m$, so that the frequencies $\nu_R$ lie from 2.3 to 5.7 kKHz. We find a linear relationship as expected, giving $\gamma = 70 \pm 10 \text{ erg/cm}^2$. In fact, the uncertainty on the resonance frequencies is large due to a large damping: the thread vibration is visible during a frequency width of $\pm 300$ Hz. We choose for $\nu_R$ the central value of the band. Another uncertainty is due to the thread thickness which is not well known: the thread is slightly wider near the bases and thinner in the center. Finally the cylindrical shape assumption cannot be really checked. In the frame of

Fig. 5. — Square of the thread resonance frequency versus thread geometric parameters.
this assumption anyway, this value, $\gamma = 70 \pm 10$ erg/cm$^2$, is larger than the one of usual liquid crystals. Note also that, for the thin strands, there is no increase of the surface tension due to the volume penetration of the surface undulation [10-11]. The penetration length of a surface bend with wave vector $\pi/L$ is [10] $\xi = L/\pi d$. $\xi$ is much larger than $d$, which explains that $\gamma$ will not change.

In figure 4, we observe, for all the threads at the resonance, that the vibration has not a symmetrical shape. The mean position of the thread is curved and the vibration occurs between the straight line (which corresponds to the equilibrium without any force) and a distance twice the mean position. If we suppose that the DC and AC components of the force are the same, the thread displacement appears to be zero when the total force is zero, suggesting that there is no inertial effect and thus a quasitotal damping. From the resonance frequency width, the thread appears as an oscillator with a quality factor $Q \sim 6$. These two observations are not consistent, so that the DC component of the force is larger than the AC component, in a ratio about 6. We conclude that $f' \sim 5 f$. To estimate the induced polarization force $f$, we assimilate the metallic wire end to a sphere in the space with a diameter $2R_0 = 30 \mu$m at a potential $V = 40$ V. The electric field at the thread position is then $E = R_0 V/r^2$, if $r$ is the distance between the thread and the wire end center. Using the value $r = 35 \mu$m measured on figure 4, we obtain, at the thread position, a field $E \sim 5 \times 10^5$ V/m and a field gradient $dE/dr \sim 3 \times 10^{10}$ V/m$^2$. Using the value $\varepsilon_r = 5$ for the relative dielectric constant of the discotic crystal, we obtain the volume induced polarization force $f = 4 \varepsilon_0 E (dE/dr) = 5 \times 10^5$ N/m$^3$, where $\varepsilon_0$ is the vacuum dielectric constant, and thus $f' \sim 2.5 \times 10^6$ N/m$^3$. In this model, $f'$ is due to the Coulomb force acting on the free ions in the sample. If $n$ is the number of free ions per unit volume, $n = f'/2 eE \sim 2 \times 10^{19}$ m$^{-3}$. Assuming that the conductivity is intrinsic, this $n$ value can be compared to the thermally dissociated molecules at the experimental temperature $T = 340$ K: with a dissociation activation energy $E_d = 0.5$ eV and a volumic number of molecules $n_0 = 9 \times 10^{26}$ m$^{-3}$, one finds $n = 2 n_0 \exp (-E_d/kT) = 7 \times 10^{19}$ m$^{-3}$. The two values of $n$ are in good agreement, so that the estimate of $f'$ seems to be correct and the model reasonable to explain the thread vibration shape.

4. Thread buckling under compression.

We apply a compression along a thread axis by moving one of the two ends. We then observe, above a displacement threshold, a thread buckling, visible under optical microscope. The existence of a buckling results from the discotic structure: for a liquid, nematic or smectic thread, buckling is not necessary to adjust the length; its section increases to maintain a constant volume. This is not possible for a discotic thread because there is no lateral flow, so that the thread buckles to keep a constant length in spite of the compression deformation. The buckling instabilities appear probably because the thread shortening is produced during a time shorter than the plastic relaxation time already discussed.

Buckling appears when the moving plate displacement is larger than typically $\sim 10$ $\mu$m. This value seems to be the threshold for thread buckling. It is 4 orders of magnitude larger than the column buckling threshold observed on a bulk specimen [2]. This difference is obvious since it is not the curvature, but the surface tension which is opposed to the thread buckling. The threshold calculated in part I, $\delta_c \sim \gamma L/Bd$, gives a value $\delta_c \sim 1$ $\mu$m for our thread dimensions. This order of magnitude is weaker but comparable to our observations. Our larger observed threshold is probably related to plastic relaxation. We were not able to check the $\delta_c$ dependence on $L$ and $d$ because our experimental set up does not allow for a sufficient accuracy on the threshold.
5. Magneto-plasticity in a thread.

We apply a magnetic field parallel to the thread axis. We observe again a thread buckling when the applied field is larger than 5.5 kG. To explain this observation, we could imagine first the following model: under the magnetic field, the discotic texture tends to rotate so that the mean normal direction to the discotic molecules becomes perpendicular to the magnetic field. One can expect that this rotation involves a column lengthening and thus a thread buckling, if the thread ends are fixed. Let us estimate this effect by writing that the field threshold $H_s$ is reached when the stored magnetic energy equilibrates the change in tension surface energy for a buckling instability of angle $\theta$: 

$$H_s = \frac{1}{2} \chi_a H_s^2 \frac{\pi}{4} d^2 L \theta^2 - \gamma \pi d L \theta^2,$$

where $\chi_a$ is a diamagnetic susceptibility of the order of magnitude $\sim 10^{-7}$ c.g.s. Then $H_s \sim (8 \gamma / \chi_a d)^{1/2} \sim 10^6$ G, which is much larger than the observed value. This model is not correct, we imagine now another mechanism: we assume that the columns are previously under stress in the base, as indicated by undulations. The magnetic field is also applied to the base and increases the column length in the base, thus increases their undulation amplitude; but the thread continues inside the base, so that the pressure increasing in the base may be partially compensated by material flow from the base into the thread, involving the thread lengthening and the buckling. This is the opposite of the striation formation when stretching the thread. This matter flow could explain that the apparent magnetic threshold is much lower than the theoretical threshold calculated for a thread with fixed ends.

During this experiment, we have broken some threads. We have realized that half threads, fixed on a base at only one end, the second end being free, are also stable. This worked only for thick threads ($d > 10 \mu m$). The existence of stable half-threads results from the discotic structure: the column ordering prevents a transverse flow; if the columns are clamped at the fixed end, there is no more flow along the column direction, so that the thread does not evolve into a drop. Note that the corresponding half-membrane with smectic crystal, i.e. a half-plane with a free edge, is not stable, because of the possibility of flow in two directions in the smectic layer plane. On these half-threads, we apply a magnetic field, successively parallel and normal to the axis; in both cases the magnetic field is increased from 0 to 13 kG and then decreased. We observe (Fig. 6) that, with the parallel field, the thread grows longer when the field increases and shorter when the field decreases, keeping a small amount of lengthening when the field comes down to zero. If we apply a normal magnetic field, the behaviour is

![Fig. 6. — Length variation $d$ of a half-thread under magnetic field parallel or normal to the thread axis.](image-url)
reversed: a shortening appears when the field increases and a lengthening when it decreases. During experiments with successive parallel and normal magnetic fields, the curve describing the length change $\delta$ versus the applied field $H$ presents the aspect of two hysteresis half-cycles. The maximum change in thread length is about 8 $\mu$m for a field equal to 13 kG. The magnetic field threshold observed for the change in length of a half-thread, $\sim$ 4 kG, is very close to the buckling threshold of an entire thread under magnetic field. This confirms the mechanism of material flow from the base, described above.

6. Conclusion.

Clark has shown that a discotic liquid crystal thread, fixed at the two ends, is stable; such a thread is the equivalent for the discotic structure of a thin film for smectic liquid crystal. We have prepared discotic threads and observed that they remain stable even when they are fixed at only one end. This stability is related to discotic ordering which prevents transverse flow as well as longitudinal flow, so that there is no drop formation.

Mechanical experiments on discotic threads are interesting because of the specimen geometry: a simple evaluation shows that the surface tension energy is preponderant compared to the column curvature energy. This analysis is confirmed by experimental results. Transverse thread vibrations are induced by an oscillating electric field. A resonance is observed when the external force frequency coincide with the first normal mode of thread vibrations. When the volume forces are relaxed, the surface tension can be deduced from the resonance frequency and the geometric parameters of the thread. The value $\gamma = 70 \pm 10$ c.g.s. is obtained from several experiments.

Thread buckling is observed under a compression along the thread axis. The compression displacement threshold, $\sim 10$ $\mu$m, is much larger than the one obtained in similar previous experiments made on a bulk specimen. The thread threshold is in good agreement with the estimation made assuming that the surface tension is opposed to the buckling and not the column curvature. Finally, plastic flow in the thread bases is induced by a magnetic field, resulting in a buckling for a thread fixed at both ends; for a half-thread fixed at only one end, the effect of the magnetic field is a thread lengthening or shortening, according to the magnetic field direction.

All these effects are capillary, i.e. controlled in these thin samples by surface tension rather than curvature volume elasticity.

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References