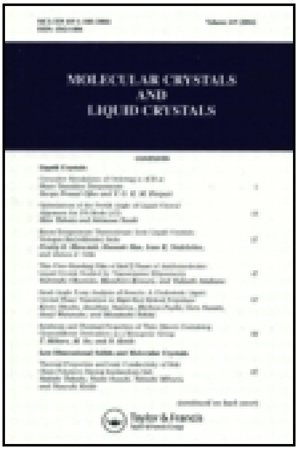

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Role of Surface Effects on the Formation and the Dynamics of Defects in a Nematic Cell with a Planar Anchoring

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We have studied the dynamics of defects (disclinations and walls) which appear in a thin nematic cell with planar anchoring, after a quench from the isotropic phase. The transient texture can be analyzed in terms of $\pm 1/2$ disclinations and surface π-walls (corresponding to a π-rotation of the director in the plane of the cell). We determine the structure of the walls and explain the main features of the dynamics. The relaxation of the texture is largely dominated by surface effects, which control the relaxation trajectories and velocities of the disclinations, as well as the dynamics of π-walls.

Keywords: anchoring; defects; disclinations; nematic; texture

INTRODUCTION

Defects in nematic liquid crystals are singularities of the director field. Among them, disclinations are well-known topological line defects [1,2]. They can be easily obtained and observed in nematic samples through appropriate boundary conditions, a thermal quench or pressure jumps [3]. If their static properties are well understood now, their dynamics raises several problems which have not been satisfactorily handled experimentally. For example, recent simulations [4,5] have focused on the dynamics of bulk pair-annihilating 1/2-disclination

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lines and have stressed the role of hydrodynamics on the velocity of the defects. The corresponding experiments (measuring the velocity of free annihilating opposite disclinations) seem however difficult to achieve because surface effects are almost always present in real cells and considerably alter the bulk dynamics: the disclinations are not isolated.

In this paper, we report observations on the formation and the dynamics of disclinations in a thin cell with a classic SiO planar anchoring. We underline the main effects of the anchoring on the formation of defects and their following dynamics.

EXPERIMENTAL SET-UP

A 5CB (4-cyano-4′-n-pentylbiphenyl from Synthon) film is sandwiched between two parallel glass/ITO plates covered by a 400 Å thick SiO layer evaporated at a 60° incident angle. The resulting anchoring is rigorously planar for 5CB [6]. The plates are assembled with parallel easy axes. The thickness of the cell is fixed by means of Mylar spacers in the range 2–20 μm and measured before filling by using a spectrophotometer.

Samples are placed in an oven (INSTEC STC200D) at a temperature T fixed below the nematic-isotropic temperature transition T_{NI}. Approaching and withdrawing a hot wire from the cell, we locally induce the transition in the isotropic phase. The nematic phase is restored after a few seconds. The change of texture and the dynamics of defects are observed under a polarizing microscope and recorded by means of a fast CCD camera (Pulnix TM-6703) connected to a PC frame grabber able to store up to 100 frames/s.

FORMATION OF DISCLINATIONS AND π-WALLS

Figure 1 shows a typical sequence of the textures obtained during the nematic phase recovery. The nematic phase appears first in the bulk of the sample, while the 5CB close to the SiO surfaces is still in the isotropic phase. During this process, the absence of any preferred director orientation in the bulk results in an inhomogeneous texture with $\pm 1/2$-disclinations. At the contact of the anchoring layer, the director of the nematic phase gets rapidly aligned along the easy axis (here along the polarizer axis P) and the remaining $\pm 1/2$-disclinations become straight and orthogonal to the substrates. Due to the surface anchoring, the elastic distortion due to the disclinations is confined within worm-like lines connecting pairs of disclinations of opposite charges. From the study of birefringence we can see that the director

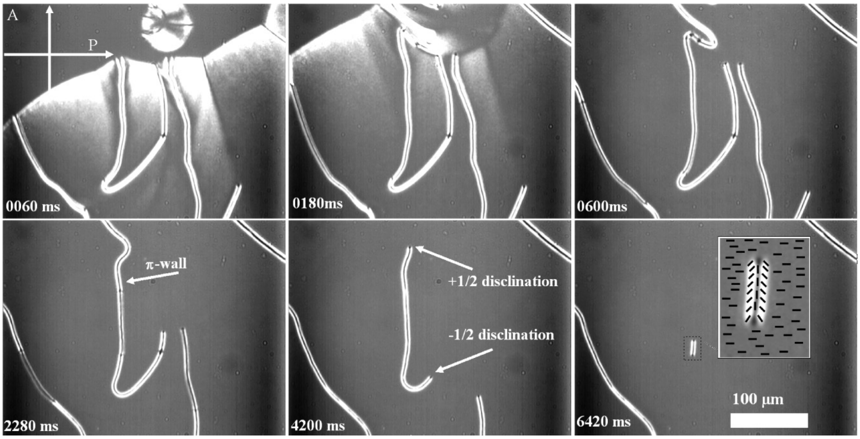

FIGURE 1 Nucleation of defects (π-walls with disclinations at the end) during the isotropic to nematic transition and their following relaxation in a cell with planar anchoring (thickness of the cell: 14 μm). Note that the disclinations are here normal to the pictures.

rotates of π across these surface walls of a few microns of thickness (see insert in last image of Fig. 1).

At temperatures T close to T_{NI}, these π-walls slowly tend to become straighter but for T a few degrees below T_{NI}, the shape of the walls is almost frozen and the disclinations annihilate by pairs of opposite signs along complex trajectories (see Fig. 1) determined by the π-walls. This observation shows that opposite disclinations do not directly interact as it could be expected for a bulk medium. They rather move under the influence of the elastic and anchoring energies confined inside the π-wall. The direct elastic interaction between disclinations is therefore screened by the anchoring above a distance which compares to the thickness of the cell [7] (here a few microns).

Given one disclination, its curvilinear velocity is found constant along a π-wall and independent from its motion direction (see Fig. 2). This suggests that both the driving force (which comes down to the energy per unit length of the π-wall) and the dissipation forces acting on the disclination depend only weakly of the orientation of the π-wall with respect to the easy axis. Detailed results concerning the dependence on thickness and temperature, the effect of an electric fields as well as a comparison between disclinations of opposite signs will be given elsewhere [8]. Let us only stress that the velocity of a $\pm 1/2$ disclination is about 10–40 $\mu m \cdot s^{-1}$ for the considered thickness range.

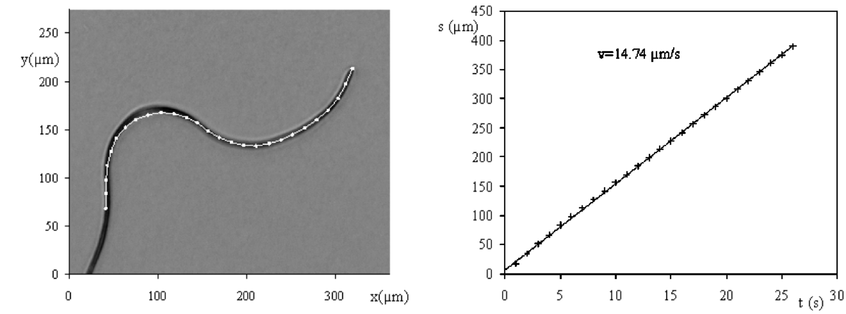

FIGURE 2 Left: the image represents a π-wall at t = 0s in a 14 μm thick cell. The superimposed white line represents the trajectory of the tip (–1/2 disclination) in the next 26 s (dots are marked every seconds). Note that the π-wall form remains worm-like during the defects annihilation but slightly moves where strongly curved. Right: curvilinear position of the disclination as a function of time.

We now focus on the structure of π-walls and discuss generic features of the dynamics.

STRUCTURE OF A SURFACE π-WALL

The π-walls are formed during the isotropic-to-nematic transition and their regular shape indicates that they are locally at equilibrium. We consider an arbitrary wall corresponding to a π-rotation of the director along a straight line making an angle α with the easy axis **x** (see Fig. 3).

The in-plane director $\mathbf{n}(\cos\phi, 0, \sin\phi)$ is parametrized by its angle ϕ(x, y, z) with the **x**-axis. For a symmetric cell of thickness d, the total

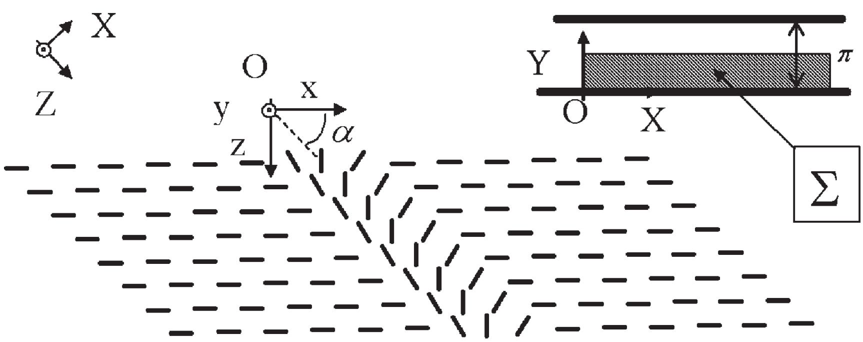

FIGURE 3 Sketch of the director field in a thin cell of thickness d in the vicinity of a π-wall.

energy E consists in the Frank energy for the bulk (we identify K_1 with K_3) and the anchoring energy (we use the Rapini–Papoular expression). We obtain:

$$E = \iiint \left\{ \frac{K}{2} \left[\left(\frac{\partial \varphi}{\partial x} \right)^2 + \left(\frac{\partial \varphi}{\partial z} \right)^2 \right] + \frac{K_2}{2} \left(\frac{\partial \varphi}{\partial y} \right)^2 \right\} \mathrm{d}x\mathrm{d}y\mathrm{d}z + \iint \frac{K_2}{2L} \sin^2 \varphi \mathrm{d}x\mathrm{d}z \qquad (1)$$

where K is the splay-bend modulus, K_2 the twist modulus and L is the azimuthal anchoring extrapolation length. In the coordinate system *(X,Y,Z)*, where

$$X = \sqrt{\frac{K_2}{K}} \frac{\pi}{d} (x \cos \alpha - z \sin \alpha); \; Z = \sqrt{\frac{K_2}{K}} \frac{\pi}{d} (x \sin \alpha + z \cos \alpha); \; Y = \frac{\pi}{d} y,$$

the normalized energy $E' = \pi E / 2Kd$ per unit length along Z is written as:

$$E' = \iint \left[\left(\frac{\partial \varphi}{\partial X} \right)^2 + \left(\frac{\partial \varphi}{\partial Y} \right)^2 \right] \mathrm{d}X\mathrm{d}Y + \int \frac{d}{\pi L} \sin^2 \varphi \mathrm{d}X \qquad (2)$$

where the integrals are evaluated on $X \in [0, \infty]$ and $Y \in [0, \pi/2]$ (dashed region Σ in Fig. 3). The Euler–Lagrange minimization of E' and symmetry considerations give the following set of equations:

$$\begin{aligned} &\Delta \varphi = 0 \\ &\varphi(0, Y) = \pi/2; \; \varphi(+\infty, Y) = 0 \\ &\left.\frac{\partial \varphi}{\partial Y}\right|_{Y=\pi/2} = 0; \; \left.\frac{\partial \varphi}{\partial Y}\right|_{Y=0} = \frac{d}{2L\pi} \sin 2\varphi \end{aligned} \qquad (3)$$

ϕ therefore satisfies the Laplace's equation with mixed (Dirichlet and Neumann) boundary conditions on Σ. To solve (3) we can use an electrostatic analogy.

We first solve the case of infinite anchoring ($L = 0$), for which the last equation of system (3) is replaced by $\varphi(X,0) = 0$. Using the conformal mapping technique in the complex plane (with $Z = X + iY$), we define a generalized potential $\phi(Z) = \psi(X,Y) + i\varphi(X,Y)$, where ψ is the conjugate harmonic of φ. Applying the mapping $W = S + iT = th^{-2}(Z/2)$, we obtain in the complex plane *(S,T)*, the boundary conditions sketched in Figure 4. It is now easy to recognize the boundary conditions of the simple (2D) harmonic potential due to a charge –1/2

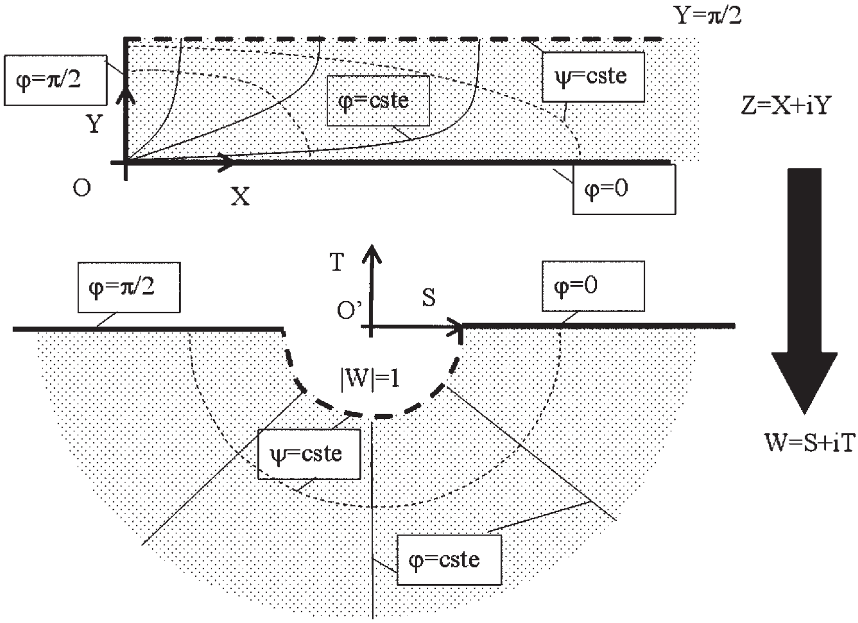

FIGURE 4 Conformal mapping of region Σ:W $= \tanh^{-2}$(Z/2).

located at the origin:

$$\phi(W) = -\frac{1}{2}\ln W\cdot \tag{4}$$

It yields:

$$\begin{aligned}\varphi(X,Y) &= \mathrm{Im}\left(-\frac{1}{2}\ln\frac{1}{\tanh^2\left(\frac{X+iY}{2}\right)}\right)\\ &= \text{arc tan}\left(\frac{\sin Y}{\sinh X}\right)\end{aligned} \tag{5}$$

In the case of a strong anchoring, the π-wall therefore consists of two symmetric twist disclinations located on the surfaces. The director field is given by:

$$\varphi(x,y,z) = \text{arc tan}\left(\frac{\sin(y\pi/d)}{\sinh\left(\sqrt{\frac{K_2}{K}}\frac{\pi}{d}(x\cos\alpha - z\sin\alpha)\right)}\right) \tag{6}$$

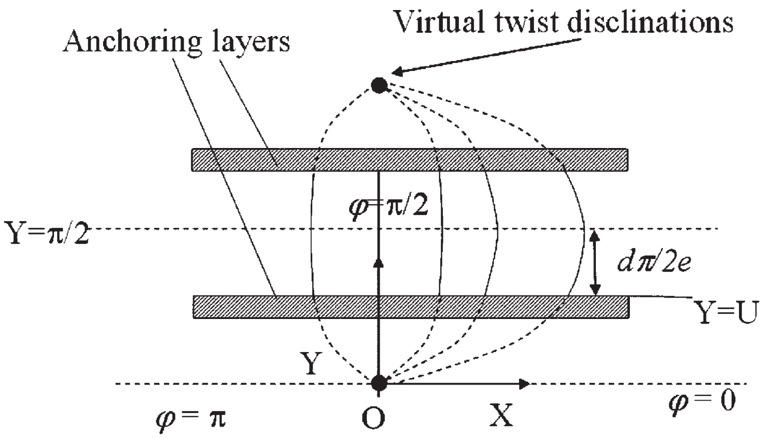

FIGURE 5 Sketch of the φ potential lines for a finite anchoring. Two virtual disclinations are located at the distance $e/2$ from the mid-cell outside the sample.

To solve (3) for a finite anchoring (L $\neq$ 0), let us notice that the infinite anchoring solution (5) checks:

$$\left.\frac{\partial\varphi}{\partial Y}\right|_{Y=U} = \frac{1}{2\tan U}\sin\ 2\varphi$$

The solution (6) therefore also fulfils (3), provided that we replace in (6) the thickness d of the cell by a virtual thickness e such as the real lower surface of the cell is located at ordinate U with $\tan\ U = L\pi/e$ (see Fig. 5).

We then obtain:

$$\varphi(x,y,z) = \text{arc tan}\left(\frac{\sin(y\pi/e)}{\sinh\left(\sqrt{\frac{K_2}{K}}\frac{\pi}{e}(x\cos\alpha - z\sin\alpha)\right)}\right) \tag{7}$$

with e defined by:

$$\tan\left(\frac{\pi d}{2e}\right) = \frac{e}{L\pi}.$$

The texture due to a weak anchoring corresponds to two virtual twist disclinations located at the distance $\pm$e/2 from the middle of the cell.

DYNAMICS OF DISCLINATIONS

The energy per unit length γ of the π-wall can be obtained by integrating Eq. (1) [7]:

$$\gamma = 2\sqrt{KK_2}\left[\frac{\pi}{2} - \text{arc tan}\left(\frac{L\pi}{e}\right) + \int_0^1 \frac{\text{arc tan}(et/\pi L)}{t}\mathrm{d}t\right] \tag{8}$$

At the tip of the disappearing wall, the disclination is submitted to a driven force $F_d \approx \gamma$ which is independent of the local orientation of the π-wall. Let us stress that this force may be slightly different from γ far from the isotropic to nematic transition. The π-wall is indeed formed during the transition and memory effects could lower the actual anchoring energy stored in the wall by changing locally the easy-axis.

The constant velocity v of the disclination can be understood as a result of the competition between the driving force and friction forces which oppose the motion. Neglecting the core dissipation, the viscous force associated to the drag of the disclination can be written as $F_v = \mu dv$ where μ is an effective viscosity (which also takes into account backflow effects) see further details in References [7,9]). The static friction F_s due to the SiO anchoring layer acting on the disclination, which opposes to the director change on the surfaces, is poorly known at the moment. Since the disclinations are not pinned, $F_s < \gamma$ is expected and the constant velocity motion is given by $v = (\gamma - F_s)/\mu$.

The effects of the static friction are much more visible on the lateral motion of the π-walls. Figures 1 and 2 show that the walls are almost motionless during the relaxation of the disclinations except in their most curved parts (that is for a curvature radius $R < 10$–$100\,\mu$m in our experiments). The elastic and anchoring energies stored in the wall should exert a lateral force $F_L = \gamma/R$ per unit length of the wall. Our observations are compatible with a lateral static friction by unit length F_{fric} which opposes the line tension pressure γ/R. Segments with large radii of curvature $R > \gamma/F_{fric}$ do not move whereas the lateral force on curved segments overcomes the static friction.

CONCLUSION

Vertical half-integer disclinations easily form in thin cells with a strong planar anchoring. Their annihilation dynamics after a quench from the isotropic phase is mainly controlled by surface effects. The trajectory of a disclination is fixed by the initial formation of surface π-walls which confine the elastic and anchoring energies. The disclination velocity is constant and independent from its orientation with respect to the surface easy axis. The π-walls are motionless except on strongly curved parts where the lateral force exceeds the static friction force due to the surface.

A quantitative analysis of the dynamics of disclinations and π-walls is currently under work. We think that relevant information on the orientational dynamics of the director on the surfaces can be obtained from the motion of defects confined in thin cells.

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