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Shear behavior of an amorphous film with bubble soap raft model

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1. Introduction.

In the boundary lubrication regime, a thin discontinuous film separates the sliding surfaces. This film is created by adhesion and packing of matter coming from the contacting surfaces and the reaction with an anti-wear additive [1]. In this case, the mechanical action of friction makes these films amorphous [2]. In addition, tribochemical films undergo high pressure, in some cases high temperature and high shear rates in the contact. These effects are responsible for a duality between brittle and ductile behavior in the wear of the film by delamination [2].
Two mechanical properties: the compressive and shear strengths are essential and related. It is well known that in the static regime the plastic yield strength of a layer compressed between two rigid solids depends on three factors: the plastic properties of the layer, the ratio of thickness to length, called the Hill number [3] and adherence between the layer and the substrates [2].

Concerning the shearing behavior, microsliding experiments show that different tribochemical films have almost the same elastic properties, but their anti-wear properties are different [4]. We must see whether these properties are not related more to a plastic or a viscoplastic behavior. In order to understand the shearing process in a ductile amorphous film in great displacement, we use the bubble soap raft model with which Bragg visualized defects in materials [5-7]. Bubble rafts provide a useful two dimensional model for the study of solids. The attractive repulsive potential between bubbles is due to the surface tension of the soap solution and the pressure inside the bubbles and governs their behavior [8]. With a uniform size of bubble, we obtain a crystalline lattice; with two different sizes appropriately mixed, an amorphous structure.

The aim of this paper is to study the evolution of plastic flow for a wide range of thickness to length ratios of the layer.

2. Experimental procedure.

The experimental configuration is shown in figure 1. Air at constant pressure is blown through short capillaries to produce bubbles at the surface of a soap solution (surface tension: $\gamma_{LV} = 6.9 \times 10^{-2}$ N.m$^{-1}$). If only one capillary is used, we obtain a raft with a crystalline structure. With two capillaries, we obtain an amorphous raft, after mixing. The crystalline structure is made up of 2.3 mm diameter bubbles, and the amorphous structure is a mixture (45-55) of 2.3 and 1.6 mm diameter bubbles respectively. It is known that the mechanical properties of an amorphous layer do not vary with the ratio of bubble sizes over a large range [9]. We create two rectangular crystalline rafts, which adhere to two parallel frames $a1, a2/3 (Fig. 1). They are about twelve bubbles thick. We separate the two crystalline rafts by an amorphous layer whose length and thickness are varied. We call $h$ the thickness of the layer and $L$ its length. The boundary conditions are determined by the crystalline rafts, and the crystal-amorphous interface is made smooth. The frame $a2 \beta2$ is then moved at a constant low speed $U$ (1 mm/s), parallel to the frame $a1 \beta1$ causing a shear where the displacement is imposed. For a large range of speeds (1-4 mm/s), the force is independent of the speed. During the test (about 20 s), the diameter of the bubble decreases very slowly. However the variation is too small to affect the mechanical behavior. Because of the size of the bubbles we can neglect their elastic deformation. The stiffness of the amorphous layer is much lower than that of the crystalline layer [10], so all the deformation due to the imposed displacement occurs in the amorphous film. During the experiment, the tangential force is transmitted to the fixed frame and continuously recorded versus displacement. By filming the experiment on a video tape system and by photographing the test at regular two-second intervals, we can determine the displacements in the amorphous layer with a resolution corresponding to less than half a bubble.

3. Results and discussion.

3.1 RESULTS FOR A GIVEN LAYER. — The mechanical behavior of an amorphous raft of bubbles is governed by local displacements of the bubbles (Fig. 2a) resulting from two simultaneous processes described by Argon [10]. First, a diffuse shear causes the rotation of
Fig. 1. — Bubble raft used to simulate a sliding process. The amorphous layer is a mixture of two different size bubbles while the crystalline substrates are made up of a single size of bubble. The displacement of the frame $\alpha_2 \beta_2$ causes a shearing of the amorphous layer. The tangential force $F$ is transmitted to the fixed frame $\alpha_1 \beta_1$ and exerts on it a momentum $C = OA \wedge F$. Its direction is $\delta \delta'$. This momentum is measured by a torque transducer.
Fig. 2a. — Local movements of bubbles inside the amorphous layer, responsible for the mechanical instabilities in great displacement. Around the fixed bubbles (hatched bubbles) there are two types of movements occurring simultaneously: — translations between lines of bubbles; — rotations of bubbles clusters.

Fig. 2b. — Mechanical behavior of the sliding amorphous layer with two periods: — Period $A'$: the tangential stress $\tau = F/L$ is proportional to the deformation $\gamma = U/h$. This period characterizes an elastic behavior. — Period $B'$: during the plastic flow of the layer, the tangential stress is reaching a limiting value $\tau_l$, characteristic from the mechanical behavior of the layer in large deformation.

clusters of 6 or 7 bubbles. Around these rotating groups, there is low amplitude sliding between lines of bubbles.

These two local transformations create mechanical instabilities, which are responsible for plastic strain. We can define a two-dimensional stress $F/L = \tau$ to describe the sliding...
behavior of the amorphous layer. A two-dimensional distortional strain \( \gamma = U/h \), where \( U \) is the relative displacement of the two frames \( \alpha_1 \beta_1 \) and \( \alpha_2 \beta_2 \), is associated to this stress.

Figure 2b shows a typical record of the force \( F \) versus displacement \( U \). At first, the stress increases in proportion to the strain. In spite of linearity, this strain is not completely reversible; however it is possible to define a pseudo elastic shear modulus characteristic of slight strains behavior. Then, we obtain an effective elastic shear modulus \( G = 1.2 \times 10^{-2} \text{ N/m} \), which is in agreement with the experimental values calculated from an indentation test [9]. During this period, we observe few local movements of the bubbles. The stress is still increasing more gradually, with the deformation and reaches a constant limiting value \( \tau_l \). Around this mean value, small perturbations due to the numerous mechanical instabilities are noted. For every test, we have observed that for a given Hill number, \( F_l \) is proportional to \( L \), and we obtain a single limiting stress \( \tau_l = F/L \).

3.2 INFLUENCE OF THE HILL NUMBER ON THE BEHAVIOR OF THE LAYER. — The sliding stress varies with the Hill number (Fig. 3). Extrema occur for simple values of \( h/L \) (respectively 0.15, 0.25, 0.5). Experiments made with different sizes of bubble produce the same curve. Two types of behavior can be distinguished in the curve (Fig. 3): one when \( h/L > 0.25 \) and another when \( h/L \leq 0.25 \). The first type can be explained by continuum solid mechanics, but the second type, where the defects in the amorphous layer are dominant effects, is explained by the physics of the amorphous state.

![Graph showing the influence of the Hill number on the tangential stress](image)

**Fig. 3.** — Evolution of the non-dimensional tangential stress \( \tau_l/\tau_o \) with the Hill number. This curve is independent of the size of the bubbles. \( \tau_o \) is the limiting tangential stress for \( h/L = 1 \). (\( \blacktriangle \)) experimental points.

3.2.1 First type of behavior (\( h/L > 0.25 \)). — The displacement field is shown in figure 4 just after the linear increase in the stress versus the shear strain (Fig. 4A) and when the stress reaches its limit (Fig. 4B). These pictures are obtained by photographing the experiment at regular intervals (every two seconds) and by superimposing the photographs for two
Fig. 4. — Evolution of the kinematic field of the plastic flow, obtained by superimposition of two successive pictures of the layer. Picture A: just after the elastic period, the tangential stress begins to increase slowly with the displacement. The shear band 2 (where the plastic deformation occurs) appears between two lateral zones 1 and 3 locked relative to the frame $\alpha_1 \beta_1$ and the frame $\alpha_2 \beta_2$ respectively. Picture B: the limiting stress is reached. The thickness of the shear band increases while the thickness of the two lateral zones (1, 3) remains constant at about five bubbles. The direction of the shear band is horizontal.

Consecutive instants. This allows us to define three zones in the amorphous layer, when the tangential stress begins to increase slowly with displacement (Fig. 4A), just after the elastic period (Fig. 2b).

The first zone is close to the fixed frame $\alpha_1 \beta_1$. Most of the bubbles are stationary here and some of them have only slight displacements. If we regard the amorphous layer in a...
referential system to be moving at the speed of the lower crystalline raft, we observe a zone close to the mobile crystalline raft, where the bubbles do not move relative to the moving frame. Between these two regions, there is a middle zone, which is about ten bubbles thick for every Hill number. Here, the displacement amplitude of the bubbles is high relative to both the fixed and the moving frame. These movements are numerous and disordered. We call this zone the shear band. While at the beginning of the test, the orientation of the shear band is controlled by \( \tan \theta = \frac{h}{L} \), we do not know what phenomena govern its thickness. The shear band crosses the whole layer, if \( h/L > 0.5 \), without hitting any crystalline rafts. It hits one of the crystalline rafts, if \( h/L < 0.5 \). These different situations introduce differences in the mechanical behavior. When the sliding stress reaches its limit, the shear band is parallel to the sliding direction and the amorphous layer contains three zones: a shear band limited by two locked zones. The thickness of the middle zone increases during the sliding process, while the thickness of the two lateral zones decreases to a minimum value of about five bubbles. We also note that around the outer edges of the amorphous layer, the paths of the bubbles are not straight but circular. Such a phenomenon has been observed by Green [11]. A plastic junction for a Hill number less than 1.47 can be divided into a middle zone undergoing pure shearing surrounded by two pure torsion zones.

We analyze our experimental results with a simple mechanical approach based on a Mohr description (see annexe). We can explain the evolution of the stress \( \tau_\ell \) characteristic from the plastic flow for a high Hill number. For the bubble rafts, we first define a plasticity criterion by:

\[
\tau = \sigma \tan \phi + c.
\]

\( c \) is the cohesion of the material \((c = 17.8 \times 10^{-4} \text{ N/m for our bubble soap rafts})\) and \( \sigma \) is the normal stress associated with the necessary reorganization of the bubbles inside the sliding layer in great deformation. We represent the stress field by the tensor:

\[
\sigma = \begin{pmatrix}
\sigma_{11} & \tau \\
\tau & \sigma_{22}
\end{pmatrix}
\]

assuming that the stress field is uniform in the layer except at the sides. Displacement in the normal direction is not possible because the crystalline raft is very rigid [9], so the mechanical instabilities can only occur with an increase of the normal stress \( \sigma_{11} \). Depending on whether \( h/L \) is greater than 0.5 or not, the shear band crosses the whole layer or hits the fixed crystalline raft.

3.2.1.1 \( h/L > 0.5 \). — We call \( h_1 \) the thickness of the shear band, \( dh_1 \) is a normal elementary thickness increase during the sliding. As \( h \) remains constant, this small increase must be balanced by the elastic deformation of the two lateral zones. This thickness increase causes a slight variation in the normal stress given by:

\[
d\sigma_{11} = E \cdot dh_1/(h - h_1),
\]

where \( E \) is the two-dimensional elasticity modulus of the amorphous layer. We checked that \( h_1 \) does not depend on the Hill number, so this equation shows that \( \sigma_{11} \) decreases if \( h \) increases and vice versa. The geometrical representation of the stress tensor is shown in figure 5. The Mohr circles which are tangent to the plasticity criterion, are built from the orientation of the shear band for each Hill number. A comparison of cases A and B (Fig. 5) shows that an increase in \( \sigma_{11} \) is related to a decrease in the sliding stress \( \tau_\ell \), which proves that if \( h/L > 0.5 \), \( \tau_\ell \) varies in the same way as the \( h/L \) ratio.
Fig. 5. — Mohr representations of the stress tensor inside the layer to describe the evolution of for high Hill numbers (A, B, C). (A): $h/L = 1$: reference situation. (B): $0.5 < h/L < 1$: because of the elastic deformation of the locked zones, the normal stress $\sigma_{11}$ increases and $\bar{\tau}$ becomes smaller than for $h/L = 1$. (C): $0.25 < h/L < 0.5$: the sliding direction is horizontal, the normal stress $\sigma_{22}$ appears, then $\bar{\tau}$ must reach the plasticity criterion and is greater than for $0.5 < h/L < 1$. 

![Mohr diagram showing stress tensor evolution](image)
3.2.1.2 \( 0.25 < h/L < 0.5 \). — The shear band hits the upper crystalline raft, therefore since the crystalline raft is much more rigid than the amorphous structure, horizontal sliding is imposed.

The sides are no longer free and a normal stress \( \sigma_{22} \) can appear. The description by a Mohr representation (Fig. 5C) shows that as the sliding direction is horizontal, \( \tau_{\text{f}} \) must reach the plasticity criterion. \( \tau_{\text{f}} \) is therefore greater than for Hill numbers above 0.5. From continuum solid mechanics, we can again find the experimental curve of the evolution of the limiting stress \( \tau_{\text{f}} \) for Hill numbers above 0.25.

3.2.2 Second type of behavior (\( h/L < 0.25 \)). — By counting the number of instabilities (in other words the local motion of bubbles defined in figure 2a) in the layer, for a given time, we determine the distribution of instabilities in the amorphous film (Fig. 6). This curve confirms the preceding results: for \( h/L > 0.25 \) the existence of two locked zones close to the fixed and the moving frame respectively, surrounding a middle zone where the bubbles have disordered and numerous movements. But for \( h/L < 0.25 \), the distribution is not centered around \( h/2 \) anymore and the number of instabilities increases from the fixed frame to the moving frame. In our experiments, the thickness of the amorphous layer corresponds to the size of the clusters of bubbles around which the local instabilities occur. Therefore, the effects of these movements are dominant, and the plastic flow is not only dependent on the Hill number anymore but also on thickness \( h \). In addition, for large Hill numbers the deformation is located in a shear band with a preferred direction: this process is related to a minimization of the energy. For low Hill numbers, the thickness is too small and the slip line is necessarily horizontal, so there is an increase in the deformation energy, which can explain the steep increase in the limiting shear stress if \( h/L < 0.25 \).

Fig. 6. — Distribution of instabilities along the thickness of the layer during the sliding experiment: for \( h/L = 0.5 \) (---): the distribution is centered around \( x/h = 1/2 \) with a maximum at \( x/h = 1/2 \). This confirms the existence of the shear band; for \( h/L = 0.25 \) (-----): the distribution is not centered anymore, the number of instabilities does not stop increasing from the fixed crystalline substrate \( x/h = 0 \) to the moving crystalline substrate \( x/h = 1 \).
4. Conclusion.

With the bubble soap raft model, we determine the shear behavior of an amorphous layer adhering to two rectangular crystalline rafts. For large displacements the tangential stress reaches a constant limiting value $\tau_l$, which characterizes the plastic flow of the layer and is dependent on the Hill number. For large Hill numbers ($h/L > 0.25$) a mechanical approach based on the observation of the kinematic field of the plastic flow explains the behavior of the layer. But for small Hill numbers, the macroscopic behavior of the amorphous film is governed by physical effects due to the movements of small-clusters of six or seven bubbles.

For small Hill numbers, scale effects occur and the number of bubbles plays a role. The evolution of the sliding strength, in this case would certainly be different if we used larger systems to avoid these scale effects.

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Addendum.

The Mohr description is a geometrical representation in the normal stress-tangential stress space. For each elementary surface $dS$ of the solid, we get a point $M$ (Fig. 7a). When angle $\theta$ is varied (Fig. 7b), point $M$, which represents the stresses, describes a circle. The radius and the center of this circle depend only on the principal stresses.

Fig. 7. — (a) Principle of the Mohr representation. The Mohr circle which describes the stresses inside the layer is tangent to the plasticity criterion at the points $G_1$ and $G_2$. This two points define two sliding directions $\alpha_1/2$, $\alpha_2/2$; (b) stress vector on an elementary surface $dS$, forming an angle $\theta$ with the horizontal direction. When $\theta$ is varied, $M$ describes the Mohr circle; (c) stress vectors on the horizontal and the vertical facet defining the points A and B on the Mohr circle.
The plasticity criterion is a function \( f \), which limits the elastic area in the stress space. To check this criterion, we must obtain:

\[
f(\sigma) < 0.
\]

So, in the Mohr representation, the plasticity criterion is the envelope of the Mohr circles, for different stress states. Here, the plasticity criterion is represented by two straight lines.

References