The friction angle in plasticized epoxy polymers during polymerization

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With 10 figures

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Introduction

The frictional behaviour of polymers is important in a great number of applications of these materials. As friction coefficient $\mu$ is defined the ratio of the tangential force $T$ to the normal load $S$ applied in a pair of similar specimens when the surface of the one specimen forming the interface of contact with the other specimen is moved relatively to the other ($\mu = T/S$) (1). The friction coefficient $\mu$ is not necessarily constant for the materials incorporating an interface, but it may depend upon a number of variables such as the applied load, the contact area, the geometry of the specimens, the temperature, the type of apparatus used for the tests, in addition to the physical and chemical properties of the constituent materials.

Many types of instruments have been used to measure friction. The agreement between these instruments is generally poor, partly because of the very complex nature of the frictional phenomena. Even when different experiments use the same type of apparatus, their results often do not agree for the same materials because of the difficulty in obtaining reproducible surfaces and comparable test conditions.

In frictional phenomena one surface of the one specimen is always in contact with another surface of the other specimen forming the so-called friction interface. The total frictional force is a complex summation of several factors including i) internal friction or mechanical damping, ii) shearing of junctions where the two surfaces are in intimate contact, iii) a ploughing process where the harder material displaces the softer material in front of it to create a friction track or scratch.

A measure of the internal friction of a polymer is the logarithmic decrement $\delta$, which is determined by measuring for example the damping of the swinging in a torsion pendulum experiment (2). The internal friction depends on the relative amount of strain energy stored as potential energy in the sample compared to the energy dissipated as heat through molecular motion by the internal friction between the chain segments (2, 3). The resistance encountered by a submolecular junction moving through its surrounding side-chains is characterized by the friction coefficient (4).

On a submicroscopic scale even smooth surfaces are rough, so that surfaces which appear to be in contact are actually touching each other in only a few protruding points. At these contact points very large forces are encountered, so that the contact points are deformed, plastic flow occurs at the surrounding areas of these points, and the two surfaces are welded together in these areas. When sliding along the friction interface takes place these junctions or contact points must be sheared. If the junctions are weak, shearing takes place at the actual friction interface. However, in many cases the junctions are welded together so strongly that shearing takes place below the surface of the softer material. This shearing action gives rise to one of the factors creating the total frictional force. If this shearing term is the largest factor contributing to the frictional force, the friction coefficient may be roughly approximated by $\mu = \sigma_B/P_y$, where $\sigma_B$ is the shear strength and $P_y$ the yield pressure of the softer material (1).

In this paper the shear apparatus was used with double shear specimens of the same material, which are bonded by another polymer under the process of polymerization, for the study of the dependence of the maximum shear stress $\tau$ on the normal applied stress $\sigma$ capable for breaking the bonding of the polymeric layer lying between the two specimens. The thin layer making up the bond of the two polymeric beams consisted of a plasticized epoxy polymer while the beams in the double-shear test were prepared from 50 percent plasticized epoxy polymers completely polymerized.

From the study of the $\tau = f(\sigma)$ curve the notion of the friction angle is introduced which corresponds to the angle whose tangent is given by the ratio of the shear stress rate to the applied normal stress rate for breaking the bond. This quantity presents a similarity with the well known in Soil Mechanics angle of shearing resistance $\phi$ which represents the inclination of the rupture line of the material (5). The value for $\phi$ is assumed to be a property of the material, and since it depends primarily upon the relative density of the material, it may range between fairly wide limits. Other properties of the material which influence the
value of $\varphi$ are the grain size distribution as well as the shape of the grain in the material.

The study of the friction angle of polymers presents great similarities with the peel test (6, 7), the main difference being that while in the peel test the mechanics of interfacial unbonding between two dissimilar polymers is studied, here the unbonding of a cement under the process of polymerization is studied when the cement is placed in a thin layer between two similar beams to be bonded which are made of different or the same polymer.

From the related subject of the peel test we adopt for our study the same assumptions which are:

i) The stresses are constant over the thickness of the friction interlayer.

ii) All three layers that is the two specimens and the friction interlayer are considered to be elastically deformed, and

iii) While in the peel test, failure occurs as a line propagation in the friction unbonding fracture of the interlayer takes place by a plane lying at the interior of the interlayer. This failure corresponds to a cohesive failure in the peel test, which is defined as substantially occurring within the adhesive layer.

**Experimental procedure**

Two series of different tests were executed in order to establish the functional relationship between the applied normal and shear forces in a double shear apparatus for breaking the bond created by thin interlayers of a plasticized epoxy polymer under the process of polymerization.

![Fig. 1. Schematic view of the shear test apparatus](image)

The double shear apparatus was a typical one (fig. 1). It consisted of two adjustable and parallel jaws whose surfaces were flat and smooth. The distance between jaws was adjustable through a pair of fine screws, so that the three layer sandwich specimen could be interposed between jaws. The apparatus was equipped with a system for applying normal loads $S$ to the sandwich specimen, which was uniformly distributed through the metallic jaws along the bases of the polymer beams of the specimens. The normal load $S$ could be measured accurately through a dynamometer interposed in the system of application of the load.

The shear load $T$ was applied through a plate jaw which was for every test cemented on the one of the lateral cross-sections of the middle movable beam of the three-stage sandwich specimen and it was connected through a flexible thin cable and a pulley to a vertically suspended recipient where thin load bullets could be pored in by an adjustable orifice which regulated the load rate accordingly.

For the preparation of the specimens a series of 10 mm thick plates made of an epoxy polymer were cast. The copolymer samples were prepared from a cold setting epoxy prepolymer (Shell Epon 828) in which 50 percent of Thiokol LP 3 polysulfide plasticizer was added. To this mixture 8 percent of Triethylenetetramine hardener was added. The three substances after a thorough mixture and degasing there were cast in plexiglas molds and left to set for 24 hours. The details of the preparation and the curing of the plates were described in detail in ref. (9).

After the curing process all plates were left for three months at ambient temperature so that a complete polymerization of the plates was assured. From the cured plates two types of beams were cut with longitudinal sections of $10 \times 60$ mm and heights either 15 mm or 7.5 mm. The lateral faces of all beams were highly polished to become fully transparent. For each test a pair of thick beams were cemented with the same mixture as cement on the polished surfaces of the jaws of the testing apparatus while a thin beam at the one of its end cross sections was cemented on the mechanism for application of the shear force.

After a complete curing of the cements the thin beam was interposed between the two thick beams cemented on the jaws of the apparatus and thin layers of the bonding material was interlaid between the thick stationary beams and the thin movable beam. The bonding material was either pure epoxy polymer or plasticized epoxy polymer with 50, 100, 150 and 200 percent of plasticizer to the weight of epoxy polymer. This cement was prepared in the same manner as the material of the plates and was spread on the interfaces immediately after the preparation of the mixture.

As soon as the sandwich specimen was prepared the normal load $S$ was applied progressively on the metallic jaws which was uniformly distributed along the specimens. This was assured by the thickness and the rigidity of the metallic jaws. With the end of the application of the normal load and the removal of any excess of the interlayers the shear force $S$ was progressively increased by adding with constant rate weight in the recipient of the instrument. Addition of weight continued until the thin beam layer slide relatively to the stationary beams of the sandwich specimen when addition of weight was stopped automatically.

These tests were executed for different polymerization times for the cement up to the complete polymerization of the polymer and for different applied normal forces $S$. In this way it was possible to measure the variation of the shear force $T$ for different values of the normal force $S$ and for different polymerization times of the interlayers, up to a complete polymerization of the substance.

All experiments were executed at an ambient and constant temperature of 26°C.