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EDGE FRACTURE IN RHEOMETRY

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ABSTRACT

Edge fracture is a flow instability which is significant in industrial applications as well as in the laboratory. This paper contains preliminary measurements of edge fracture diameter in a number of different systems, including polymers, polymer solutions and suspensions in the parallel plate rheometer.

The results from the measurement of fracture diameter in the parallel plate rheometer indicate that the edge fracture diameter (a) is approximately constant for $0.5 < h < 1.4$ mm and the ratio (a/h) is not a constant for $0.5 < h < 1.4$ mm. The lack of constancy of (a/h) suggests it may not be valid to use equation 13 of Tanner and Keentok, 1983 without calibration of the equation by measuring the fracture diameter.

A preliminary analysis of edge fracture and elastic instability has been undertaken; the early data indicates that when edge fracture occurs, elastic instability does not. Conversely when elastic instability occurs, then edge fracture does not.

INTRODUCTION

Edge fracture is a flow instability and like other flow instabilities (such as Taylor-Couette instability and melt fracture) is significant in industrial applications as well as in the laboratory (Larson, 1992). Edge fracture occurs in polymer solutions (and other liquids) which are undergoing shearing in the cone-plate and the parallel plate rheometer. Edge fracture begins with meniscus distortion which is followed by a crack or fracture propagating into the sample. Hutton (1963, 1965, 1969) observed edge fracture and explained it in terms of the sample exceeding a critical first normal stress difference. Subsequent work by Tanner and Keentok (1983) showed that for a second order fluid, the edge fracture occurs when a critical second normal stress difference is exceeded. Lee et al (1992) have confirmed Tanner and Keentok's equation in an experimental study which compared edge fracture for six polymer solutions having widely differing ratios of second to first normal stress difference.

This paper contains preliminary measurements of edge fracture diameter in a number of different systems, including polymers, polymer solutions and suspensions in the parallel plate rheometer. The examination of edge fracture in suspensions is new work which has not been previously published although work has been published mentioning rupture in suspensions (Deysarkar et al, 1976), which may or may not be a related effect and also fracture in greases (Hutton, 1975). A short analysis of flow parameters was made to distinguish edge fracture from elastic instability.

THE THEORY OF EDGE FRACTURE IN VISCOELASTIC LIQUIDS

Tanner and Keentok (1983) showed that for the second-order fluid, when the second normal stress difference exceeds the critical second normal stress difference ($N_2 > N_{2c}$), edge fracture will occur, where:

$$N_{2c} = \frac{2\,\Gamma}{3\,a}$$

and N_{2c} is the critical second normal stress difference, Γ is the surface tension coefficient and a is the edge fracture 'diameter'.

The edge fracture 'diameter' is a term used to denote the width dimension of the edge fracture (see Tanner and Keentok, 1983) and is not intended to imply an exactly semi-circular indentation. Note that in the above equation both the surface tension coefficient and the edge fracture diameter are needed to compute the critical N_2.

THE SAMPLES AND THEIR RHEOLOGICAL CHARACTERISATION

The samples studied were :

a. 12,500 cSt Silicone
b. Shell Barbatia automotive grease,
c. 0.03% polyisobutylene in kerosene and HYVIS 10
d. Liquid M1.

The silicone (a) has been well characteristed (see e.g. Tanner and Keentok, 1983) and exhibits second order behaviour up to a shear rate of 120 s^{-1}, i.e. a Newtonian viscosity and first normal stress difference N_1 which varies with shear rate squared. The grease (b) follows the Bingham model and has a yield stress of ~ 5000 dyne/cm^2 (Keentok, 1982). The polyisobutylene solution (c) has a Newtonian viscosity and square law N_1, for shear rates less than 10 s^{-1} (Ilic, 1994). The liquid M1 has been studied by many and exhibits Newtonian viscosity ($< 10^3$ s^{-1}) and square law N_1 ($< 10^2$ s^{-1}) (see e.g. Binding et al 1990).

After studying the rheology of these samples, it is reasonable to consider samples (a), (c) and (d) to be second-order fluids in the appropriate (i.e. low) shear rate range, however the grease sample is a Bingham/Herschel-Bulkley fluid and could not be considered to be a second-order fluid.

The measurements of N_2 in table 1 were obtained by the method of Keentok and Tanner, 1982, that is by the comparison of cone-plate and parallel plate normal thrust data. Note that the rheological data does not always extend to the high shear rates used here to induce edge fracture.

THE FRACTURE DIAMETER

The only published measurement of fracture diameter was one measurement in Tanner and Keentok (1983). Lee et al (1992) did not measure fracture diameter and used the approximation equation (Equation 13 in Tanner and Keentok, 1983) which assumes that the ratio of fracture diameter to parallel plate gap (a/h) is a constant. The validity of this assumption will be considered later.

The edge fracture measurements were undertaken on an Instron Model 3250 Rotary Rheometer, using parallel plates of radius R= 20 mm. The angular velocity Ω of the plate was varied gradually from 1 RPM (log Ω = 0.0) up to a maximum of 315 RPM (log Ω = 2.5). The meniscus of the sample was continuously recorded with a video camera (National WV-CD-20) using a zoom lens. At each Ω, ~20 seconds was allowed for the stresses and surface tension forces to equilibrate before moving on to the next Ω. When surface disturbances were observed, the time was increased to allow the meniscus to stabilise. The measurements of edge fracture diameter together with the experimental conditions Ω and h, are contained in table 1.

Duration of shearing - is this important ? To answer this question knowing the relaxation time constant for N_2 or the time for N_2 to reach equilibrium during start up of shearing flow is not enough : the time taken for rearrangement of the surface under the influence of surface tension is considerably longer.

Current measurements of fracture diameter for the above samples in the parallel plate rheometer indicate that the edge fracture diameter is a constant when h is varied in the range 0.5 to 1.4 mm. Thus (a/h) is not a constant (see column (a/h) in Table 1) and Equation 13 from Tanner and Keentok, 1983 needs to be used with care.

For comparison purposes, Table 1 includes the measurement from Tanner and Keentok (1983) for silicone in the cone-plate (0.5°) rheometer (the gap quoted is the gap at the rim). The fracture diameter for the cone-plate is considerably smaller than even for h = 0.5 mm in the parallel plate, however this may be due to a gap dependence of the fracture diameter - that is 2a increases as h increases. Note also that there appears to be a trend in the ratio (a/h) which increases as h decreases (inverse relationship).

INSTABILITY ANALYSIS

A preliminary study of elastic instability was undertaken and the results are contained in Table 2 :

Edge fracture ? — indicates whether edge fracture does (YES) or does not (NO) occur and reflects the data of table 1.

Elastic Instability ? — reflects whether elasic instability is (YES) or is not (NO) observed. If data does not exist, then it reflects the value of $\lambda\Omega$; when $\lambda\Omega < (\lambda\Omega)_c$, elastic instability is not expected; when $\lambda\Omega > (\lambda\Omega)_c$, elastic instability is expected. For these samples $(\lambda\Omega)_c \sim O(1)$.

The relaxation time, λ was computed from :

$$\lambda = \frac{N_1}{2\dot{\gamma}^2 \eta_0}.$$

Elastic instability has been observed in the M1 liquid by Binding et al 1990 when $N_1/\tau \sim 8$. The data in table 2 indicates that edge fracture and elastic instability appear to be mutually exclusive - when one occurs, the other does not. The occurrence of elastic instability may be linked to both N_1/τ and $\lambda\Omega$ in that both of these have to be large enough for elastic instability to occur.

DISCUSSION

The results from the measurement of fracture diameter in the parallel plate rheometer indicate that :

1. the edge fracture diameter (a) is approximately constant for $0.5 < h < 1.4$ mm,
2. the ratio (a/h) is not a constant for $0.5 < h < 1.4$ mm.

The lack of constancy of (a/h) suggests it may not be valid to use equation 13 of Tanner and Keentok, 1983 without calibration of the equation by measuring the fracture diameter.

A preliminary analysis of edge fracture and elastic instability has been undertaken; the early data indicates that when edge fracture occurs, elastic instability does not. Conversely when elastic instability occurs, then edge fracture does not.

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Table 1 Edge Fracture Data

Edge fracture data for the parallel plate rheometer with gap h, angular velocity, Ω and shear rate, $\dot{\gamma}$. The symbol (-) means edge fracture does not occur. For comparison purposes, cone-plate data (0.5°) is included from Tanner and Keentok, 1983 (*).

SAMPLE	log Ω (rpm)	$\dot{\gamma}$ (s^{-1})	h (mm)	$-N_2$ (dyne/cm²)	Γ (dyne/cm)	2a (mm)	$2\Gamma/3a$ (dyne/cm²)	a/h
12,500 cSt Silicone	2.0	1429.	1.40	?	22.9	0.27	1150	0.10
	1.8	2524.	0.50		22.9	0.24	1280	0.24
Shell Barbatia grease	0.2	32.	1.00	N_1~3,000	~30	0.29	1379	0.15
0.03% poly-isobutylene in HYVIS10	> 2.4	>2512	2.00	?		-	-	-
	> 2.4	>5024	1.00	?		-	-	-
M1 liquid	> 2.5	>6325	1.00	?		-	-	-
12,500 cSt Silicone *		487.	0.175	~5,000	22.9	0.074	3660	0.22

Table 2 Instability Analysis

Includes edge fracture data from Table 1 and rheological data (N_1/τ), estimate only for grease. See text for explanation of λ and elastic instability.

SAMPLE	log Ω (rpm)	$\dot{\gamma}$ (s^{-1})	h (mm)	N_1/τ (dyne/cm²)	Edge fracture ?	Elastic instability?	$\lambda\Omega$
12,500 cSt Silicone	2.0	1429.	1.40	~1	YES	NO ?	0.15
	1.8	2524.	0.50	~1	YES	NO ?	0.10
Shell Barbatia grease	0.2	32.	1.00	~0.5	YES	?	3.8
0.03% poly-isobutylene in HYVIS10	>2.4	>2512	2.00	17.5	NO	YES ?	>29
	>2.4	>5024	1.00	17.5	NO	YES ?	>29
M1 liquid	>2.5	>6325	1.00	8.4	NO	YES	>104