Modeling Acoustic Agitation for Enhanced Development of PMMA Resists

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High frequency acoustic agitation is known to increase development rates of LIGA features [1]. Although the physical origin of this enhancement is not well understood, it is often suggested that the collapse of acoustic bubbles may help to dislodge polymer fragments from the gel layer at the feature bottom, increasing the fragment dissolution rate. However, with increasing feature depth the development rate becomes limited not by this dissolution process but rather by fragment transport from the feature bottom into the bath. In this transport-limited regime, we believe that the benefit of acoustic agitation is derived from a steady acoustically-driven streaming motion that circulates developer fluid within the feature, carrying dissolved fragments from the feature bottom into the bath. Because this acoustic streaming flow reaches all the way to the feature bottom, it is far more effective than conventional bath stirring that only circulates the fluid to a depth of a few feature widths.

To better understand and to quantify this acoustic streaming process, analytical and numerical methods are used to solve the equations governing flow and species transport within trench-like LIGA features. The sinusoidal acoustic motion of the fluid within the feature is described by superposing known exact solutions. These solutions reveal the presence of submicron-scale viscous boundary layers on the feature walls. The steep velocity gradients within these layers produce time-mean Reynolds stresses that drive a steady flow commonly referred to as acoustic streaming [2]. This steady motion is computed by numerically solving the time-averaged Navier Stokes equations which include both the steady terms and the time-averaged Reynolds stress of the harmonic motion. The resulting steady flow is finally used to calculate the transport of polymer fragments by diffusion and convection.

The results of a typical numerical calculation are shown in Figure 1. The steady streaming flow is torroidal with downflow along the walls coupled with upflow in the feature center. The maximum fluid speed near the feature wall is about one-fourth of the nominal streaming speed, $u_o = I/\rho c_o^2 \sim 44\ \mu$m/s, where $I \sim 10$ W/cm^2 is the acoustic intensity, $\rho \sim 1000$ kg/m^3 is the liquid density and $c_o \sim 1500$ m/s is the sound speed. In response to the flow field, the contours of constant fragment concentration shown on the right of Figure 1 are bent down along the wall and up in the center.

The benefit of acoustic agitation may be expressed by the Sherwood, Sh, representing the ratio of the total vertical fragment transport to that in the absence of agitation. Figure 2 shows the variation of the Sherwood number, with the Peclet number, $Pe = u_0 w/D$, based on the nominal streaming speed, u_0, the feature width w, and the fragment diffusivity, D. It is seen that the numerical results (symbols) are in excellent agreement with the following analytical approximation (dotted lines)

$$Sh = 1 + \frac{Sh_0\, Sh_\infty}{Sh_0 + Sh_\infty} \qquad \text{where} \qquad Sh_0 = \left(\frac{2-\sqrt{3}}{1200}\right) Pe^2 \qquad \text{and} \qquad Sh_\infty = 1.11 A Pe^{1/3} \tag{1}$$

in which Sh_0 and Sh_∞ are the asymptotic limits (solid lines) of the quantity Sh-1 in the limits of small and large Peclet number.

In a quasi-steady process the development rate, dh/dt, is simply related to the dissolution rate, R(1-C*), and to the rate of fragment transport from the development surface to the bath, ρ_ℓShC*D/h.

$$\rho_s \frac{dh}{dt} = R(1 - C^*) = \rho_\ell\, ShD \frac{C^*}{h} \qquad \text{where} \qquad C^* = \frac{\Gamma}{1+\Gamma} \qquad \text{and} \qquad \Gamma = \frac{Rh}{\rho_\ell\, Sh\, D} \tag{2}$$

Here, ρ_s is the PMMA solid density, ρ_ℓ is the bulk fluid density, h is the feature depth, R is the kinetic-limited dissolution rate (kg/m^2/s) for developer containing no fragments, and C* is the partial mass density of fragments in the fluid at the feature bottom. Eqn. (2b) is obtained by rearranging the second equality in Eqn. (2a). In the calculations presented in Figure 3 the nominal dissolution rate, R, is related to the local radiation dose and the developer temperature by fitting the model of Griffiths et al. [3] to the data of Pantenburg et al. [4]. For a given feature depth and local absorbed dose, this value of R and the value of Sh from Eqns. (1) are used in Eqns. (2b,c) to compute C*. The development rate is then computed from Eqn. (2a). To obtain the development history, these calculations are repeated for a series of discrete time steps, Δt, each time using the product dh/dt Δt to calculate the incremental increase in feature depth.

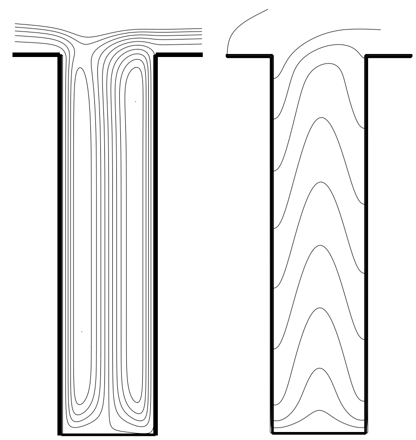
Figure 3 compares our computed development histories with measurements made by Zanghellini et al. The PMMA fragment diffusivity of $D=4.5\times10^{-12}$ m^2/s used in all three calculations was chosen to provide a good fit to the measured data for development in the absence of sonic agitation (i.e. I=0). This diffusivity, although quite small, appears consistent with available data for comparable molecular weights and fragment concentrations. It is seen in Figure 3 that the predicted increase in development depths for sonic agitation at 2 and 10 w/cm^2 is in reasonably good agreement with Zanghellini's measurements, given the simplicity of the model and the uncertainty in local acoustic power levels.

It is concluded that fragment transport by acoustic streaming is probably the mechanism responsible for the observed enhancement of development rates in high-aspect-ratio LIGA features. Thus, the physically based model presented here can be used to compute development rates for a broad range of processing conditions. Sherwood numbers increase with increasing Peclet number (Eq. 1), and the Peclet number is proportional to the feature width, so transport rates under acoustic agitation should increase with feature width (Eq. 2). This suggests the possibility of disparate development rates. However, for sufficiently strong agitation the transport rates in all features will be great enough to ensure that all develop at the same rate limited only by surface dissolution kinetics. Thus, it remains to define the practical range of agitation power levels, taking into account possible damage to free-standing features. Further effort is also needed to develop reliable models relating fragment diffusivity to fragment size and concentration.

Figure 1. Computed streamlines (left) and concentration contours (right) for w=30 μm, h= 120 μm, I=10 W/cm^2, $D=10^{-11}$ m^2/s, and f=1 MHz. Transport is enhanced by 3.5X.

Figure 2. Sherwood number is ratio of transport with sonic agitation to that without. Symbols are numerical calculations; dotted lines are composite Eqn. (1a), solid lines are asymptotes of Eqns. (1b,c).

Figure 3. Computed development histories (lines) are in reasonable agreement with Zanghellini data (symbols) for three agitation intensities.



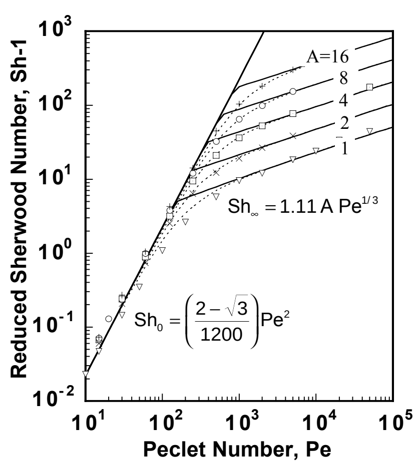


Figure 2. Sherwood vs. Peclet number.

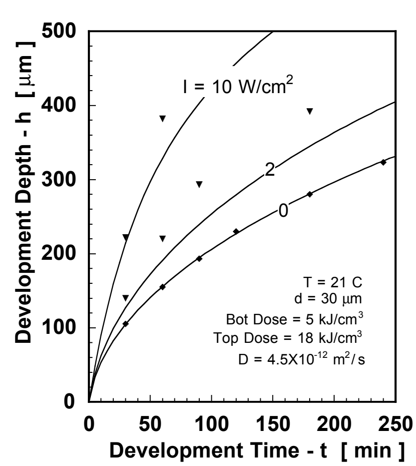


Figure 3. Development depth vs. time.

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[3] S. K. Griffiths, J. M. Hruby, and A. Ting, J. Micromechanical Microengineering **9** (4) 353-361, 1999.
[4] F. J. Pantenburg, S. Achenbach, and J. Mohr, J. Vac. Sci. Tech. B **16** (6) 3547-3551, 1998.