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The roughness and growth of a silver–mercury reaction interface

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Abstract

The spreading of small droplets (50–200 μm) of Hg on thin Ag films has been studied, using optical microscope, scanning electron microscope (SEM) and atomic force microscope (AFM). The growing rough surfaces have been analyzed in order to determine the roughness (α) and growth (β) exponents. For Ag thickness of 500–2000 Å we have found that $\alpha = 0.66 \pm 0.03$ and $\beta = 0.46 \pm 0.02$, while for Ag thickness of 0.1 mm, $\alpha = 0.77 \pm 0.04$ and $\beta = 0.60 \pm 0.02$. Both sets of exponents satisfy the scaling relation $\alpha + \alpha/\beta = 2$. In both systems the roughness exponent α crosses over to 0.5 in the final stages of the experiment and for relatively long length scales (order of a few μm).

Keywords: Surface growth; Interface; Reaction; Diffusion; Wetting

Spreading of liquids on solids and wetting of solid surfaces are rich physical, chemical, and statistical phenomena [1]. Modern statistical methods [2–5] of analyzing the interface between the liquid and the solid use two exponents to characterize the interface and associate it with a specific universality class.

In this work we study the dynamics and geometry of the interface between liquid metal (Hg) and a thin metal (Ag) film. Our system consists of Ag metallic films in various thicknesses deposited on glass microscope slides by vacuum evaporation (thin films of 500–2000 Å). Thicker Ag foils (0.1 mm) were polished by diamond powder. Small drops of Hg in various diameters (50–200 μm) were placed on these metal substrate surfaces (Fig. 1).

The spreading process of Hg on the Ag surface has been observed using an optical microscope equipped with differential interference contrast (DIC) system. The Hg front

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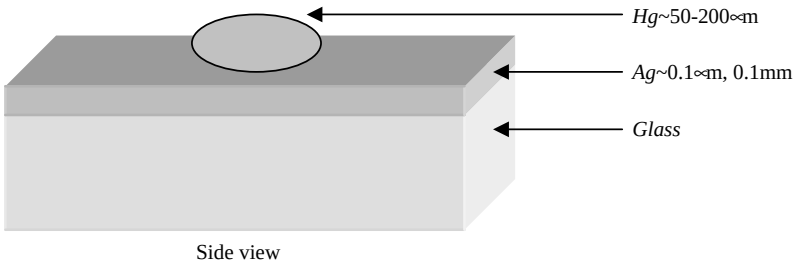

Fig. 1. A schematic side view of the experimental system.

propagation has been recorded by a video camera. The images were analyzed in order to determine the geometrical and dynamical properties of the front. A few days after the experiment, the specimen has been checked by a scanning electron microscope (SEM) and by an atomic force microscope (AFM) in order to closely look at the geometrical and chemical structure of the interface.

In Fig. 2 we show a series of typical microscope snapshots, recorded by our video system. These were taken from an experiment in which the silver thickness was 0.1 mm and the mercury droplet diameter was 150 μm. These figures indicate the possibility of two different fronts in the propagation of the mercury droplet. In this case the leading propagating interface is 600 Å above the silver surface (according to AFM studies), and is followed by a hydrodynamic Hg bulk front, which is about 1 μm above the surface.

A similar microscope snapshot of a droplet running on a thinner Ag film (2000 Å) is shown in Fig. 3a. Fig. 3b was taken at the end of this process. The droplet diameter was 150 μm. In this case the film has been exposed to air prior to the experiment [6] and a single front has been observed.

The roughness exponent α and the growth exponent β are determined through a function $h(x,t)$ associated with the front line (Fig. 4). A width function W is then defined as

$$W^2(L,t) = \langle h(x,t)^2 \rangle - \langle h(x,t) \rangle^2 , \tag{1}$$

where L varies from the smallest length scale to the system size L_0. The width W satisfies [5]

$$W \sim \begin{cases} t^{\beta}, & t \ll t_0 , \\ L^{\alpha}, & t \gg t_0 , \end{cases} \tag{2}$$

where $t_0 \approx L^{\alpha/\beta}$.

Using Eqs. (1) and (2) we have analyzed the interfaces and found $\alpha = 0.66 \pm 0.03$ and $\beta = 0.46 \pm 0.02$, in the thinner Ag film systems. This value $\beta = 0.46$ is new and has never been obtained in experiments. The two exponents satisfy the well-known scaling relation for isotropic systems $\alpha + \alpha/\beta = 2$ [5], within the error bars. However, these new scaling exponents associate this experiment to a new universality class.

A possible universality class is the one suggested by Hentschel and Family [7]. They considered quenched Kardar–Parisi–Zhang (Q-KPZ) systems and claimed that for rough

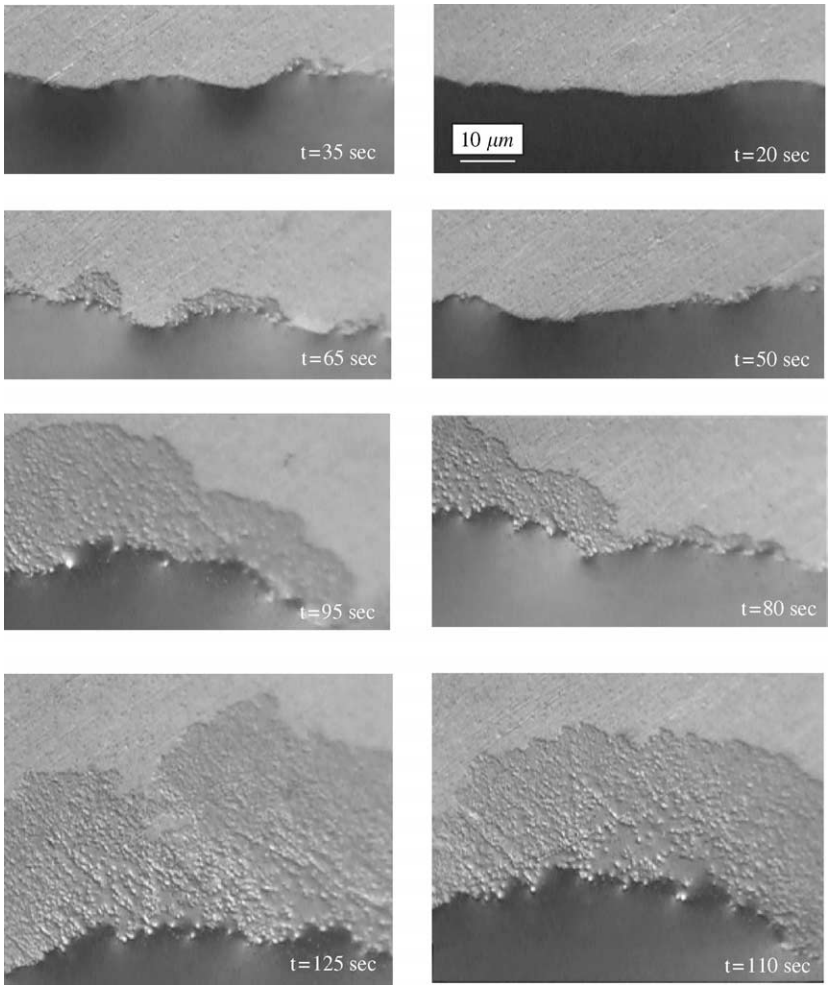

Fig. 2. Typical microscope snapshots for silver thickness of 0.1 mm and mercury droplet diameter of 150 μm, taken at a series of times as shown.

surfaces and small surface tension forces, one obtains $\alpha = 4/(d+4), \beta = 2/(d+2)$, which yields, for our two-dimensional spreading, the values $\alpha = 2/3, \beta = 1/2$, in agreement with our experimental data. A detailed study of this conjecture is currently underway.

When the spreading process has completely stopped we have calculated α again and found that $\alpha = 0.76 \pm 0.02$ for short length scales ($L < 2$ μm), and $\alpha = 0.47 \pm 0.02$ for long length scales ($L > 2$ μm). The high value of α ($\alpha \approx 0.76$) does not obey the scaling relation $\alpha + \alpha/\beta = 2$ since the isotropic assumption which this relation is based on [5] is no longer relevant. The strong correlation in short scales is probably due to the chemical reaction $4Ag + 3Hg \rightarrow Ag_4Hg_3$ (for more details see Ref. [6]). The value $\alpha \approx 0.47$ for long length scales is in good agreement with the KPZ theory [8].

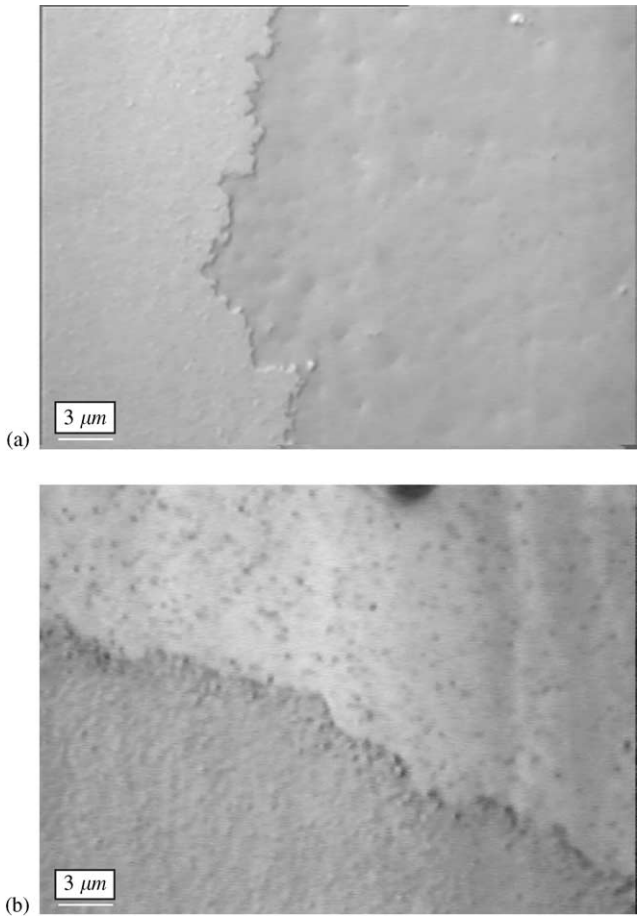

Fig. 3. Snapshots for the thinner system (silver thickness 2000 Å). The mercury diameter is 150 μm. (a) During the propagation process (from right to left). (b) At the end of the process (direction of spreading from bottom to top).

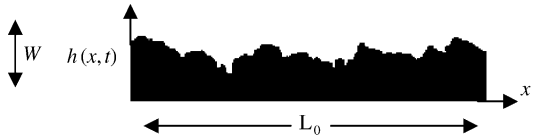

Fig. 4. The function $h(x,t)$ for describing the interface characteristics. The width W satisfies Eqs. (1) and (2).

For the thicker silver substrates (0.1 mm), the exponents were found to be $\alpha = 0.77 \pm 0.04$ and $\beta = 0.60 \pm 0.02$. These exponents, although very much different from the thin film exponents, still obey the scaling relation $\alpha + \alpha/\beta = 2$. Similar exponents have been obtained by Horvath et al. [9], for the geometry and dynamics of a macroscopic (order

Table 1
Summary of the roughness (α) and growth (β) exponents obtained for the silver–mercury interface

	During the process	End of process
Thin film 2000 Å	$\alpha = 0.66 \pm 0.03$ $\beta = 0.46 \pm 0.02$	$\alpha_{L<2\ \mu m} \sim 0.76$ $\alpha_{L>2\ \mu m} \sim 0.47$
Thick foil 0.1 mm	$\alpha = 0.77 \pm 0.04$ $\beta = 0.60 \pm 0.02$	$\alpha_{L<8\ \mu m} \sim 0.82$ $\alpha_{L>8\ \mu m} \sim 0.50$

of tens of centimeters) system in which immiscible liquid is inserted between two pinned boards (Hele-Shaw Cell).

When the spreading process stopped (after 5 min), we have calculated α again and found that $\alpha \approx 0.82$ for short length scales ($L < 8\ \mu m$), and $\alpha \approx 0.5$ for long length scales ($L > 8\ \mu m$). This crossover phenomenon is quite similar to the thinner system but the correlation length L is larger due to the larger bulk of the silver, and probably due to a different chemical reaction process stemming from a different granular surface structure.

To summarize, we have presented data on the geometry and dynamics of a silver–mercury reaction interface. We have calculated the roughness and growth exponents and discussed the corresponding universality classes. The results are summarized in Table 1. The crossover behavior of the roughness exponent sheds light on different mechanisms and correlation lengths in the process.

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