Scaling behavior of polished (110) single-crystal nickel surfaces

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The kinetic surface roughening of the polished (110) plane of a single-crystal nickel is investigated using atomic force microscopy. The polished (110) surfaces exhibit the scaling behavior characterized by the roughness exponent α=0.83$\pm$0.05, the growth exponent β=0.83$\pm$0.07 and the skewness= –0.52$\pm$0.06, whose values are compared with the theoretical values in statistical growth models in deposition. These characteristics indicate that the scaling behavior of the polished nickel surfaces can be related to a statistical growth model of nonlinear diffusion dynamics in deposition.

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1. Introduction

In recent years, many theoretical and experimental investigations into the kinetic surface roughening in deposition growth have been made [1,2]. The rough surfaces have been thought to be associated with scaling invariance and to be described by the time and spatial dependent surface profile h(**r**,t) that satisfies $h(r,t)=\phi^{-\alpha}h(\phi r,\phi^{\alpha/\beta}t)$ where ϕ is a scaling factor [3]. The roughness exponent α and growth exponent β characterize the scaling behavior of statistical surface growth models [4] based on symmetry principles. Such scaling invariance will be found not only in the kinetic surface roughening in deposition growth but also in that in the polishing process. In fact there has been an experimental report about a fractal model for the polished surfaces of polycrystalline silver [5]. Our motivation of this study starts from questions of what the exponents α, β and the skewness [6] are for the polished surfaces of a single-crystal nickel and of what statistical model makes it possible to describe the scaling behavior. The skewness is related to the up-down symmetry, i.e., $h\rightarrow -h$. As a result of the symmetry breaking, any continuum equations that describe the evolution of the roughening surfaces should be nonlinear. The scaling analysis of the polished surfaces is of technological and scientific importance to make clear the polishing mechanism. Unfortunately there have been very few studies on the scaling behavior of the polished surfaces in light of the statistical surface growth models [7]. A single-crystal nickel is chosen in our investigation to avoid complicated effects of grain boundaries in polycrystalline nickels on the polishing process. Atomic force microscopy (AFM) is employed to characterize the surface morphology of the single-crystal nickel. The exponents α, β and the skewness are calculated from the AFM images with a resolution of 512x512 pixels. In this paper we report the scaling relations of the polished (110) surfaces of the single-crystal nickel and the values of the exponents. In order to assure asymptotic behavior, the average surface roughness in the range of 20 to 1000 nm is measured.

2. Experimental

The sample was a disk of 5 N purity single-crystal nickel of 10 mm in diameter with the (110) surfaces. Four kinds of polishing pastes including diamond powders of different sizes, 15, 6, 1 and 0.1μm were prepared to investigate the effect of the powder size on the scaling behavior. The (110) surface was polished on polishing pads at a fixed polishing rate for several random time intervals using the polishing paste. After that, the surface was cleaned ultrasonically in acetone and ethanol in order to remove the pastes and adhered particles. The sample was scanned in air with AFM with a resolution of 512x512 pixels. The tip radius of curvature dramatically affects the quality of the AFM images. The Si_3N_4 cantilever used in this study has a tip radius of 15nm, which gives a high resolution enough to observe nickel bumps formed on the surface. The maximum scanning size of the AFM image is 30μmx30μm. The AFM images with different scan regions of LxL=1x1, 3x3, 5x5, 10x10, 20x20 and 30x30 μm^2 were used for calculation of the exponents.

3. Results and discussion

Fig.1 shows typical AFM images of the polished (110) surfaces in different stages of the polishing process characterized by the different values of the average height <h>. It is noted that the vertical size of the images is magnified by a factor of 5.7. The surface morphology appears to be continuous bumps.

In order to determine the exponents α and β from the AFM images, we calculate the height-height correlation function G(**r**,t) and the rms roughness w(t), which have the forms [1],

$$G(\boldsymbol{r},t)=\left\langle\left[h(\boldsymbol{r}+\boldsymbol{r}_1,t)-h(\boldsymbol{r}_1,t)\right]^2\right\rangle_{\boldsymbol{r}_1} \propto \rho(t)r^{2\alpha} \text{,for } r<<\xi, \tag{1}$$

$$w(t)=\left\langle\left[h(\mathbf{r},t)-\langle h\rangle\right]^2\right\rangle^{1/2} \propto t^{\beta}, \tag{2}$$

where ⟨ ⟩ is the spatial average over the measured area, ξ the correlation length and ρ(t) the average local slope of the bumps [8,9] given by $<(\nabla h)^2>^{1/2}$.

Fig.2 shows a log-log plot of w(t) vs <h> for the (110) surface polished by the use of the pastes including the different diamond powder sizes. The points plotted in Fig. 2 are mean values calculated from several AFM images for the fixed scanning sizes. All data, which are a little scattered, almost collapse on a single straight line, independent of the system size L (μm) and the diamond powder size. The slope best fitted to the data gives 0.83±0.07, which indicates that the polishing process is different from the Poisson one, i.e., $w(t)\propto<h>^{1/2}$.

Here let us make an attempt to determine the growth exponent β. In the polishing process, we may consider that the amount of the removed materials from the surface is the proper measure of time. Hence the volume of the bumps calculated from the AFM images can be related to time. If the amount of the removed materials is proportional to time and the system size L^2, i.e., the polishing rate $d<h>/dt \approx constant$, we have

$$w(t) \propto \langle h \rangle^{\beta}. \tag{3}$$

Since the polishing rate is fixed for each diamond powders, it is reasonable that the mean height <h> is in proportion to the polishing time. This relation gives $\beta=0.83\pm 0.07$ from the slope in Fig.2. The growth exponent β larger than 1/2 in the statistical growth models has been explained by the diffusion bias [10] due to the Schwoebel barrier [11,12]. What in the polishing process corresponds to the diffusion bias in deposition growth? In the case of silicon wafers, there exist preferred abrasive planes [7]. Single-crystal nickels also have the slip systems (111) <110>. However no cleavage or (111) planes are apparently observed in the polished (110) nickel surface. At present the reason for $\beta>1/2$ in this experiment is unclear. Further experiments using amorphous nickel plates may be required to make clear the effect of the crystallographic planes on the growth roughness β.

Fig.3 shows a log-log plot of G(**r**,t) vs the lateral distance r for the average heights. It can been seen that G(**r**,t) increases linearly with r and reaches a saturated value. These curves do not collapse onto a single curve, which indicates an anomalous behavior. This arises from the time-dependence of the average local slope of the bumps $\rho(t)$ in Eq.(1). The similar anomalous behavior in deposition growth has been already reported by Yang et al. [8] and Jeffries at al. [9]. The plateau point in Fig.1 corresponds to the correlation length ξ. We obtain an average value of the roughness exponent $\alpha=0.83\pm0.05$. The values of α and β in this experiment are not in agreements with those predicted theoretically by the statistical growth models. However, since we obtain the definite value of α, we may say at least that the polishing process does not belong to the universality class that the materials are randomly removed from the surface.

Invariance under $h\to -h$ rules out the nonlinear term such as $(\nabla h)^2$. If the height configurations are asymmetric under vertical reflection $h\to -h$, the skewness [6] defined by $\left\langle \left(h(r,t)-\langle h\rangle\right)^3 \right\rangle / w^3$ becomes nonzero. In order to ascertain the asymmetric configuration of the polished surface, we calculate the skewness for the polished surfaces with the average height from 20 to 1000 nm. Fig.4 shows a plot of the skewness vs the average height. The skewness appears to be scattered mainly in a negative regime and has an average value of -0.52 ± 0.06. Das Sarma et al. [6] reported negative values of the skewness by numerical simulations, for example, –0.5 for their DT growth model in 1+1 dimensions. The value of α and the skewness in our investigation suggest the polishing process related to the nonlinear term.

If the noise η is a quenched noise that does not change with time and has a power-law distribution, the surfaces indicate multiscaling for length scales shorter than a characteristic length [13]. A typical example of the quenched noise is a pinned surface due to the inhomogeneities in materials. In the polishing process, the pinned surface results in a higher bump and brings an anomalous value of α far from the theoretical value. The multiscaling properties can be calculated by the qth-order height-height correlation function $C_q(r)$ defined by

$$C_q = \left\langle \left| h(r + r_i) - h(r_i) \right|^q \right\rangle_{r_i} \propto r^{q\alpha} . \tag{4}$$

Fig.5 shows a typical plot of $(1/q)\log C_q$ vs r in a log-log scale (a) for <h>=60.9nm and (b) for <h>=399.1nm. It can be seen that the polished surfaces have very weak multiscaling and the noise distribution in this study is Gaussian. This indicates that great sudden changes of the noise amplitude due to an increase in the force for removal of bumps do not take place in the polishing process.

4. Conclusions

In summary, the scaling exponents for the polished (110) nickel surfaces are determined by the analysis of the AFM images. It is found that the kinetic roughening of the polished (110) surface can be related to the statistical growth model.

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Figure captions

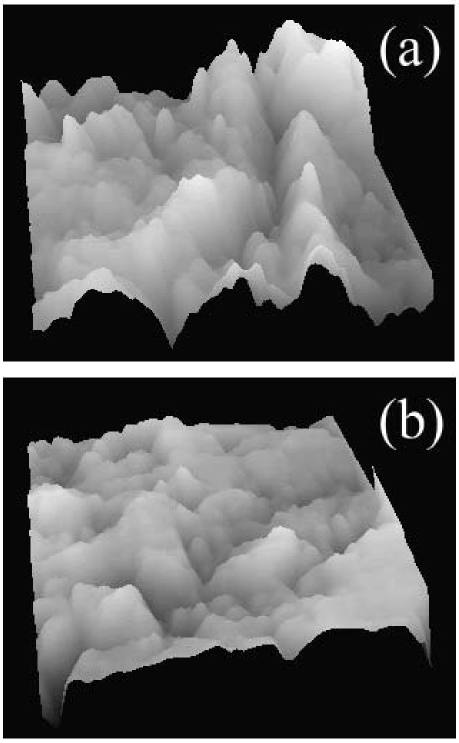
Fig.1 AFM images of the polished (110) nickel surfaces for the average heights: (a) 527nm and (b) 316nm. Each image size is 10μmx10μm and the vertical size is magnified by a factor of 5.7 to enhance viewing.

Fig.2 Log-log plot of the rms roughness w(t) vs the average height <h>, calculated from the AFM images of the polished (110) nickel surfaces. The slope best fitted to the data using the linear least square method gives $\beta=0.83\pm0.07$.

Fig.3 Log-log plot of the height-height correlation functions G(r,t) vs r, calculated from the AFM images of the polished (110) nickel surfaces. The average value of α is 0.83 ± 0.05.

Fig.4 Plot of the skewness vs the average height <h> for the AFM images of the polished (110) nickel surface. The average skewness is -0.52 ± 0.06.

Fig.5 Typical plot of qth-order correlation function C_q (a) at <h>=60.9nm and (b) at <h>=399.1nm.



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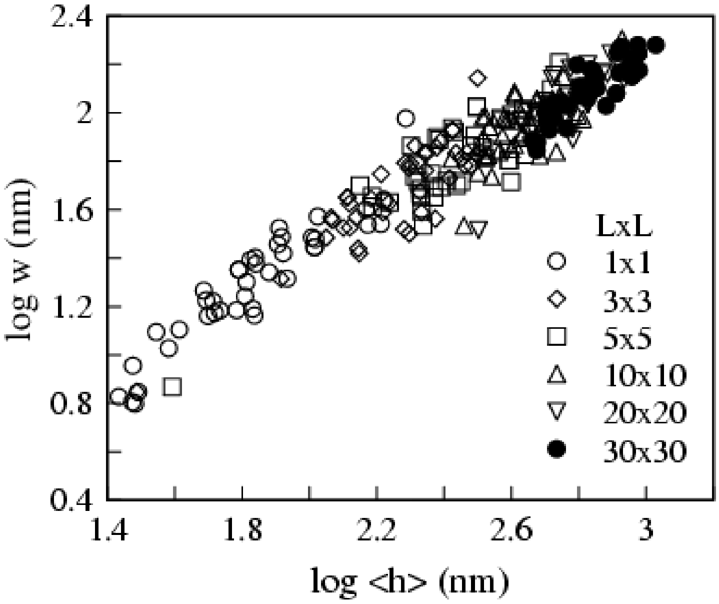

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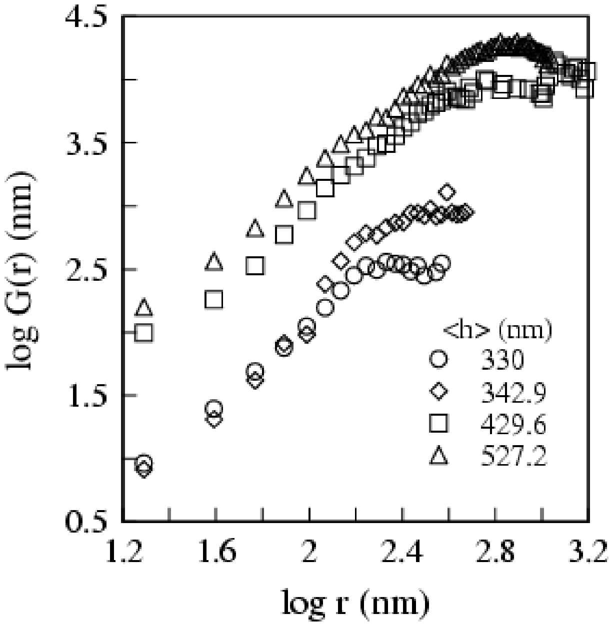

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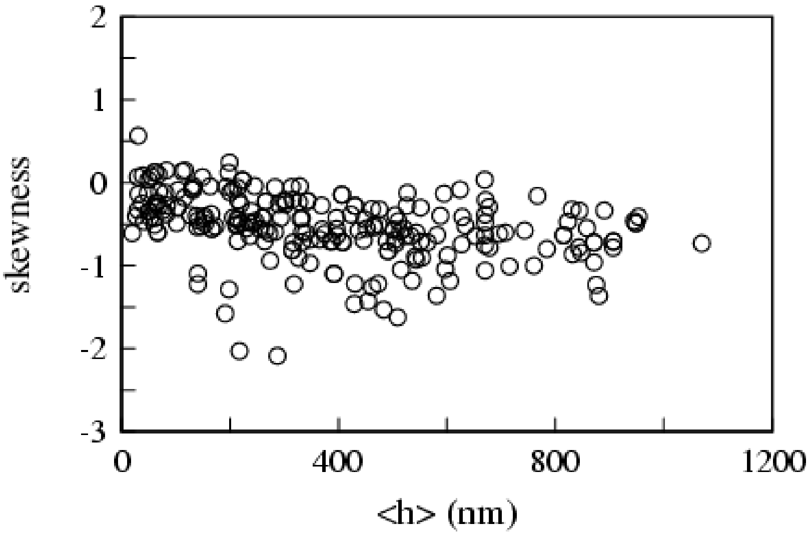

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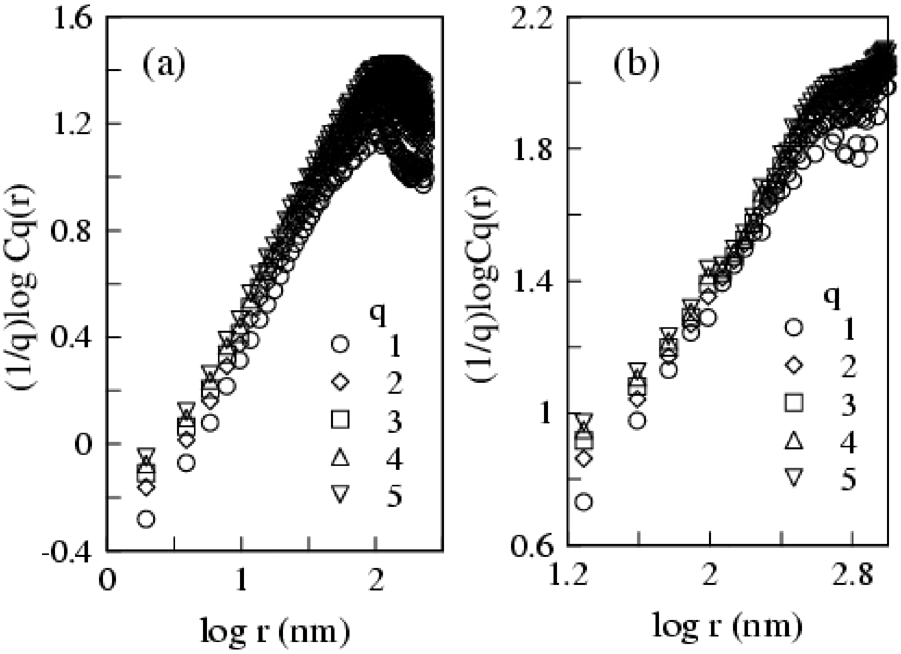

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