Domain-wall roughening in $Co_{28}Pt_{72}$ alloy films

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We have studied the interface dynamics of growing magnetic domains in thin $Co_{28}Pt_{72}$ alloy films experimentally where the growth of the domains was investigated with Kerr contrast imaging. The data are analyzed with dynamic scaling methods. The results suggest that the motion of the domain wall can be described by the Edwards-Wilkinson equation with quenched disorder. [S0163-1829(98)04009-0]

I. INTRODUCTION

In recent years a variety of studies were done to understand the phenomenon of interface roughening in a time-independent (quenched) disordered environment (for an overview see Ref. 1, and references therein) since it is of great technical importance. Examples are the immiscible-fluid displacement in oil recovery and the dynamics of magnetic domain walls; see, for example, Ref. 2. These problems have the occurrence of a so-called depinning transition in common; i.e., depending on a driving force the interface gets trapped by the random impurities or the interface moves steadily with nonzero velocity. Since in real systems there is always the additional effect of temperature, a sharp depinning transition can only be observed in model systems where temperature can be set to zero.

Generally, at the depinning transition the equations of motion of the interfaces belong either to the Edwards-Wilkinson (EW) (Ref. 3) or to the Kardar-Parisi-Zhang (KPZ) (Ref. 4) universality class. In the first case the equation of motion for the interface profile function $h(\mathbf{x},t)$ reads

$$\frac{\partial h}{\partial t}=\nu\nabla^2 h+\eta[\mathbf{x},h(\mathbf{x},t)]+F, \tag{1}$$

where the first term on the right-hand side of this equation models a surface tension having a smoothing effect on the interface while the noise term $\eta[\mathbf{x},h(\mathbf{x},t)]$ roughens the interface and F denotes a homogenous driving force. In the second case the so-called KPZ nonlinearity $\lambda/2\,(\nabla h)^2$ with λ proportional to the interface velocity occurs additionally:

$$\frac{\partial h}{\partial t}=\nu\nabla^2 h+\frac{\lambda}{2}(\nabla h)^2+\eta[\mathbf{x},h(\mathbf{x},t)]+F. \tag{2}$$

The interfaces are characterized by their roughness exponent α and by their dynamic exponent z (see Ref. 5), where the values of these exponents depend on the universality class of the considered model. One possibility for obtaining the exponents is to measure the height correlation function

$$C(r,t)=\langle[h(\mathbf{x}+\mathbf{r},t)-h(\mathbf{x},t)]^2\rangle\sim[\xi(t)]^{2\alpha}g\left(\frac{r}{\xi(t)}\right) \tag{3}$$

with $\xi(t)\propto t^{1/z}$ denoting the time-dependent correlation length and where the angular brackets denote an average over $\mathbf{x}$. The scaling function g has the properties $g(y)\approx$ const for $y\gg 1$ and $g(y)\propto y^{2\alpha}$ for $y\ll 1$ so that asymptotically Eq. (3) becomes

$$C[r\gg\xi(t),t]\propto t^{2\beta} \tag{4}$$

with $\beta=\alpha/z$ and

$$C[r\ll\xi(t),t]\propto r^{2\alpha}, \tag{5}$$

respectively. Another characteristic function is the roughness

$$w(L,t)=[\langle h^2(\mathbf{x},t)\rangle-\langle h(\mathbf{x},t)\rangle^2]^{1/2}\sim L^{\alpha}f\left(\frac{t}{L^z}\right) \tag{6}$$

with L denoting the linear system size and where the scaling function f must have the properties $f(y)\approx$ const for $y\gg 1$ and $f(y)\propto y^{\beta}$ for $y\ll 1$ to obtain limiting scaling behaviors consistent with Eqs. (4) and (5). However, as we will show below this quantity is less useful if spherical or nearly spherical objects are considered.

Valentin *et al.* reported recently[6] that depending on the film thickness the magnetization reversal process in CoPt alloy films is dominated either by domain wall motion (thinner films) or by domain nucleation processes (thicker films). It is the purpose of the present paper to investigate the morphology and dynamics of these moving domain walls in a $Co_{28}Pt_{72}$ alloy film. Arguments will be given that the motion of a domain wall in this material can be described by the EW equation with quenched disorder Eq. (1).

II. EXPERIMENTAL REALIZATION

The investigated thin $Co_{28}Pt_{72}$ alloy films with thicknesses of $d=10\cdots30$ nm were prepared using e-beam evaporation in ultrahigh vacuum onto polished fused silica of SiN_x precoated Si(100) substrate. The films were deposited at elevated temperatures of approximately 500 K yielding a high-quality sample with perpendicular magnetic anisotropy. The domain pattern analysis was performed using a polarizating microscope with high lateral resolution in the polar configuration. For the real time recording of the data a

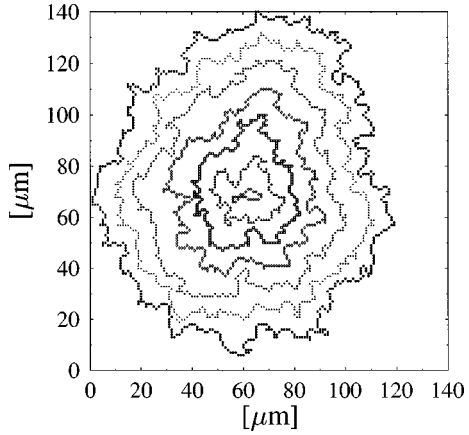

FIG. 1. Contour plot of a growing domain for different times as indicated in Fig. 3 at $T=364$ K and $H=14.9$ kA/m.

charge coupled device camera connected to a PC was placed in the focal plane of the microscope. The camera has 288 $\times 384$ pixels, each pixel representing 0.86 μm^2 of the film. The usual image processing methods were performed for noise reduction. A gray scale analysis yields to the normal component of the magnetization at a given external field. To obtain a sharp phase boundary the pixels with a gray scale above a certain threshold value are assigned a magnetization $+M_s$ while for a gray scale smaller this threshold the magnetization was set to $-M_s$. We make sure that, to some degree at least, the results do not depend on the particular value of this threshold. Domain growth was obtained for external fields up to 19 kA/m and for temperatures from 299 up to 394 K.

III. RESULTS AND DISCUSSION

Figure 1 shows typical domain patterns for various times τ after applying an external field of $H=14.9$ kA/m at $T=364$ K. The interface position $\mathbf{r}_n(t)$ between the *black* and the *white* domain is defined as these positions where the black pixels has less than four black neighbors. For a quantitative analysis the positions $\mathbf{r}_n(t)$ are mapped onto a single valued function $h(s,t)=|\mathbf{r}_n(t)|$. Since the interface has foldovers, for the spatial parametrization we chose the arc length

$$s=\sum_{i=0}^{n} |\mathbf{r}_{i+1}(t)-\mathbf{r}_i(t)| \tag{7}$$

to guarantee the requirement of a single valued interface profile function $h(s,t)$. For the time parametrization one has to recall that dynamic scaling analysis involves the assumption that for the time $t=0$ the average height or the mean radius, respectively, of the interface is zero. Therefore we must rescale our time scale. This can be done using $t\equiv\tau-\tau_0$, where τ_0 is the time at which the nucleation of the domains starts. Due to noise effects this time cannot be defined in a unique way. A better ansatz is to define $t\equiv\langle r(\tau)\rangle$ since $\langle r(\tau)\rangle \propto \tau-\tau_0$ (see Fig. 2).

Since the circumference of the domain, which can be regarded as the system length L, is proportional to $\langle r(\tau)\rangle$ and thus proportional to t Eq. (6) reads as

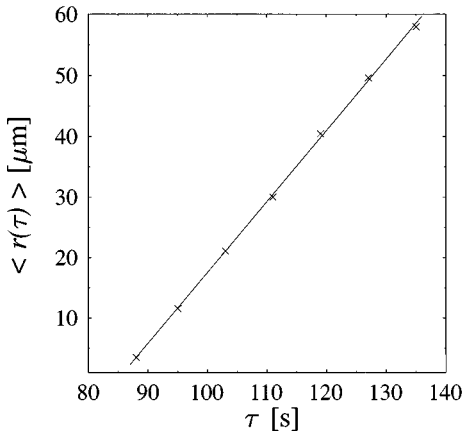

FIG. 2. Time dependence of the mean radius $\langle r(\tau)\rangle$ of the domains. The solid line represents a linear fit ($T=364$ K, $H=14.9$ kA/m).

$$w(L,t)\propto t^{\alpha} f\left(\frac{t}{t^z}\right)\propto t^{\alpha} f\left(\frac{1}{t^{z-1}}\right). \tag{8}$$

Since the dynamic exponent z has a value larger than one, the argument of the scaling function f goes to zero for large t, thus $f(y)\propto y^{\beta}$ and finally $w(L,t)\propto t^{\beta}$. Therefore, in a cylindrical geometry with the width w the exponent β can only be obtained. Thus, to analyze the morphology of the interface we consider the height correlation function Eq. (3). Figure 3 shows this quantity as a function of the distance s for different times on logarithmic scales. For small values of s, linear behavior is observed which leads according to Eq. (5) to $\alpha=0.77\pm0.01$ for the roughness exponent, while for large values of s saturation sets in at a C value depending on time. However, at higher s values a reduced value for the roughness exponent $\alpha\simeq 0.34$–0.39 can be obtained, depending on the particular curve. Since in the experimental situation presented here no summation over different realizations of the disorder can be done, as is usual in computer simulations, these effective roughness exponents for higher s values as well as the fluctuations around the saturation values are statistical effects and are not due to a possible crossover to a different scaling behavior on large length scales as it was

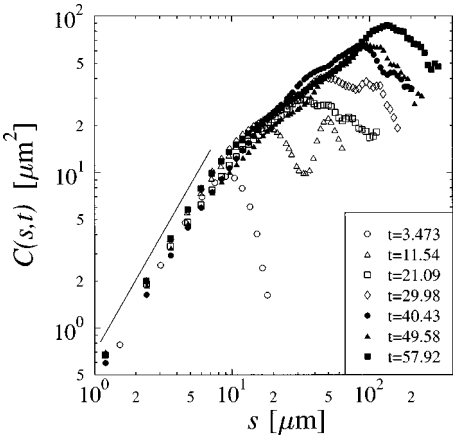

FIG. 3. The height correlation function $C(s,t)$ at various times t as indicated. The line represents a fit $C[r\ll\xi(t),t]\propto r^{2\alpha}$ [Eq. (5)] ($T=364$ K, $H=14.9$ kA/m).

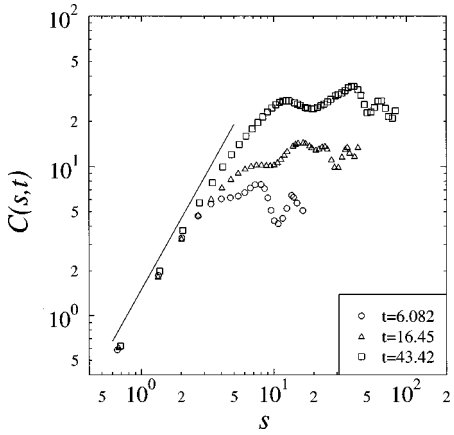

FIG. 4. The height correlation function $C(s,t)$ at various times t as indicated. The line represents a fit according to Eq. (5) with $\alpha=0.78\pm0.01$ ($T=364$ K, $H=17.7$ kA/m).

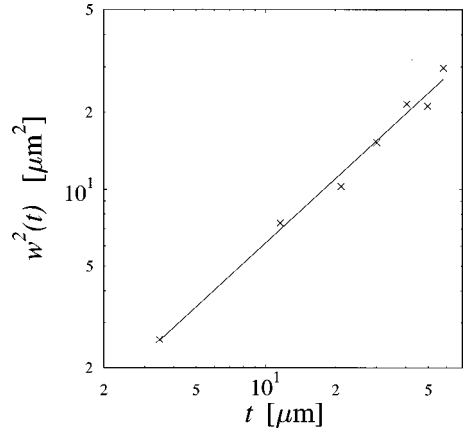

FIG. 6. The width $w^2(t)$ as a function of the rescaled time t where the line represents a fit according to $w^2(t)\propto t^{2\beta}$ ($T=364$ K, $H=14.9$ kA/m).

discussed earlier for fluid invasion problems.[7] To support our point of view we present additionally in Fig. 4 the height correlation function of a domain pattern for a somewhat larger external field of $H=17.7$ kA/m (Fig. 5). Here no crossover to another s-dependent scaling regime can be observed. Furthermore, for $s\rightarrow0$ the value $\alpha=0.78\pm0.01$ for the roughness exponent α can be observed in agreement with the result presented above. Thus it is suggestive to assume that the reduced roughness exponent observed for the domain pattern presented first is only a sample-to-sample fluctuation so that the morphology of the domain walls is characterized by a roughness exponent $\alpha\simeq0.77$.

According to Eq. (4) with the time dependence of the saturated C values the small time exponent β can be obtained. However, the fluctuations of the height correlation function for large s are too large to obtain a satisfactory quality for a fit. Here we favor the time dependence of the width Eq. (6) for a determination of β, leading to $\beta=0.42\pm0.02$ (see Fig. 6). Finally, with the values for the roughness exponent α and the small time exponent β we obtain for the dynamic exponent $z=\alpha/\beta=1.86\pm0.11$.

The $Co_{28}Pt_{72}$ alloy film has a polycrystalline structure where the grains have diameters from 10 to 25 nm. Nowak *et al.*[10] showed recently that the film can be described by a model which can be interpreted as a generalized random field Ising model (RFIM) with dipole interaction and an additional energy barrier describing the magnetic reversal of an isolated grain. For a discussion of the results we are neglecting at first the generalization of the RFIM and compare the results which one obtains for the pure RFIM. The experiments were done at temperatures which are much smaller than the critical temperature $T_C\approx600$ K of the material. Grinstein and Ma[12] showed for the RFIM that for the structural properties in the low-temperature phase thermal effects can be neglected in comparison with the random field effects. Therefore, the experimental results can be compared with results for the RFIM at $T=0$ K. Additionally, the applied external field is much smaller than the critical field $H_C\approx40$ kA/m (see Ref. 11) at which the depinning transition occurs. For this case, Jost and Usadel[13] obtained in a Ginzburg-Landau model of ferromagnetism with quenched disorder for the roughness exponent in the pinned phase $\alpha\approx0.78$ without a driving field and $\alpha\approx0.88$ at the depinning transition and the values for the small time exponent β are in the range of $\beta\approx0.41$–0.44 leading to dynamic exponents $z\approx1.85$–2.07. Thus, the experimental results and the numerical results of the corresponding model are in fairly good agreement. A roughness exponent $\alpha\simeq0.75$ was obtained also by Kessler *et al.*[14] by a numerical integration of Eq. (1) in the interface dimension $\mathcal{D}=1$ in the moving regime and not, as present here, in the pinning regime. In their case the value $\alpha\simeq0.75$ can be explained by a crossover from the quenched noise value $\alpha\equiv1$ to the annealed noise value $\alpha\equiv0.5$ for very large velocities. Additionally, a similar value ($\alpha\simeq0.81$) was obtained also by Martys *et al.*,[15] who studied a fluid invasion problem which should be described by Eq. (1).[2] However, a detailed analysis of experiments[7] and computer simulations[8] leads to the conclusion that interfaces in fluid invasion problems can be described by the KPZ equation with an effective time-dependent noise which has an algebraic distribution. Furthermore the obtained exponents are in agreement with theoretical treatments.[9] Thus one can conclude that the fluid invasion problem is not in the same universality class as the domain wall problem. Due to the obtained values it is reasonable to assume that neither the dipole interaction nor the energy barrier effects on the values of the characteristic exponents. Furthermore, the experimental results may be a con-

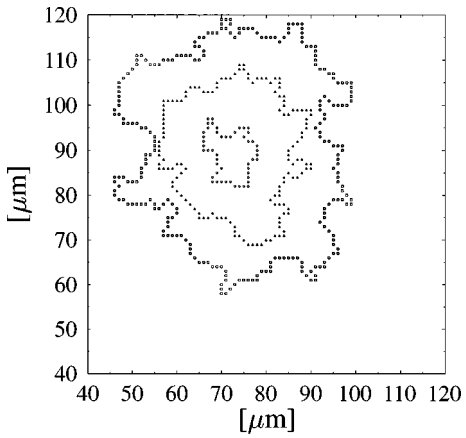

FIG. 5. Contour plot of a growing domain for different times as indicated in Fig. 4 at $T=364$ K and $H=17.7$ kA/m.

firmation of the dynamic scaling analysis of Eq. (1) which leads to $\alpha = 1$ and $z = 2$ at the depinning transition.[16]

IV. CONCLUSIONS

To summarize, we have analyzed the morphology and the dynamics of domain walls in a thin $Co_{28}Pt_{72}$ alloy film. The obtained values for the roughness exponent and the dynamic exponent are in general agreement with previous numerical and theoretical values for the Ginzburg-Landau realization of the RFIM and the quenched EW equation, respectively. Therefore, we can conclude that a domain wall in the investigated material can be described by the EW equation with quenched disorder. Furthermore, the extensions of the RFIM which are necessary to describe the magnetic reversal processes correctly may not have an influence on the universality class to which an interface in such a system belongs.

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