Effect of Dispersion Quality on Particulate Magnetic Recording Disk Properties

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The production of particulate magnetic disks or tapes requires consistent and uniform magnetic characteristics over the entire disk or tape to have as few defects as possible. To achieve this goal, the magnetic particle suspension used to coat the disk must be well dispersed. This article describes the use of a rheomagnetic instrument that provides an indirect measurement of the dispersion quality prior to coating application. The instrument was designed, tested, and put on a manufacturing scale line to characterize the relationships between the measured dispersion quality and functional characteristics of the magnetic coating. The results of tests done during scale-up for production yielded a qualitative correlation between the in-situ measurements made on the magnetic particle suspension at the coater with the surface roughness due to flocs, the on-disk orientation ratio, and the signal to noise ratio. The current results are the first demonstration of the dispersion quality measurement in a practical manufacturing environment.

Introduction

As the storage density requirements for magnetic recording disks continue to increase, the computer industry has been making demands on the particulate disk for higher density, reliability, and quality. At the same time, there is competitive pressure to reduce the cycle time between the development and availability of products. In a disk manufacturing plant, generally a large amount of data is continuously collected from various tests. Direct correlation of the available data from all these tests is impractical because of a large number of steps involved in the process and the difficulty of parametric control at each step. This study focuses on the particulate coating step of the disk manufacturing process.

Some of the key steps involved in manufacture of particulate recording disks are shown in Figure 1. For this discussion, the steps are divided into three groups: substrate preparation, magnetic suspension preparation, coating, and surface treatment. In the substrate preparation, the aluminum/magnesium (Al-Mg) substrates are milled and polished with diamond tooling. In the magnetic suspension preparation (Burns et al., 1989), a mixture of iron oxide, alumina, epoxy-phenolic resin and solvent (1.5 vol. % iron oxide) is dispersed in a media mill. This well-dispersed magnetic particle suspension is then stored in 100 kg vessels at the coating line where it is spin-coated on the Al-Mg substrate. The coating is visually examined for uniformity. The coating thickness is measured by X-ray fluorescence, and the coating parameters, such as rotation rate, are adjusted to maintain the desired coating thickness. A magnetic field is applied to the coating as it dries on the disk to orient the particles in the tangential direction. Adjustments are also

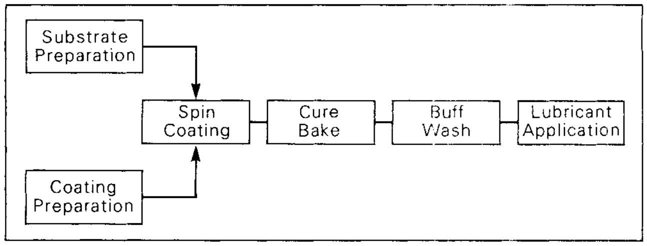

Figure 1. Steps involved in particulate magnetic disk production.

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made in this orientation magnetic field strength and duration during the setup of the coater for each new batch of coating. The coating is cross-linked at 230°C, polished to 5 nm·rms roughness, washed, and treated with a polyperfluoroalkylether lubricant. Each of the three steps shown in Figure 1 aims to provide a consistent product. However, uncertainties can arise because of process variations at any one step in production. It was initially suspected that variations in the dispersion quality of the magnetic particle suspension were going undetected. Hence, the objective was to provide a measure of uniformity at the coater to minimize dependence on subjective evaluations of dispersion quality.

The magnetic properties of iron oxide particles tend to attract the particles to one another forming flocculates. In most formulations, surfactant addition improves the stability (Fowkes et al., 1988; Dasgupta, 1988a,b). The milling of the suspension breaks up the flocs and agglomerates. In the manufacturing environment, however, as the milling media wear, the ability to break up the flocs decreases and therefore a dispersion quality measurement can provide a means of predicting the useful life of the milling media. In addition, the dispersion quality data can provide an indicator for particle flocculation during coating which in turn can be used to tell when the suspension is too flocculated to produce the desired high-quality coating.

Dispersion quality is a measure of the degree of flocculation of the magnetic particles in the polymeric solution in organic solvents. Few means are currently available for characterizing the dispersion quality of a turbid suspension. For example, the absorbance of the magnetic particle suspension is too high to employ light scattering or birefringence techniques. Rheological and sedimentation measurements can provide a qualitative measure of magnetic suspension properties (Huisman, 1985; Yang et al., 1986; Kuin, 1987; Dasgupta, 1988a,b; Gooch, 1989).

Since the iron oxide particles possess a magnetic moment, one option is to employ this property in a measurement of dispersion quality or particle size distribution in the suspension. An instrument for measuring dispersion by magnetic measurement (DIMAG) was previously explored by Brunsch et al. (1988). DIMAG provides a qualitative indication of the "mobility" of the magnetic particle flocs. In the DIMAG method of analysis, a strong DC magnetic field pulse is applied perpendicular to a weak AC magnetic field. The DC field pulse rotates single domain particle assemblies (flocs), hence changing the inductance experienced by the AC magnetic field. The time rate of inductance change during and immediately following the DC field pulse application, in principle, contains information about the degree of suspension flocculation. Experiments illustrated the relation between the DIMAG measurement, surfactant level, and microscopic observation of flocculation in dried magnetic particle suspension. However, due to the complexities of the interacting particle system under the influence of the DC field pulse, the DIMAG apparatus could provide only qualitative comparison between various degrees of dispersion quality, and the method is destructive since the DC field itself induces flocculation of the suspended magnetic particles.

An alternative device called a rheological magnetic analyzer (REMA) (Karis and Jhon, 1986, 1988, 1991; Jhon and Karis, 1989) was employed in this study. The REMA potentially offered a more quantitative measure of particle flocculates in suspension than other methods. The REMA method is described below.

Apparatus

The essential part of the REMA apparatus (Karis and Jhon, 1991), shown in Figure 2, is the glass flow cell. The flow cell consists of a 5-cm-diameter chamber, through which the magnetic particle suspension is pumped into a 3-mm-diameter glass tube. The volumetric flow rate was in the range of 0.026 to

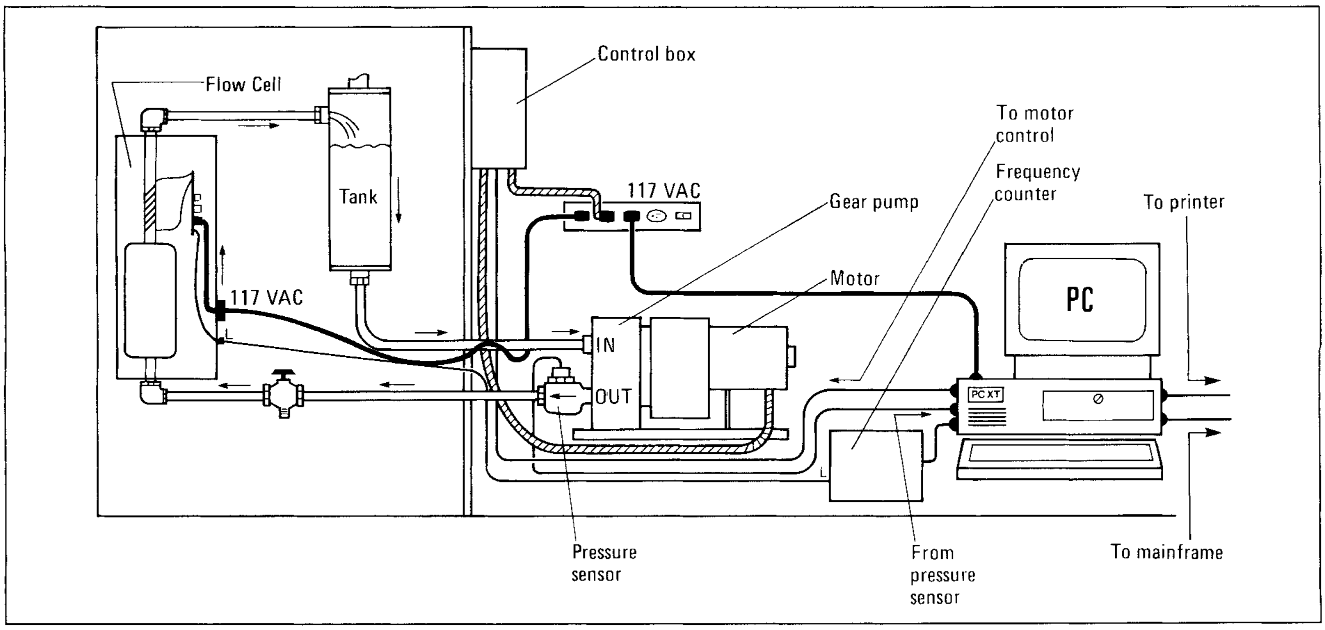

Figure 2. REMA apparatus.

The magnetic particle suspension is recirculated through the chamber and flow cell by the gear pump.

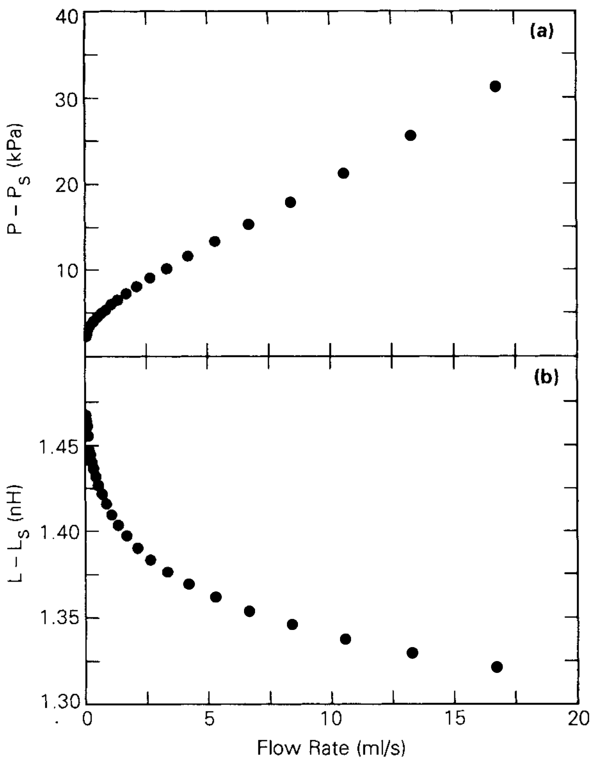

Figure 3. a. typical extra pressure drop and b. decrease in the inductance.

They occur due to orientation of the suspended particles as a function of flow rate.

$26\,cm^3/s$. When the particles are carried from the large chamber into the small tube, they experience a hydrodynamic force which tends to align (orient) the rod-like magnetic particles in the flow direction near the mouth of the small tube. The intensity of the hydrodynamic force is determined by the flow rate. In this apparatus, the extension rate was in the range of 1 to $10^3\ s^{-1}$. At low flow rate, the particle orientation distribution tends to be nearly random due to rotary Brownian diffusion, while at the higher flow rate, the particles become more nearly aligned with the flow direction. The effect of the hydrodynamic force on the particle alignment depends on the particle shape. Long, narrow particles are more easily aligned than globular flocs, because flocs tend to rotate rather than to align in the flow field. Particle orientation shows up in the pressure drop across the capillary as a non-Newtonian or power-law behavior. The typical pressure drop-flow rate characteristics are shown in Figure 3a. Here, P is the pressure measured with the suspension in the system, and P_s is the pressure at the corresponding flow rate with only the suspending fluid in the system. The smooth pressure drop-flow rate curve in Figure 3a shows that the flow remains laminar over this range of flow rate, since a transition to turbulence would be accompanied by a break in the curve. Further, the Reynolds number was in the range of 1 to 10^3, which is well below the critical Reynolds number of 2,300 for transition to turbulence in the pipe flow.

The particle flow orientation curve contains information about the particle shape. Changes in the dispersion quality affect the particle orientation through changes in the particle shape. A probe of orientation, which is uniquely suitable to the magnetic particle suspension, is the measurement of the bulk magnetic permeability. The shape of the magnetization curve is a function of the particle orientation distribution. The magnetic permeability provides a measure of the orientation distribution, because the permeability is proportional to the limiting low magnetic field slope of the magnetization curve (Karis and Jhon, 1986).

Changes in the suspension permeability due to changes in the flow rate can be obtained from the inductance of a solenoid coil (2-cm-long) on the 3-mm-diameter glass tube, just downstream from the entrance. Changes in the coil inductance are proportional to those in the permeability of the magnetic particle suspension produced by the flow orientation as shown in Figure 3b. Here, L is the inductance measured with suspension in the system, and L_s is the inductance at the corresponding flow rate with only the suspending fluid in the system. To measure the coil inductance, an L-C oscillator is attached with the coil as the inductor in the tank circuit. This provides a sensitive means to measure small changes in the coil inductance, since frequency can be measured to at least eight significant figures. The oscillator frequency is $\simeq$ 10 MHz. The apparatus is described in detail by Karis and Jhon (1991).

Hydrodynamic and electromagnetic theory are combined (Karis and Jhon, 1986) to solve for the relation of the coil inductance L as a function of the flow rate Q to the particle rotary diffusion coefficient D_r (Karis and Jhon, 1988).

$$RRDC \equiv \frac{D_r}{\gamma} = \frac{1}{2\sqrt{5}} \left(\frac{1}{d^3}\right) \times \left(-\frac{\partial L}{\partial Q}\right)_{Q\to 0}^{-1/2} \times \left(\frac{\partial L}{\partial(1/Q)}\right)_{Q\to\infty}^{1/2} \quad (1)$$

where d is the inner diameter of the tube inside the coil (3 mm), and γ is a hydrodynamic coefficient. Equation 1 was derived from the hydrodynamic model for a rigid rod-like Brownian particle at the centerline of an extensional flow in conjunction with the magnetic chain of spheres model for the single domain particle. Nonidealities arising from entrance effects and vorticity are discussed by Karis and Jhon (1991). The relative rotary diffusion coefficient is related to floc size and shape by:

$$\frac{D_r}{\gamma} \propto \frac{\ln(p)}{\eta_s (ap)^3} \quad (2)$$

where p is the effective particle aspect ratio (length to diameter ratio), a is the effective particle diameter, and η_s is the (Newtonian) binder solution suspending the fluid viscosity. For an isolated single-domain magnetic particle, $p \simeq 6$, $a \simeq 20$ nm, and $\eta_s \simeq 0.01$ Pa·s in this study. The limiting high shear rate shear viscosity of the particle suspension with volume fraction $\phi \simeq 0.015$ was approximately 0.015 Pa·s.

Equation 2 provides the link between the effective particle (floc) size and shape and the flow curve inductance gradients through Eq. 1. Any variation in the state of flocculation of the suspension changes a and p, causing D_r to change. In the apparatus, these show up as the changes in the gradients of the inductance as a function of the flow rate. Since the floc size and shape are unknown, measuring the inductance gradients provides a measure of the relative changes in the floc size and shape, regardless of how the flocs are formed, e.g., bundles or strings.

The inductance data are recorded and analyzed by the personal computer in Figure 2 according to the relations derived

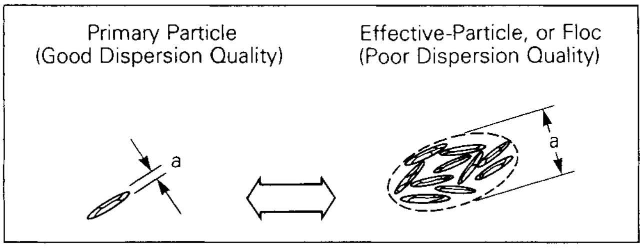

Figure 4. Flocculation process.

Primary particles (on the left) flocculate into larger flow units or effective particles (on the right).

to calculate the relative rotary diffusion coefficient D_r/γ, referred to as *RRDC* in Eq. 1. Since the flocs in the magnetic particle suspension are polydisperse, the rotary diffusion coefficient is actually an effective rotary diffusion coefficient, determined by the effective particle shape and aspect ratio. The REMA instrument thus provides an indirect measure of dispersion quality.

Figure 4 shows how the flocculation process can occur (Smith, 1972; Smith and Bruce, 1979; Scholten et al., 1990). Consider the primary magnetic particle on the left. As the suspension ages, or if the particles are insufficiently milled, the equilibrium floc size and shape are shifted toward those of the floc on the right, with an effective particle diameter a and aspect ratio p. This changes the rotary diffusion coefficient. When flocculation takes place, both a and p change simultaneously. The relation of D_r to a and p (Eq. 2) is illustrated by the three-dimensional surface plot in Figure 5. When the particles flocculate, changing the a and p coordinates, D_r moves along the response surface. Another way to represent the effect of a and p on D_r is by a contour plot, Figure 6. This is analogous to a topographical map: the closer the contour lines, the steeper the gradient. During flocculation, the aspect ratio decreases toward unity as the diameter increases. A likely

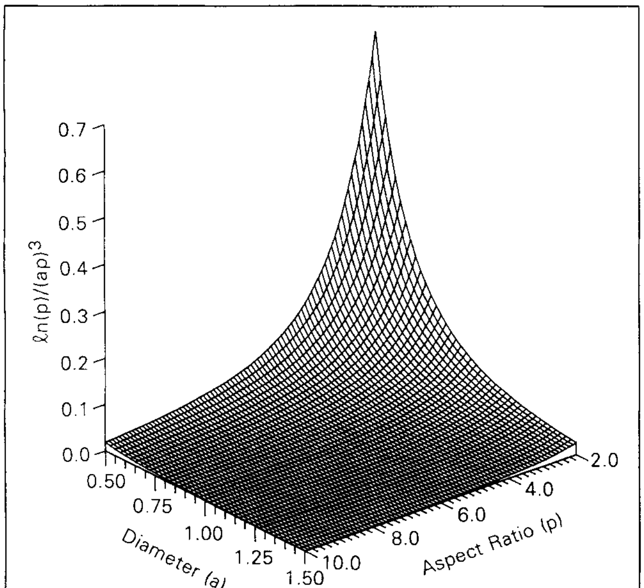

Figure 5. Three-dimensional surface plot.

It shows the dependence of the rotary diffusion coefficient on the effective particle diameter a and the aspect ratio p from Eq. 2.

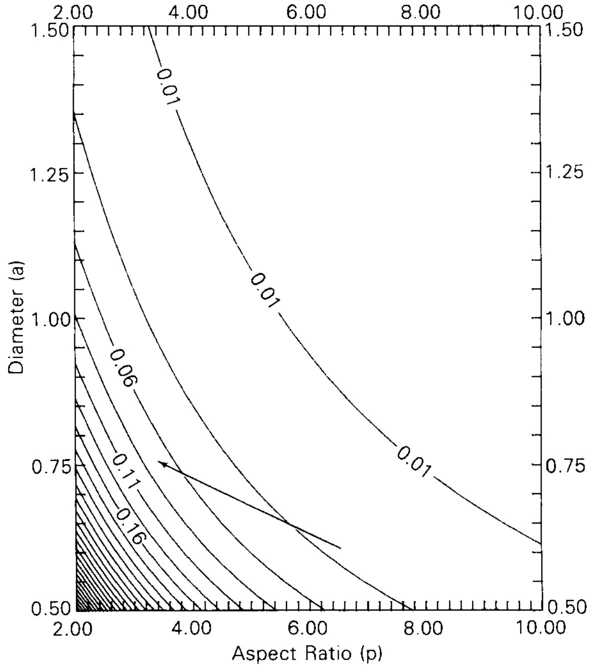

Figure 6. Contour plot of the surface in Figure 5.

Low D_r is in the upper right corner and high D_r is in the lower left corner. One likely path along the a, p coordinates as the particles flocculate (dispersion quality decreases) is shown by the arrow.

path for the change in particle shape during floculation, which increases D_r, is shown by the arrow in Figure 6. It is reasonable to expect some deviation of a and p from the ideal path, resulting in D_r drift. This drift is observed when the suspension recirculates in the measurement system (through the gear pump) during multiple repeated measurements on the same sample as a result of mechanical energy input (Sonntag and Russel, 1987). Since the flocs are held together by the strong magnetic forces between the particles, they are not expected to be broken down by the relatively weak extension rates in the flow cell.

Procedure

A computer program on the PC prompts the operator to fill and clean the apparatus, as well as to perform a sequence of measurements over a range of flow rates. This procedure was set up to apply a consistent and well-defined flow history and to minimize the effects of recirculation on dispersion. The operator is first requested to verify that the system is filled with clean solvent. The solvent is then drained. At this point, the operator obtains approximately 1 L of the magnetic particle suspension and immediately fills the system (without allowing time for flocculation and sedimentation). The suspension is then recirculated for 2 minutes at 26 mL/s to eliminate air bubbles, which can cause noise in the inductance measurement, and to attain thermal equilibrium. Following this recirculation period, the flow rate is decreased in 30 logarithmically spaced decrements over three orders of magnitude to 0.026 mL/s with 2-second hold times at each flow rate prior to the coil inductance measurement (see Figure 3). The computer program then calculates the limiting low flow rate intercept $(\partial L/\partial Q)_{Q\to 0}$ and limiting high flow rate intercept $[(\partial L)/\partial(1/Q)]_{Q\to\infty}$ from the data and outputs the relative rotary diffusion coefficient

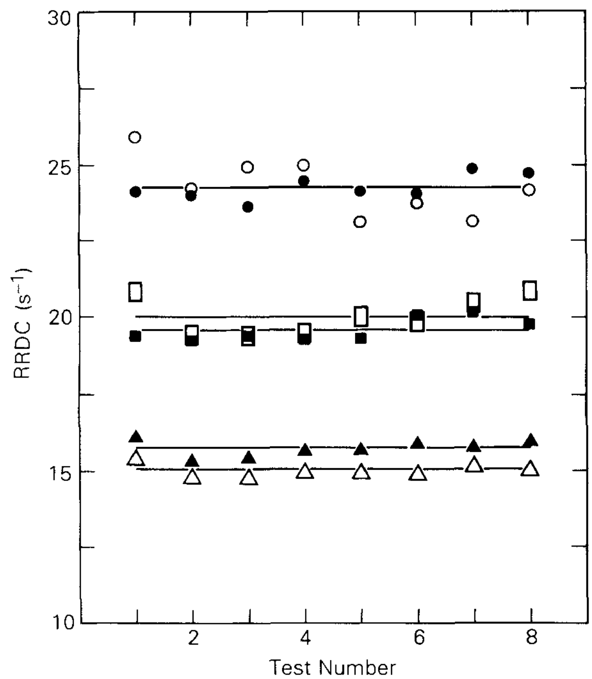

Figure 7. Repeated tests (measurement cycles) on magnetic particle suspension batches under different conditions.

Open symbols are the first sample drawn, and solid symbols are the second successive sample drawn, from a given batch. Circles are from an aged suspension batch made with worn milling media, squares from aged suspension made with new media, and triangles from new suspension prepared with new media.

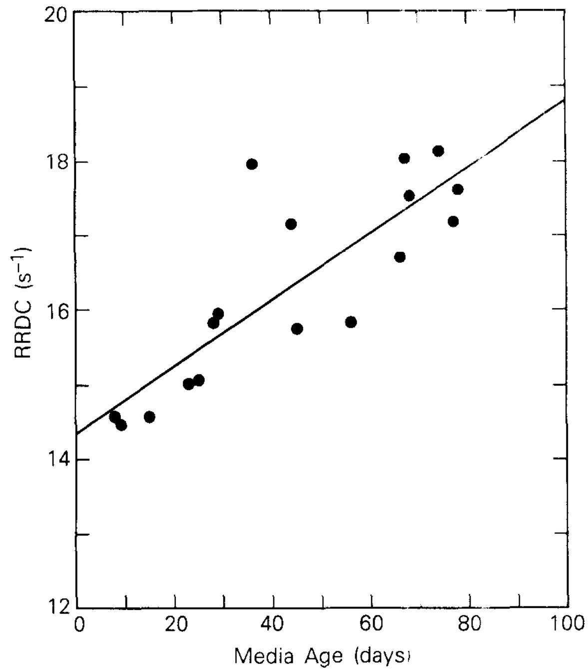

Figure 8. Effect of mill media age on the producibility of a well-dispersed suspension.

(*RRDC*) according to Eq. 1. Beginning with the 2 min of recirculation at constant flow rate, this comprises one measurement cycle.

The value of *RRDC* is stored, and the measurement cycle beginning with the recirculation for 2 min at high flow rate is repeated until a certain number of *RRDC* values have been obtained for averaging. The *RRDC's* for eight repeated measurement cycles, as described above, to study measurement reproducibility are shown in Figure 7. Each symbol type shows one of the sets of eight cycles. The solid symbol is from one sample and the open box symbol from another sample, drawn from the same batch of suspension. Different symbols indicate different batches of suspension and will be discussed below. Note that the *RRDC* from the first measurement cycle is typically higher than that from the subsequent measurements. This is attributed to equilibration of the dispersion quality in the recirculating environment. The *RRDC* value used for analyzing the relation to the disk properties was the average of eight sequential measurement cycles. This average was not significantly different from the average calculated by discarding the result from the first cycle and averaging the results from cycles two, three and four. After the first measurement cycle, significant changes in the dispersion quality due to recirculation were detected only after long periods of recirculation at high flow rate.

Scope

The following measurements were studied:

- Inductance vs. flow rate through the capillary tube in the REMA
- Relative rotary diffusion coefficient of the magnetic particle suspension as measured by the REMA
- Roughness of the particulate magnetic recording media surface as measured by diffuse reflectance and optical profilometry
- On-disk magnetic orientation ratio
- Single-disk tests including signal to noise ratio and errors in "read" and "write" operation as seen by bit errors.

Results

In addition to demonstrating the reproducibility of the measurement apparatus, the data in Figure 7 illustrate the effect of two process variables on the dispersion quality. The circles indicate data for an aged suspension that was prepared using worn milling media. The squares show an aged suspension that was prepared using new media, and the triangles are with new suspension prepared using new milling media. A key observation from these tests is that the *RRDC* decreases with increasing dispersion quality, because the worst dispersion results from the combination of aged media and suspension, the best from new suspension and media, and intermediate dispersion quality from aged suspension and new media.

As suggested above, the ability of the milling media to grind the suspension to a good dispersion quality decreases over time as successive batches are passed through it. Each batch is milled for the same amount of time, which is determined during process development to optimize the dispersion and to minimize the fracture of the single-domain primary particles. A series of tests was performed to characterize this media aging effect on the *RRDC* of freshly prepared suspension. The results are shown in Figure 8. Each point is for a separate 100-kg

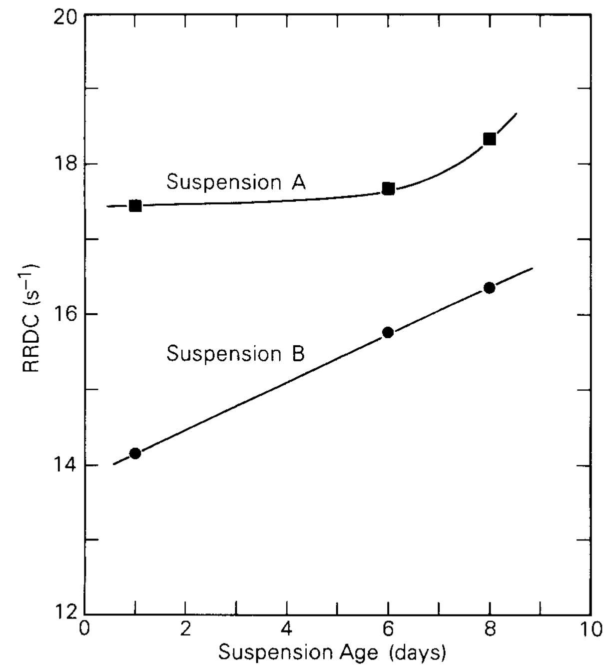

Figure 9. Effect of age on dispersion quality for two batches of suspension.

One with initially flocculated suspension *A* and the other with initially well-dispersed suspension *B*.

batch of suspension. As the milling media deteriorate with use, the *RRDC* steadily increases, indicating a gradual increase in flocculation with increasing hours of media use. The scatter in the data is caused by variations in the age and stirring among the suspension batches during storage prior to the dispersion quality measurement.

Once produced, the magnetic particle suspension is inherently unstable due to strong interparticle magnetic forces. Polymer binders and surfactant improve the stability (Fowkes et al., 1988; Dasgupta, 1988a,b), slowing the rate of flocculation and prolonging the useful lifetime of the coating batch. To further maintain the dispersion, the suspension is continuously stirred and recirculated through 5-micron filters. Despite these efforts to maintain the dispersion quality, the dispersion still gradually flocculates. A series of tests was done to study these

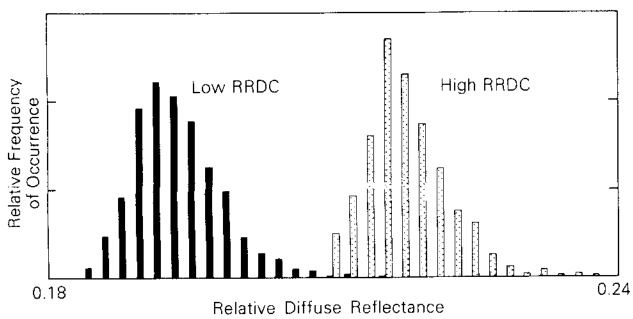

Figure 10. Diffuse reflectance measurement of the unbuffed surface roughness for a number of disks coated with well-dispersed suspension (low *RRDC*) and with flocculated suspension (high *RRDC*).

Diffuse reflectance increases with increasing surface roughness.

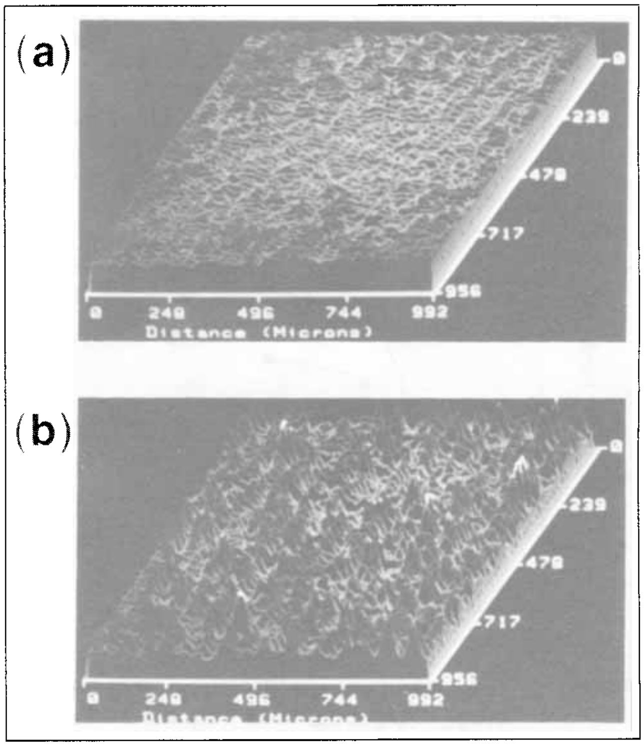

Figure 11. Three-dimensional surface profiles measured by optical profilometer on the unbuffed surface.

They show (a) the smooth coating obtained with the initially well-dispersed suspension and (b) the rough coating made with the flocculated suspension.

changes over time for several batches of suspension. The *RRDC* as a function of age is shown in Figure 9. Suspension batch B started out well-dispersed and flocculated steadily over 9 days, while batch A was initially flocculated and changed little over the 9-day period. This initial flocculation of batch A is attributed to an approximately 5-h delay that occurred between suspension preparation by milling and the application of stirring and filtration.

When the suspension is spin-coated onto the substrate to form the particulate magnetic media for recording, the flocs may collapse due to solvent evaporation or spin off with the excess binder. To examine whether the flocs measured by REMA in terms of *RRDC* remain on the disk after coating, disks were spin-coated with the suspensions shown for which the *RRDC* was measured. These coatings were then cured at the normal conditions, but they were not buffed. Next, the coatings were examined by a diffuse reflectance measurement over their entire surface. The higher diffuse reflectance indicates higher roughness. A histogram of the reflectance number of disks coated with suspension having either high *RRDC* > 17.5 or low *RRDC* < 15 is shown in Figure 10. The reflectance number for the disks with the higher *RRDC* is significantly higher than for those with low *RRDC*, suggesting that a generally rôugher surface results from coating the flocculated magnetic particle suspension. The surface roughness effect measured by the diffuse reflectance technique was verified by three dimensional optical profilometry (Perry et al., 1985) with a 10× objective. Approximately 1 cm × 1 cm sections were cut from the disks and coated with 30 nm of Au with 10% Pd

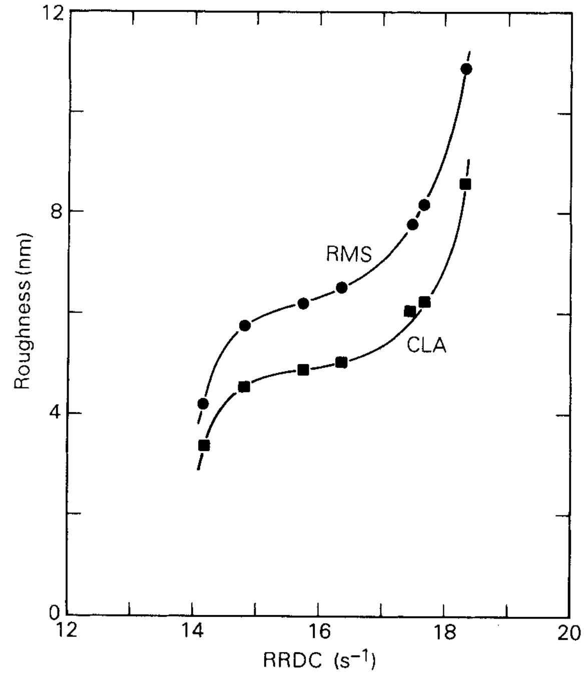

Figure 12. Root mean square (RMS) and center line average (CLA) roughness from the surface profiles (as in Figure 11) for unbuffed disks with a range of dispersion quality (*RRDC*).

to provide high and uniform reflectivity. Two example surface profiles from disks coated with suspensions having high and low *RRDC* are shown in Figure 11, where (a) was coated with the well-dispersed suspension and (b) with the flocculated suspension. The centerline average (CLA) and root mean square (RMS) surface roughness from the optical profiles of disks coated with a wide range of dispersion quality (*RRDC*) are shown in Figure 12. The roughness increased dramatically with increasing *RRDC*. The corresponding peak to valley roughness is shown in Figure 13. The separation between the suspension A and B curves is due to the different adjustments of the spin coating parameters made during machine setup. As the *RRDC* increased beyond 18 s^{-1}, the peak to valley roughness approached 100 nm, which is nearly half the 250 nm total thickness of the coating. Coating roughness, as measured by stylus profilometer, has also been observed to decrease with an increase in the thickness of adsorbed polymer on the particles, which improves the dispersion quality (Inoue et al., 1990).

Another sensitive measure of the effect of dispersion quality on the magnetic coating performance is the orientation ratio (OR). The OR is the ratio of the remanent magnetization in the tangential to that in the radial direction (Teng and Johnson, 1982). The OR refers to orientation of the particles in the coating on the disk rather than the flow orientation produced in the REMA apparatus to measure dispersion quality. Just after the spin coating, a strong magnetic field is applied in the tangential direction as the solvent evaporates from the coating. This tends to align the rod-like single-domain particles in the tangential direction (Newr [illegible]3; Williams, 1982; Fischer et al., 1982). Increasing t[illegible] [illegible]nproves the squareness of the M-H loop which stores t[illegible] [illegible]agnetic bits written and read by the slider (Mian and Yamaguchi, 1986), where M is the magnetization and H is the applied magnetic field. As more of the individual rod-like particles are incorporated in flocs, their ability to rotate and align with the field of the orientation magnet is decreased. Thus, if the flocs in the coated suspension

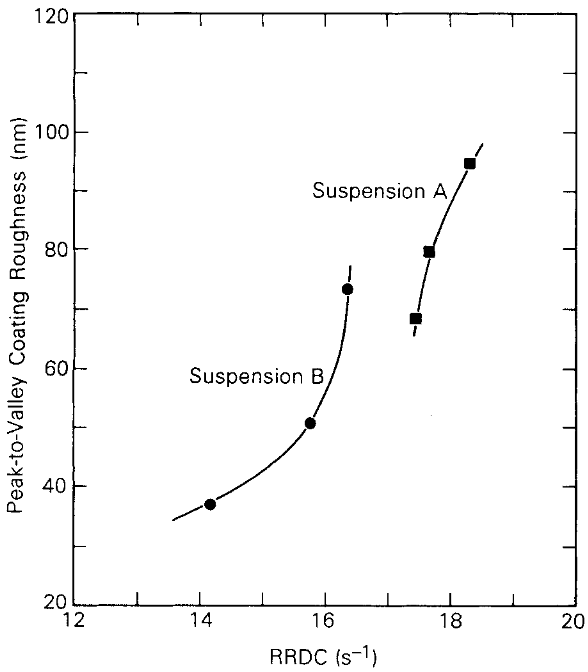

Figure 13. Peak to valley roughness corresponding to disks coated with the initially flocculated suspension *A* and the initially well-dispersed suspension *B* (as in Figure 9) measured from the optical surface profiles.

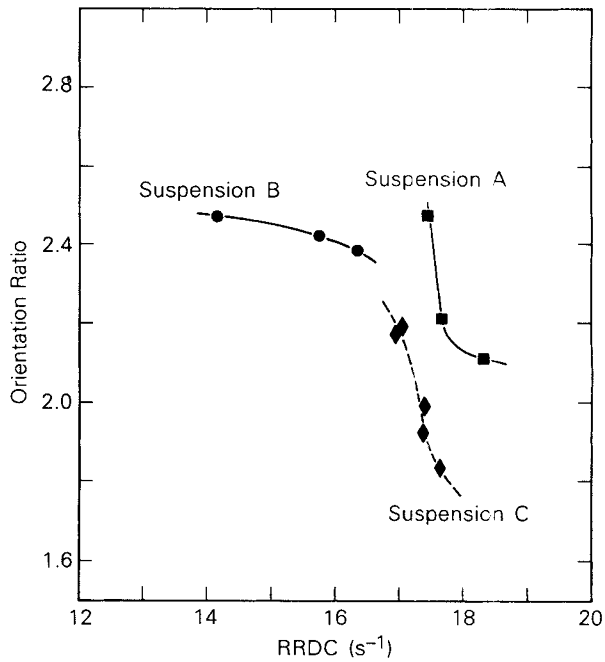

Figure 14. Magnetic particle orientation ratio on disks coated with suspension with a range of dispersion quality.

The letters *A*, *B*, and *C* indicate different batches of suspension.

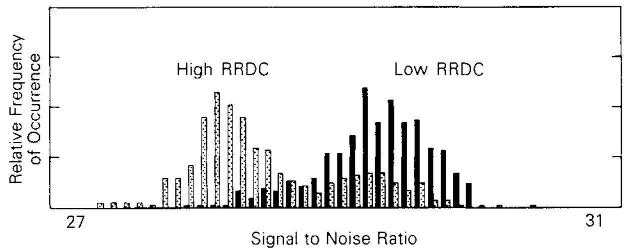

Figure 15. Signal to noise ratio for disks coated with flocculated suspension (high *RRDC*) and well-dispersed suspension (low *RRDC*).

This illustrates that disks coated with the well-dispersed suspension tend to have improved magnetic performance characteristics.

remain on the disk, the OR should decrease with increasing *RRDC*. Figure 14 shows the OR measured on disks for which the *RRDC* of the suspension during coating was measured. An additional batch, *C*, is shown in Figure 14. There is a tendency for the OR to decrease with increasing *RRDC*. The variation in the OR curves between batches is due to setup parameter adjustments on the spin coater, including changes in the field conditions of the orientation magnets, which are made for each new batch of suspension.

Since one goal of magnetic disk production and improvements in the technology is to store information at higher densities with lower error rates, a key measure of coating performance is the signal-to-noise ratio (SNR). Disk coatings with higher SNR tend to have fewer bit errors at a given bit density. Two factors affecting the SNR are the orientation and uniformity of the particles in the coating. As shown above, the OR depended on the suspension dispersion quality as measured by the *RRDC*. An increase in the SNR should accompany the increase in the OR and the decrease in the as-coated roughness resulting from improved dispersion quality (Ogawa and Ogawa, 1979; Maeda et al., 1982). A large number of disk surface SNR measurements on coatings made with suspensions having a wide range of *RRDC* were examined. A histogram of the SNR on disks coated with suspension having either high $RRDC > 17.5$ or low $RRDC < 15$ is shown in Figure 15. Although it is not a clear separation, the SNR of disks coated with flocculated suspension was somewhat lower than that on those coated with well-dispersed suspension. Apparently, there are other process variables in addition to dispersion quality which influence the SNR (e.g., coater settings).

Summary and Conclusions

The rheomagnetic analyzer apparatus for measuring the dispersion quality of single-domain magnetic particle suspension has been described. Principles linking the measurement to the suspension dispersion quality were illustrated. The apparatus was then evaluated on the practical large-scale operation of rigid magnetic disk production development. The relative rotary diffusion coefficient measured by the REMA was demonstrated to measure relative changes in the dispersion quality of the magnetic particle suspension. This was done in one regard by examining the effects of milling and aging on the suspension *in situ* prior to coating application. The *RRDC* accurately tracked the decrease in dispersion quality with suspension age and mill media wear. The cured particulate coating on the disk was then studied. Changes in the coating roughness were studied by relative changes in reflectance and by optical profilometry. The coating roughness increased with decreased dispersion quality, as if the flocs remained intact on the disks coated with flocculated suspension. In the worst case examined, the peak to valley roughness approached nearly 1/2 the finished coating thickness. The ability of the particles to be oriented on the disk by the orientation magnets increased with improved dispersion quality as indicated by the increase in the coating orientation ratio with decreasing *RRDC*. Dramatic differences in the coating roughness and OR consistently occur between *RRDC*'s = 16 to 18 s^{-1}. This may be the point at which the flocs become too large to be broken up and oriented by the orientation magnets on the coater. Finally, the signal-to-noise ratio, a measure of the coating magnetic performance, tended to be improved on disks with better dispersion quality. These measurements indicated that the REMA apparatus is a reasonably accurate tool for measurement of single-domain magnetic particle suspension dispersion quality in the manufacture of particulate magnetic recording films. This methodology provides the means to maintain consistent high quality dispersion in particulate disk and tape products. The instrument was used in the manufacturing line to determine preventive procedures for maintaining consistent high dispersion quality and subsequently producing disks with the desired magnetic properties.

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Notation

a = effective particle diameter
d = capillary tube diameter
D_r = rotary diffusion coefficient
H = applied magnetic field
L = coil inductance
L_s = coil inductance with only suspending fluid in the system
M = magnetization
p = effective particle aspect ratio
P = pressure drop across capillary
P_s = pressure drop across capillary with only suspending fluid in the system
Q = volumetric flow rate
$RRDC = D_r/\gamma$ = relative rotary diffussion coefficient
γ = hydrodynamic coefficient

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