Quantum Design

Introduction to:
AC Susceptibility

AC Magnetic Measurements

Dinesh Martien

Introduction

AC magnetic measurements, in which an AC field is applied to a sample and the resulting AC moment is measured, are an important tool for characterizing many materials. Because the induced sample moment is time-dependent, AC measurements yield information about magnetization dynamics which are not obtained in DC measurements, where the sample moment is constant during the measurement time. This application note will briefly describe how AC magnetic measurements are performed, discuss the meaning of the data that come out of an AC measurement, and show some measurement examples.

DC Magnetometry

DC magnetic measurements determine the equilibrium value of the magnetization in a sample. The sample is magnetized by a constant magnetic field and the magnetic moment of the sample is measured, producing a DC magnetization curve $M(H)$. The moment is measured by force, torque or induction techniques, the last being the most common in modern instruments. Inductive measurements are performed by moving the sample relative to a set of pickup coils, either by vibration or one-shot extraction. In conventional inductive magnetometers, one measures the voltage induced by the moving magnetic moment of the sample in a set of copper pickup coils. A much more sensitive technique uses a set of superconducting pickup coils and a SQUID to measure the current induced in superconducting pickup coils, yielding high sensitivity that is independent of sample speed during extraction. Inductive magnetometers can also be used to perform AC magnetic measurements.

AC Magnetometry

In AC magnetic measurements, a small AC drive magnetic field is superimposed on the DC field, causing a time-dependent moment in the sample. The field of the time-dependent moment induces a current in the pickup coils, allowing measurement without sample motion. The detection circuitry is configured to detect only in a narrow frequency band, normally at the fundamental frequency (that of the AC drive field).

In order to understand what is measured in AC magnetometry, first consider very low frequencies, where the measurement is most similar to DC magnetometry. In this case, the magnetic moment of the sample follows the $M(H)$ curve that would be measured in a DC experiment. As long as the AC field is small, the induced AC moment is $M_{AC} = (dM/dH) \cdot H_{AC} \sin(\omega t)$ where H_{AC} is the amplitude of the driving field, ω is the driving frequency, and $\chi = dM/dH$ is the slope of the $M(H)$ curve, called the susceptibility. The susceptibility is the quantity of interest in AC magnetometry.

As the DC applied magnetic field is changed, different parts of the $M(H)$ curve are accessed, giving a different susceptibility. One advantage of the AC measurement is already evident: the measurement is very sensitive to small changes in $M(H)$. Since the AC measurement is sensitive to the slope of $M(H)$ and not to the absolute value, small magnetic shifts can be detected even when the absolute moment is large.

At higher frequencies than those considered above, the AC moment of the sample does not follow along the DC magnetization curve due to dynamic effects in the sample. For this reason, the AC susceptibility is often known as the dynamic susceptibility. In this higher frequency case, the magnetization of the sample may lag behind the drive field, an effect that is detected by the magnetometer circuitry. Thus, the AC magnetic susceptibility measurement yields two quantities: the magnitude of the susceptibility, χ, and the phase shift, φ (relative to the drive signal). Alternately, one can think of the susceptibility as having an in-phase, or real, component χ' and an out-of-phase, or imaginary, component χ''. The two representations are related by

$$\begin{matrix} \chi' = \chi\cos\varphi \\ \chi'' = \chi\sin\varphi \end{matrix} \quad \Leftrightarrow \quad \begin{matrix} \chi = \sqrt{\chi'^2 + \chi''^2} \\ \varphi = \arctan(\chi''/\chi') \end{matrix}$$

In the limit of low frequency where AC measurement is most similar to a DC measurement, the real component χ' is just the slope of the $M(H)$ curve discussed above. The imaginary component, χ'', indicates dissipative processes in the sample. In conductive samples, the dissipation is due to eddy currents. Relaxation and irreversibility in spin-glasses give rise to a nonzero χ''. In ferromagnets, a nonzero imaginary susceptibility can indicate irreversible domain wall movement or absorption due to a permanent moment. Also, both χ' and χ'' are very sensitive to thermodynamic phase changes, and are often used to measure transition temperatures. AC magnetometry allows one to probe all of these interesting phenomena. Typical measurements to access this information are χ vs. temperature, χ vs. driving frequency, χ vs. DC field bias, χ vs. AC field amplitude, and harmonic measurements. Some of these will be discussed in the examples below.

Measurement Examples

SPIN-GLASS.

Spin-glass behavior is usually characterized by AC susceptibility. In a spin-glass, magnetic spins experience random interactions with other magnetic spins, resulting in a state that is highly irreversible and metastable. This spin-glass state is realized below the freezing temperature, and the system is paramagnetic above this temperature. The most studied spin-glass systems are dilute alloys of paramagnets or ferromagnets in nonmagnetic metals, typified by $Cu_{1-x}Mn_x$.

The freezing temperature is determined by measuring χ' vs. temperature, a curve which reveals a cusp at the freezing temperature. The AC susceptibility measurement is particularly important for spin-glasses, because the freezing temperature cannot be extracted from specific heat.[1] Furthermore, the location of the cusp is dependent on the frequency of the AC susceptibility measurement, a feature that is not present in other magnetic systems and therefore confirms the spin-glass phase. Both of these features are evident in AC susceptibility data for $Cu_{1-x}Mn_x$ as shown in Fig. 1.

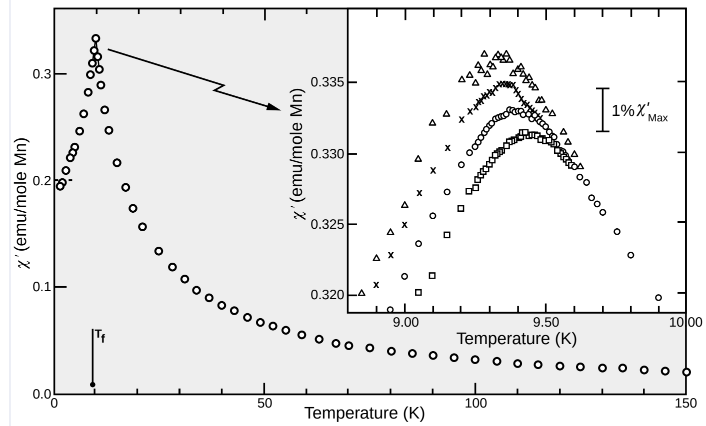

Figure 1. AC susceptibility of CuMn (1 at% Mn) showing the cusp at the freezing temperature. The inset shows the frequency dependence of the cusp from 2.6 Hz (triangles) to 1.33 kHz (squares). Figure reprinted with permission.[2]

The irreversibility in spin-glasses leads to a nonzero out-of-phase component, χ'', below the spin-glass freezing temperature. Because spin-glasses have unique magnetization dynamics, many interesting effects are observed in the susceptibility behavior. For example, Jonsson, et al. showed how χ'' has a "memory" for temperature treatment.[3] They cooled a sample of $Ag_{89}Mn_{11}$, paused at 23 K, and then continued cooling. Upon warming, χ'' showed a dip at 23 K, indicating a memory of the pause. By examining the behavior of χ'' during various temperature treatments, these workers probed the dynamics of the $Ag_{89}Mn_{11}$. They developed a detailed picture of the dynamics in terms of spin-glass domains and droplet excitations.

SUPERPARAMAGNETISM.

AC susceptibility measurements are an important tool in the characterization of small ferromagnetic particles which exhibit superparamagnetism, the theory of which was originally explained by Néel and Brown.[4,5] In this theory, the particles exhibit single-domain ferromagnetic behavior below the blocking temperature, T_B, and are superparamagnetic above T_B. In the superparamagnetic state, the moment of each particle freely rotates, so a collection of particles acts like a paramagnet where the constituent moments are ferromagnetic particles (rather than atomic moments as in a normal paramagnet).

In the Néel-Brown theory, the particles are assumed to be non-interacting and the blocking temperature is given by

$$T_B = \frac{\Delta E}{\ln(\tau/\tau_0)k_B},$$

where ΔE is the energy barrier to magnetization reversal in a single particle, τ is the measurement time, τ_0 is called the attempt frequency, and k_B is the Boltzmann constant. The measurement time is typically 1-100 sec for DC measurements, and is the inverse of the measurement frequency for AC measurements. The utility of AC susceptibility for superparamagnetism stems from the ability to probe different values of τ by varying the measurement frequency.

Above the blocking temperature, χ'' is small and χ' follows the Curie law $\chi' \propto T^{-1}$, as expected for paramagnetic behavior. From the slope of $1/\chi'$ vs. T, one obtains the volume of the magnetic particles (assuming monodisperse particle size).[6] In a recent experiment, Lee and coworkers used this method to determine the size of Fe platelets in Cu/Fe multilayers.[7] Futhermore, the imaginary component of the susceptibility peaks at the blocking temperature. Since T_B depends on the measurement frequency, the peak in χ'' vs. T occurs at different temperatures for different frequencies. From such a measurment, one can check that the particles are truly noninteracting by verifying the dependence of T_B on measurement time as given by the Néel-Brown theory. Departures from this theory indicate interparticle interactions, for example dipole-dipole or interparticle exchange interactions.

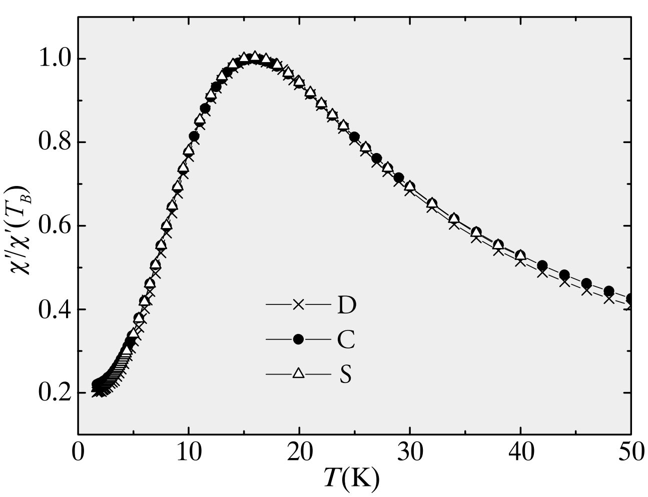

Figure 2. In-phase susceptibility of horse-spleen ferritin normalized to the value at the blocking temperature. The ratio between the concentrations of samples D, C, and S is 1:5:17. Note that the normalized curves are identical, indicating that interparticle interactions are not important over the concentration range studied. Figure reprinted with permission.[8]

The scaling behaviors of χ' and χ'' provide additional information about particle interactions and the distribution of particle sizes. For noninteracting particles, χ' vs. T curves for various particle concentrations are identical when properly normalized. Deviation from this behavior indicates that interparticle interactions are important. As shown in Fig. 2, Luis, et al. applied this method to ferritin particles and found no evidence for interactions.[8] The same experimenters plotted χ'' vs. a scaling variable that depends on the measurement frequency to find that the particle sizes follow a gamma-function distribution.

MAGNETIC PHASE TRANSITIONS.

The dynamic susceptibility is also a powerful tool for examining the nature of magnetic phase transitions, such as ferromagnetic transitions. Typically, χ diverges at the critical temperature of a ferromagnetic phase transition. Critical exponents characterize the nature of the divergence as a function of temperature and DC applied field. Determination of these critical exponents allows one to distinguish between various models of magnetic interactions, such as the 3-d Heisenberg, X-Y, or Ising model. For example, Berndt, et al., characterized two phase transitions in amorphous $(Fe_{1-x}Mn_x)_{75}P_{16}B_6Al_3$ and found exponents consistent with the Heisenberg model for the higher temperature transition.[9]

SUPERCONDUCTIVITY.

AC susceptibility is the standard tool for determining the physics of superconductors, in particular for measuring critical temperature. In the normal state (above the critical temperature), superconductors typically have a small susceptibility. In the fully superconducting state, the sample is a perfect diamagnet and so $\chi' = -1$. Typically, the onset of a significant nonzero χ' is taken as the superconducting transition temperature. An example is the long-awaited detection of superconductivity in platinum, which was found to have a critical temperature in the 1 mK range for compacted powders.[10] An example of AC susceptibility of the high-temperature superconductor $LaBaCa(Cu_{1-x}Zn_x)O_{7-\delta}$. is shown in Fig. 3.[11]

The out-of-phase component of the susceptibility is nonzero for temperatures slightly below the transition temperature, where magnetic irreversibility occurs in the sample. Measurement of χ'' allows determination of the critical current, the maximum current a superconductor can carry before becoming electrically resistive. By finding the temperature at which χ'' is maximum for various AC drive field amplitudes, one can determine the critical current vs. temperature.[12]

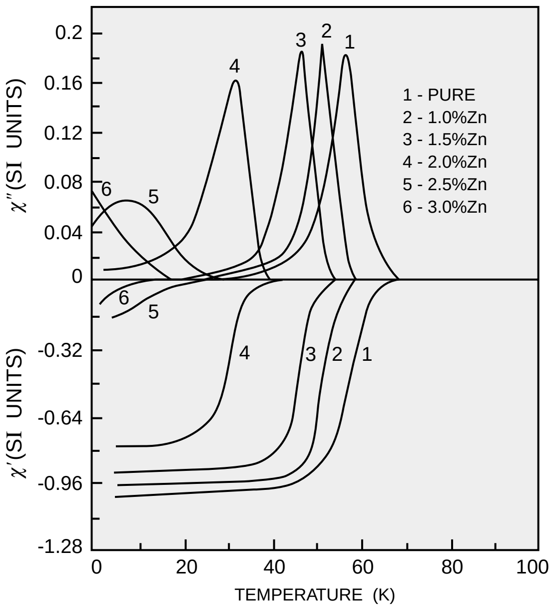

Figure 3. AC susceptibility of LaBaCa($Cu_{1-x}Zn_x$)$O_{7-\delta}$ for various concentrations of Zn. From the real part of the susceptibility, the authors determined the critical temperature. By examining the peak location and the width of the peaks in the imaginary susceptibility, the authors were able to understand the behavior of the superconductivity in the weak links between grains in the sample. Figure reprinted with permission.[11]

References

1 J. A. Mydosh, J. Magn. Magn. Mater. **157/158**, 606 (1996).
2 C. A. M. Mulder, A. J. van Duyneveldt, and J. A. Mydosh, Phys. Rev. B **23**, 1384 (1981).
3 T. Jonsson, K. Jonason, P. Jönsson, and P. Nordblad, Phys. Rev. B **59**, 8770 (1999).
4 L. Néel, C. R. Hebd. Seances Acad. Sci. **228**, 664 (1949); Ann. Géophys. **5**, 99 (1949).
5 W. F. Brown, Phys. Rev. **130**, 1677 (1963).
6 R. W. Chantrel and E. P. Wohlfarth, J. Magn. Magn. Mater. **40**, 1 (1983).
7 D. W. Lee, D. H. Ryan, Z. Altounian, and A. Kuprin, Phys. Rev. B **59**, 7001 (1999).
8 F. Luis, et al., Phys. Rev. B **59**, 11837 (1999).
9 A. G. Berndt, X. Chen, H. P. Kunkel, and G. Williams, Phys. Rev. B **52**, 10160 (1995).
10 R. König, A. Schindler, and T. Herrmannsdörfer, Phys. Rev. Lett. **82**, 528 (1999).
11 R. Singh, et al., Phys. Rev. B **55**, 1216 (1997).
12 R. W. Rollins, H. Küpfer, and W. Gey, J. Appl. Phys. **45**, 5392 (1974).

Conclusion

The above examples give a brief introduction to the wide applicability of AC magnetic measurement. Many important material properties require characterization by this technique. Interesting and exciting materials are well characterized by the combination of AC magnetic measurements and other techniques, such as DC magnetization.

Quantum Design

CORPORATE HEADQUARTERS
11578 Sorrento Valley Road
San Diego, California, USA 92121-1311
Phone: 858.481.4400 800.289.6996
Fax: 858.481.7410
E-Mail: service@qdusa.com
www.qdusa.com