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NOTES

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Saturation in "nonmagnetic" stainless steel

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Scientific equipment often uses "nonmagnetic" stainless steel, relying on the steel's nonmagnetic behavior to leave external magnetic fields unaltered. However, stainless steel's permeability can rise significantly when it is welded or machined, possibly perturbing an external field. Such perturbations will diminish well above the stainless steel's saturation point. The authors measured the permeability of both welded and machined 304 stainless steel as a function of an external magnetic field, and found that both saturate at fields of approximately 0.25 T. © *1998 American Institute of Physics.* [S0034-6748(98)00110-5]

When nonmagnetic[1,2] stainless steel is welded or machined its permeability rises, potentially introducing field errors in experiments done in magnetic fields. However, at fields higher than its saturation field, stainless steel's effective susceptibility will drop inversely with the strength of the field, causing it to be effectively nonmagnetic in fields much greater than its saturation field. Thus knowing the saturation fields of welded and machined 304 stainless steel can help determine its usefulness in high-field experiments.

We determined the saturation field of several stainless steel samples by measuring their permeability while varying an external magnetic field. We inserted the samples into the core of an inductor, immersed the inductor in a variable magnetic field, and measured its inductance as the field varied (see Fig. 1). The ratio of this inductance to the unloaded inductance is proportional to the steel's permeability.

We used three different stainless steel samples. The first was a set of 1/16 in. thick 304 stainless steel sheets, cut to an appropriate size with a break. We used a low-field permeability meter[3] to determine that the stainless steel sheet's permeability was between 1.01 and 1.02. The second sample was made by welding through these same sheets with a heli-arc welder. Welding increased the permeability to approximately 1.4. The last sample was a set of 20 1 3/4 in. long 1/4-20 304 stainless steel bolts, sold by Lesker[4] for vacuum flanges. The bolt threads' permeability was about 1.2, and the bolt heads' permeability ranged up to 1.8. All samples were separated by paper insulation to reduce eddy currents.

The inductor had 700 turns of wire, was 5.1 cm long, 3.8 cm in diameter, and had an inductance of about 13.6 mH. The samples filled the core, extending 7.6 cm to either side of the inductor. The samples had a sizable effect on the inductance, increasing the inductor's inductance by as much as 6%. (We measured the inductance with a Stanford Research Systems SR715 *LCR* meter.) Because of the samples' unknown filling factor, we could not determine their absolute permeability from the inductance increase. The inductor was inserted into a superconducting solenoid with a 25 cm inner-

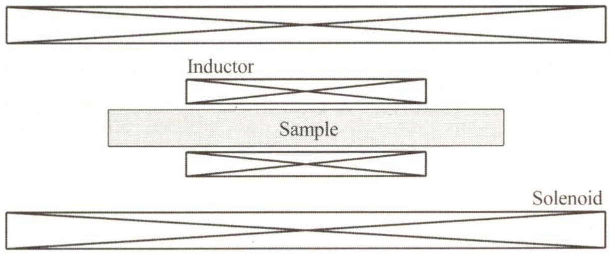

FIG. 1. Experiment schematic (not to scale).

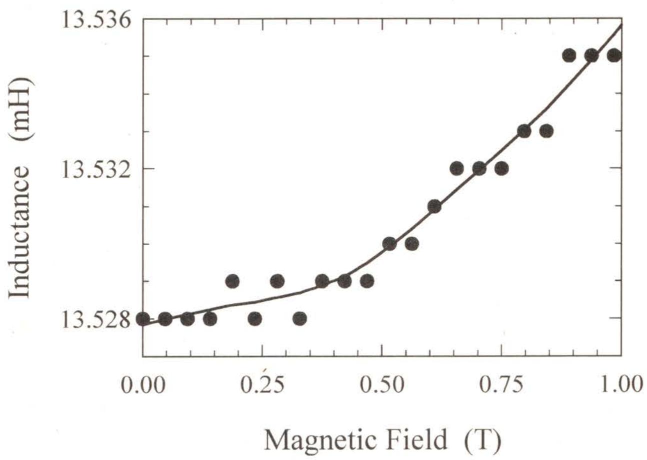

FIG. 2. Air-core inductance as a function of applied magnetic field. The line shown was fit to the data points.

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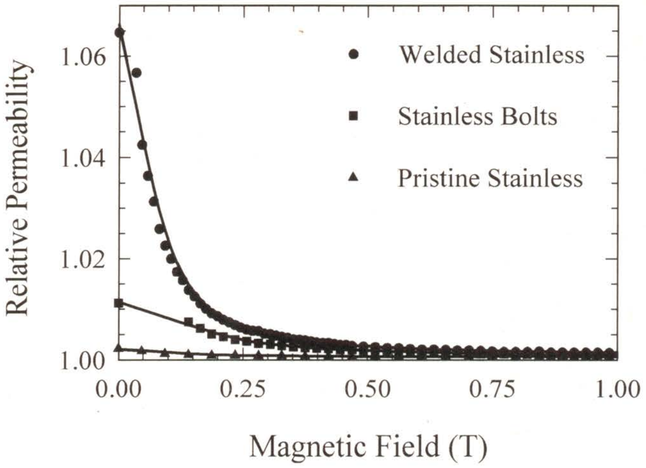

FIG. 3. Relative permeabilities as a function of applied magnetic field for welded, machined (bolts), and unwelded (pristine) 304 stainless steel.

diameter stainless steel bore. The solenoid's maximum field was 3 T, and its field was very uniform over the inductor.

Figure 2 shows the measured inductance without any samples inserted into the core. The inductance rises with the applied magnetic field. Measurements showed that this rise is not due to an interaction of the fringe magnetic field with the *LCR* meter, and that it does not depend on the orientation of the inductor in the magnetic field. Eddy currents in the solenoid's stainless steel bore decreased the measured inductance from 13.62 to 13.53 mH, but do not explain the rise in inductance with magnetic field. (We found similar changes in the inductance when the inductor was placed inside similar aluminum bores.) Whatever the cause, this air-core effect is on the order of 0.05% at 1 T, while the change in inductance due to the core materials is around 6% for welded steel and 1% for machined steel. Even for unwelded steel the inductance change is about twice the air-core effect.

Figure 3 shows the relative permeabilities of the steel samples as functions of the applied field. As no significant trends were observed beyond 1 T, we do not graph our higher field data in either Fig. 2 or Fig. 3. (Note that we used the curve fit[5] through the data in Fig. 2 as a base line; at each value of the magnetic field, we divided the measured inductance with the sample by the inductance without the sample.) The relative permeability of the welded steel sample is much higher than that of the machined steel, most likely because the welded steel sample was welded through, while only a small part of the machined sample volume was actually machined, thereby making the magnetic fraction of the welded sample higher than the magnetic fraction of the machined sample. All the samples are mostly saturated at an applied field of 0.25 T. Thus, above this field, welded and machined 304 stainless steel becomes increasingly nonmagnetic, and may be used with decreasing effect on applied fields.

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[1] J. Moore, C. Davis, and M. Coplan, *Building Scientific Apparatus: A Practical Guide to Design and Construction* (Addison–Wesley, Redwood City, CA, 1989), p. 14.
[2] A. I. H. Committee, *Metals Handbook*, 10th ed. (ASM International, Materials Park, OH, 1990), p. 837.
[3] Permeability indicator No. 5150, manufactured by Severn Engineering Company, Annapolis, MD.
[4] Other samples of bolts supplied by Kurt Lesker had lower permeabilities.
[5] The curve was fit to the data points by smoothing with Mathcad's (MathSoft, Cambridge, MA) supsmooth routine, and interpolating between points with a spline routine.