ALUMINUM STABILIZER FOR THE D0 MAGNET SUPERCONDUCTOR

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ABSTRACT

This note presents a review of the electrical properties of the high purity aluminum used to stabilize the superconductor for the DØ solenoid magnet. The state of cold work, cyclic strain, and magnetoresistivity all affect the final resistivity of the aluminum during the operation of the magnet. Since it bears on the issue, we also consider the stress-strain relationship of high purity aluminum.

1 CONSTRUCTING AN RRR TABLE

The quantity of the aluminum stabilizer specified for the DØ magnet conductor and its electrical resistivity will influence the stability and quench behavior of the magnet. An understanding of what resistivity can be expected for the aluminum during operation of the magnet is useful in order to predict these aspects of the magnet's operating behaviour throughout its lifetime.

The electrical resistivity of high purity aluminum is characterized by its "residual resistivity ratio" or RRR, the ratio of its resistivity at the ice point divided by its resistivity at 4.2K: $\rho(273K)/\rho(4.2K)$.

For further discussion concerning the low temperature resistivity of high purity aluminum, see Appendix A.

In what follows we examine the issues of initial resistivity, winding prestrain, room temperature annealing, cyclic strain at 4.2 K, and magnetoresistivity as they pertain to the aluminum stabilized conductor in the DØ magnet. For a range of choices of initial RRR, we construct a table that illustrates the final values of RRR actually expected to be present in the conductor stabilizer during magnet operation at full field.

2 WINDING PRESTRAIN

Beginning with an assumed "as delivered" RRR in the aluminum stabilizer of the DØ conductor on the spools ready to wind, it is useful to ask what resistivity increase in the high purity aluminum is occasioned by the winding process itself.

When the D0 conductor is wound into the magnet, the winding strain of the stabilized conductor is $\epsilon = \Delta R/R \approx 0.024$ if the full cross section of the stabilizer participates. In fact the superconducting insert should "dominate", i.e. a neutral axis would be present near the insert and the strain adjacent the insert will be much less; thus the winding prestrain in the aluminum should not exceed half this value (and the average over all the aluminum will be somewhat less).

We therefore assume the stabilizer need not experience a prestrain greater than ≈ 0.01 during the coil winding process. We assume that the conductor is supplied on spools such that its prestrain from being put on or taken off the spools is negligible (presumably it is supplied wound the "easy way" on large-diameter spools); "back winding" a length of conductor from the magnet back to the storage spool to correct a winding flaw can be minimized in any case.

Hartwig[9] presents for a variety of alloys the increase in 4.2K resistivity as a function of room temperature percent area reduction (PAR) of annealed samples which were swaged and drawn to a given total area reduction (Figure 1).

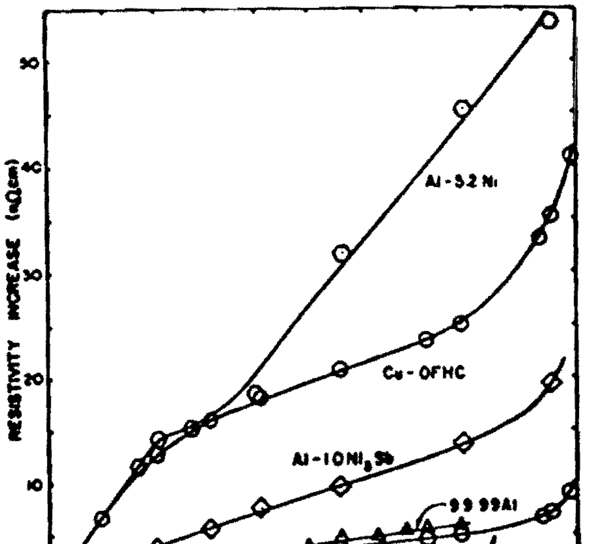

Figure 1 4.2K Resistivity Increase of Various Annealed Alloys as a Function of Room Temperature Prestrain.

From the curve in Figure 1 for the 99.999% Al, the increase in ρ is about 2 nano-Ohm-cm for 10% area reduction cold work; assuming the curve is linear below 10%, at 1% prestrain the increase in ρ will not exceed 0.2 nano-Ohm-cm.

It happens that many of the defects which are produced by cold work have appreciable mobility even at room temperature, so much of the increase predicted by Figure 1 will anneal out over time. We assume some of this annealing pertains to the data quoted since unspecified lengths of time elapsed before the 4.2K tests were conducted; the resistivity increase obtained from Figure 1 may therefore be somewhat conservative.

The resistivity increment generated by the winding prestrain is seen not to be severe provided the conductor is not grossly mishandled during the winding process. If the magnet is warmed to cure epoxy used in the winding process, this resistivity increment will be even smaller than that calculated due to the accelerated annealing occasioned by the elevated curing temperatures.

3 WINDING PRESTRESS

Considering the issues noted in appendix A concerning the purity and hardness of aluminum, and with Mathiessen's rule in mind, one typically chooses an aluminum purity as high as is practicable and then tailors the final hardness to meet the mechanical needs of the conductor. By implication the RRR is essentially fixed by these choices.

The mechanical strength of annealed very high purity aluminum can be very low. Kim[8] measured a 4K yield strength of about 6 MPa (870 psi !) for annealed aluminum samples having RRR = 5000 – 6000. Evidently the yield strength of such material can be extremely low if its purity is great enough and it is fully annealed. Clearly, while very pure aluminum may have very appealing electrical properties, its mechanical properties must be understood thoroughly if it is to be subject to appreciable mechanical stress.

Annealed high purity aluminum rapidly work hardens with cold work so that yield strengths up to an order of magnitude higher than that of the annealed state can be obtained from the effects of cold work. Hartwig [9] has measured the increase in yield strength caused by room-temperature cold work (Figure 2):

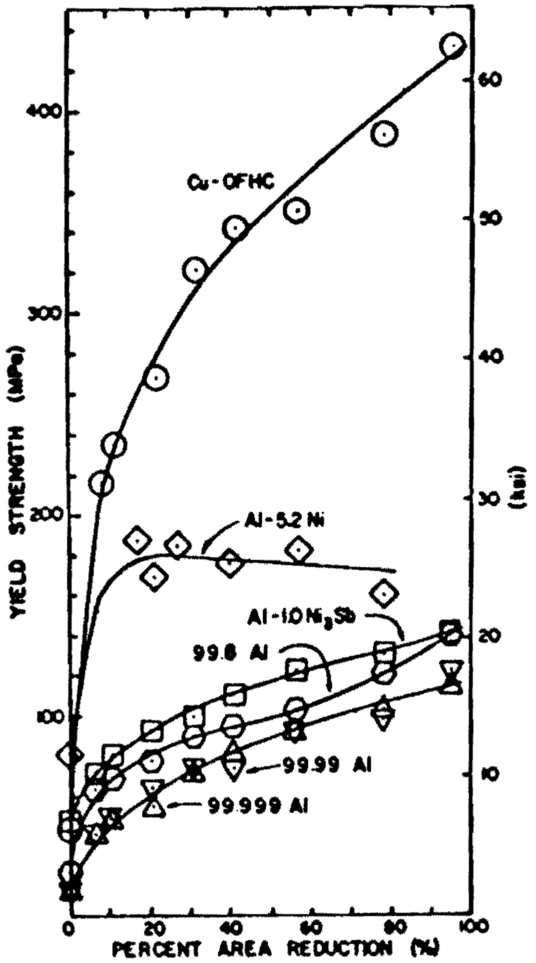

Figure 2 Room Temperature Yield Strength Increase of Various Annealed Alloys as a Function of Room Temperature Prestrain.

As in the case of the resistivity, the cold work increases the yield strength in a dramatic and characteristic way. However the type of defects introduced by cold work that increase the strength of the material do not anneal at room temperature like the type of defects from the cold work that increase the resistivity.

Evidently the final state of cold work/anneal of the material can be chosen to meet a desired yield strength.

The anticipated axial compressive stresses due to the Lorentz forces in the D0 solenoid are approximately 11 Mpa; the anticipated maximum hoop stresses are about 20.8 MPa.

It is desireable during the winding of the magnet to apply an axial prestress at least as large as that anticipated during excitation; to ensure that the aluminum in the stabilizer remains in the elastic region during the winding process its yield strength must exceed the prestress loads. Thus the room temperature yield strength of the stabilizer must at least exceed 11

MPa(1600 psi).

In measurements made by Hartwig [13] a sample of aluminum having purity 4N7 (99.997% pure) was shown to have a room-temperature yield strength of 12.9 MPa and RRR of 3450. Another sample in the series studied had a yield strength of 20.6 MPa and an RRR of 1024. We could select an aluminum similar to either of these an meet our winding prestress yield strength requirement.

It is instructive to review acutal RRR's achieved in contemporary detector magnets. The RRR of the conductor after it has been wound into the magnet is relatively easy to measure upon magnet cooldown. For CDF, a value of 2000 in the aluminum is found; for TOPAZ, 2500; for ALEPH, 2000; for VENUS, 1800; for AMY, > 3500; and for CLEO II, 1000.

4 OPERATING STRESSES

Similar requirements concerning stabilizer strength are imposed during excitation of the magnet: the stabilizer must remain in the elastic region at all times. Both axial and radial (i.e. hoop) stresses are impressed on the conductor while the magnet is energized and the combined effect of these must be considered. It is conservative to use the Von-Mises criterion for combined stresses which indicates yielding will occur when

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_y^2.$$

We take the hoop and axial stresses to be the principal stresses $\sigma_1 = 20.8$ MPa and $\sigma_2 = -11$ MPa; $\sigma_3 = 0$. The yield stress then evaluates to $\sigma_y =$ 27.9 MPa.

Evidently we must select an alumnium stabilizer that has a 4.2 K yield point exceeding 28 MPa in order to ensure that the material remains in the elastic region at all times.

Reed [5] indicates that for a given purity, the yield stress increases with decreasing temperature. The effect is larger with increasing purity, and Reed estimates that it is about 1.5 for 2N-3N aluminum and about 1.75 for 4N-5N aluminum. In Ladkany [7] this ratio was measured as 1.47 ± 0.04 for RRR 3700 aluminum. We conclude that for a yield strength of 28 MPa at 4.2K, the room temperature strength must not be less than 28/1.5 or about 19 MPa.

Just as the winding process caused the resistivity of the aluminum to increase so too will it cause the yield strength to increase. We fit the curve in Figure 2 for the 5N aluminum below 20% prestrain to a third-order polynomial and use the results to calculate the yield strength at 0.01 prestrain. We obtain a predicted low temperature yield strength increase of 5 MPa due to the room-temperature winding prestrain.

Since we require a minimum strength of at least 19 MPa, evidently the initial strength of the stabilizer can be as low as 14 MPa for the delivered "ready to wind" conductor. The actual increase in yield strength of such a soft material upon a single prestrain of 0.01 should of course be checked before taking advantage of this last effect.

5 CYCLIC STRAIN

Finally, it is necessary to consider the mechanical behavior of the aluminum at low temperature when the magnet is energized. The charging and discharging of the magnet generates cyclic strain which can continuously modify the properties of the aluminum.

The magnet outer support cylinder has been sized so that the magnetic loads in the coil do not subject the conductor to large strain when it is energized. With a maximum hoop stress of 20.8 MPa (at the z-location of the peak field in the coil – where the current density is graded), and using 78 GPa (11.3 x 10^6 psi) for aluminum (ignoring the stiffening effects of the superconductor and the weakening effects of the interturn and interlayer insulation), the anticipated radial strain from the hoop stress is $\epsilon = \sigma/E = 3 \times 10^{-4} =$ 0.03%.

In Hartwig [15, 17], the change in resistivity as a function of cycle number for a variety of pure aluminums at a variety of cyclic plastic strain levels is reported. The resistivity increase is quite rapid for the first few hundred cycles, nearly reaching at 1000 cycles the fully saturated level it reaches at 3000 cycles. In Figure 3 are shown the resistivity changes at 3000 cycles for a variety of pure aluminums cyclically strained at various levels.

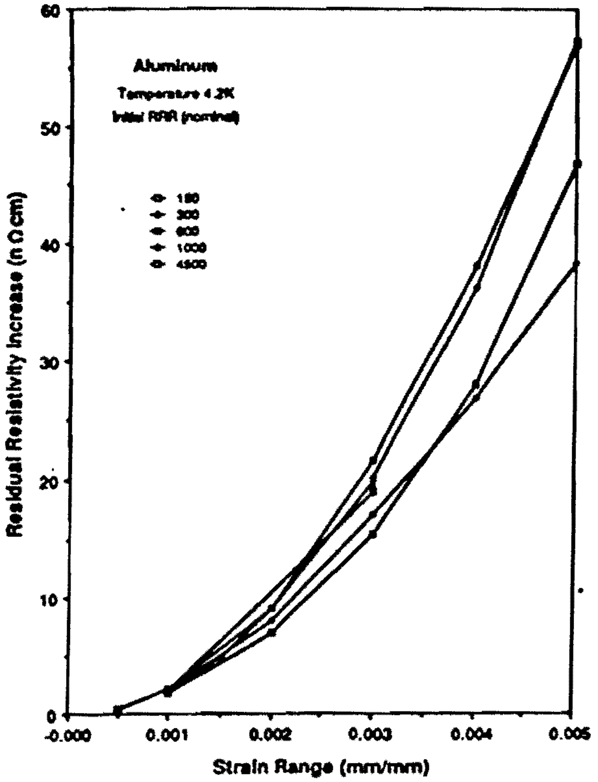

Figure 3. Change in Resistivity After 3000 Strain Cycles Versus Strain Range for Five Grades of Pure Aluminum.

Hartwig has shown that reasonable fits to the data are obtained with the simple parameterization $\Delta\rho(3000 \text{ cycles}) = A \times \epsilon^2$ nano-Ohm-cm, with A ranging from $1.8 - 2.3 \times 10^6$ for nominal unstrained RRR's ranging from 300 to 4500. If the DØ magnet were cycled 3000 times at a strain level of 0.03% the resistivity increase expected would be about 0.2 nano-Ohm-cm for RRR 1000 aluminum.

Since we have chosen an aluminum with a yield strength of not less than 28 MPa, little plastic strain is expected below strains of 28 MPa/76 GPa = 0.00037. This implies that the Hartwig result is surely an upper limit to any resistivity increase encountered.

It may be noted also that since plastic cyclic strain (i.e. work hardening) also increases the strength of the stabilizer, the yield point of the DØ stabilizer also would increase with plastic cyclic strain. Hartwig [15] also shows that pure aluminum can support a stress after 3000 strain cycles $\sigma = \epsilon \times E/2$, where ϵ is the magnitude of the cyclic strain. Because the DØ stabilizer already operates in the fully elastic regime and experiences essentially no plastic strain, little additional hardening of the material is expected from

this effect.
Hartwig [14] has measured the recovery that ensues when strained aluminum is warmed to room temperature (Figure 4).

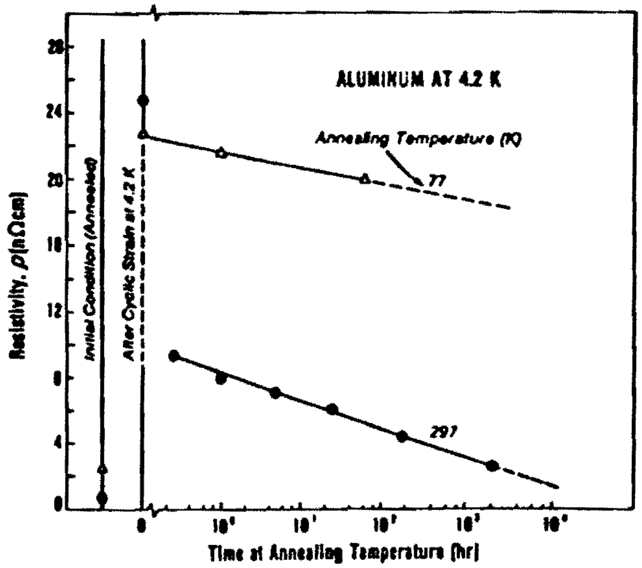

Figure 4. Recovery of Strained Aluminum after a Room Temperature Anneal.

This result is quite comparable that that observed by Kim [8].

The expected operational mode of the DØ magnet is perhaps at most 250 energization cycles between thermal cycling; it is extemely unlikely that saturation properties of the stabilizer are ever reached. Moreover, the magnet is likely to remain warm many months between cool-downs. This "annealing" available to the stabilizer in fact supplies an additional conservative factor for the magnet.
It is reasonable to suppose that for the DØ stabilizer the recovery when the magnet is warmed to room temperature will be at least as thorough as would have been the case if the magnet had been energized 3000 times. Since an eighty-five percent recovery after a few days at room temperature can be expected, a 0.2 nano-Ohm-cm increase anneals to 0.03 nano-Ohm-cm; the recovery from 250 cycles would be to at least this negligible level prior to the second cool-down.

This small recovered increment will not sum repeatedly over many operating periods since no new strain levels are encountered in subsequent cool-downs. Thus in the resistivity table below, we are confident that an increase of 0.2 nano-Ohm-cm during any one cold period is conservative and the effects won't integrate over many cool-down cycles.

6 MAGNETORESISTIVITY

One attempts to characterize the increase in resistivity with magnetic field by means of a "Kohler Plot" [2]. This phenomenological result anticipates that the fractional increase in resistance with increasing magnetic field is affected by purity and temperature only as a function of the variable H/R_0, or equivalently, H*RRR.

Kohler's Rule is remarkably successful for aluminums with RRR below 1000; for higher purities, the effects of temperature variation are quite different than those of impurities. This last effect is visible in the data of Purcell [1] where for RRR = 2600 aluminum, the 4K correlation no longer overlies those from higher temperatures. At 4K however the RRR = 1370 aluminum correlation and that for the RRR = 2600 material are essentially identical: $\Delta\rho/\rho \approx 1.8$ at 2.2 Tesla at 4K.

To calculate the magnetoresistivity increase we choose a recent parameterization of Kohler's Rule by Huang [16],

$$\frac{\Delta\rho}{\rho} = \frac{\rho(T,B) - \rho(T,0)}{\rho(T,0)} = \frac{2B_*^2(1 + 0.006B_*)}{4 + 3B_* + B_*^2},$$

where $B_* = 10^{-2}B\rho(300K)/\rho(T,0)$. The authors used data from fields up to 5T in developing this expression for the Kohler correlation. Inserting B = 2.2 T, we find the magnetoresistivity increases for various RRR of interest at 4.2 K.

This parameterization describes the data of Hartwig [14] reasonably well where data for RRR = 215 and RRR = 1012 material is presented, especially at the 2T point. This data shows that samples with different purities and degree of cold work, but having the same RRR, have the same resistivity behavior in magnetic fields.

7 RESISTIVITY RESULTS FOR D0

In the following table we present a tabulation of the degradation of RRR as a function of the coil winding itself, cyclic strain from magnet energization, and degradation due to the magnetic field. For a given choice of initial RRR the final RRR to be expected at the peak field in the coil after 3000 energization cycles is predicted.

Resistivity Degradation [nano-Ohm cm]					
RRR_0	1500	2000	2500	3000	4000
Equivalent ρ_o	1.62	1.22	0.97	0.81	0.61
$\Delta\rho_{wind}$	0.2	0.2	0.2	0.2	0.2
$\rho_{postwind}$	1.82	1.42	1.17	1.01	0.81
$RRR_{postwind}$	1335	1711	2076	2406	3000
$\Delta\rho_{cycle}$	0.2	0.2	0.2	0.2	0.2
$\rho_{postcycle}$	2.0	1.6	1.4	1.2	1.0
$RRR_{postcycle}$	1215	1520	1740	2025	2430
$\Delta\rho_m/\rho$	2.08	2.19	2.27	2.37	2.50
ρ_{final}	6.16	5.10	4.58	4.04	3.50
RRR_{final}	394	476	531	601	694

In the above table, the RRR's are referred to the ice point (273 K) where $\rho = 2.43x10^{-6}$ Ohm-cm. If RRR's referred to room temperature are desired, the RRR's in the table can be multiplied by approximately 1.1. The initial RRR's are intended to describe the stabilizer in the "as delivered" conductor. The resistivities are in nano-Ohm cm.

APPENDIX

For specific detail on the resistive mechanisms in aluminum, the articles by Fickett[2, 3] as well as that by Schauer[6] and Brechna [4] are helpful. Schauer and Brechna contain useful measured data as well. The review by Reed[5] contains material on the mechanical properties of aluminum and its alloys.

The electrical resistivity of pure aluminum at "room temperature" i.e. 293K is about $2.75x10^{-6}$ Ohm cm and at the ice point it is about $2.43x10^{-6}$ Ohm cm. In this temperature range, the temperature coefficient for resistivity is $\alpha = 0.0113$ μ-Ohm-cm/K. It happens also that at these temperatures the resistivity is largely insensitive to the degree of purity, or state of alloy of the aluminum and its degree of anneal or work hardening. Furthermore, these "warm" resistivities are not influenced by the presence of magnetic fields. At cryogenic temperatures however, the resistivity of aluminum is strongly influenced by its purity, state of work hardening, external magnetic fields, precise temperature, etc.

The term residual resistivity is used to describe the low-temperature resistivity when the material is sufficiently cool that the electron-phonon scattering has become negligible and only electron-impurity or electron-defect scattering remains. At 4.2K for aluminum essentially all resistance is due to defects or impurities; if the material is fully annealed the RRR can be taken as an equivalent measure of its purity.

The Delphi thin magnet conductor stabilizer was carefully monitored for atomic impurities and the RRR was seen to depend linearly on the purity composition of the stabilizer data [10].

Plastic deformation, or work hardening, increases the yield strength of pure aluminum, and also increases its electrical resistivity. For a given annealed sample, the electrical resistivity increases rapidly for added strain cycles such that at about 3000 cycles both the resistivity and the yield strangth are saturated. For strain cycles of magnitude 0.003 Hartwig [11] has shown that over a range of RRR from 300 to 1000 the saturated values of resistivity and yield strength are essentially the same (i.e. $\sigma_y \approx$ 100 MPa and RRR $\approx$ 100).

Annealing high purity aluminum has just the opposite effect: recrystallization for various time durations and at various temperatures from about 570K to about 870K indicate that for a given purity, the yield strength of a sample follows the Hall-Petsch relationship, i.e. that yield strength falls as the reciprocal of the square root of average grain size [5]. Annealing has a similar effect on electrical resistivity – the electron mean free path increases as various dislocations are absorbed by grain size growth and the resistivity falls towards some ideal "bulk" crystal resistivity.

It is customary to interpret the various resistive mechanisms according to Mathiessen's Rule, which indicates that the contributions to the resistivity add independently. Thus the contributions stemming from impurities can be characterized independently from those stemming from cyclic strain or plastic deformation. Hence for the contribution due to impurities it is possible to express the RRR as a sum over the percentage of each impurity type, each weighted by an empirical factor.

A "nines" code is often used to describe the chemical purity of aluminum: e.g. 5N8 means 99.9998% pure.

Hartwig[12] has shown that if a sample of aluminum is to be cycled at 4.2 K to saturation resistivity (N = 3000 cycles), then the final strain-induced resistivity is a function of the initial state of cold-work of the sample. For e.g. for cyclic strain of 0.1%, the final RRR after 3000 cycles is least if the sample is given $\approx$ 12 percent area reduction cold work rather than starting from the fully annealed state. (This optimization is not useful for D0 since the energization strain levels for the D0 magnet are so much smaller than Hartwig considers.)

Kohler's Rule, which relates the increase in resistivity due to an applied magnetic field solely in terms of the strength of the field and the RRR of the material is useful in predicting magnetoresistivity provided one does not attempt to use data from a variety of temperatures when RRR exceeds 1000 or so.

A recent compendium of measurements of high purity aluminum in magnetic fields[18] gives magnetoresistivity for RRR's up to 10000, from 7.5K to 50K, and magnetothermal conductivity as well. This last data is useful in understanding the variability of the Lorenz number L_0 with temperature and purity for aluminum, as defined by the Wiedemann-Franz law:

$$\frac{\lambda * \rho}{T} = L_0 = const.$$

By a straight-forward determination of the resistivity ratio (e.g. by immersing the sample in ice water then in liquid helium), and using its generally well-determined value at warmer temperatures, one then derives the absolute value at 4.2 K as well. The direct V-I "Four-Point" method can be used to determine RRR, and an eddy current decay technique is often used for convenience. (Note well that some recent measurements, e.g. Hartwig, 1993 CEC/ICMC, Albuquerque, to be published in Advances of Cryogenic Engineering, which use the eddy current technique in high magnetic fields for very low resistivity samples where H*RRR exceeds several thousand Tesla, have given apparently anomalous results. Some type of Hall effect might be the source of the discrepancy; further work is warranted to demonstrate the acceptability of the eddy current decay method in applied magnetic fields).

One must use caution also when determining the resistance of very small samples, such as films or tapes, for which a "size effect" correction (the Fuchs-Sondheimer theory) may be necessary if the sample is not substantially larger than the electron mean free path length in the aluminum. This correction exceeds a few percent only for a very pure, very small sample.

One typically does not distinguish between resistivity and resistance when using RRR values; the correction for thermal contraction effects is not normally necessary because the area/length factor between room temperature and 4K is only about 0.37%.

The elastic modulus of high purity aluminum at 4.2 K is about 76 GPa (11 $\times 10^6$ psi) [11]. At 300 K it falls to about 70 GPa (10.2 $\times 10^6$ psi) [5]. Poisson's ratio is about 0.35.

References

[1] Purcell, J.R., and Jacobs, R. B., "Transverse Magnetoresistance of High Purity Aluminum from 4 to 30 K", Cryogenics 3,109, (1963).

[2] Fickett, F.R., "Aluminum 1: A Review of Resistive Mechanisms in Aluminum", Cryogenics 11, 349 (1971).

[3] Fickett, F.R., "Magnetoresistance of Very Pure Polycrystalline Aluminum" Phys. Rev. B, 3, 1941 (1971).

[4] Brechna, H., et. al., "Cryogenic Properties of Metallic and Non-Metallic Materials Utilized in Low Temperature and Superconducting Magnets", 8th International Conference on High Energy Accelerators, CERN, 218, (1971).

[5] Reed, R.P., "Aluminum 2: A Review of Deformation Properties of High Purity Aluminum and Dilute Aluminum Alloys", Cryogenics 12, 259, (1972).

[6] Schauer, W., Proceedings of the 5th International Conference On Magnet Technology, 629 (1975).

[7] Ladkany, S.G., and Young, W., "Problems Associated With the use of High Purity Aluminum in the Design of Composite Conductors in the Elasto- Plastic Region", IEEE Transactions on Magnetics MAG 13, 105 (1977)

[8] Kim, S.H,. and Wang, S.T., "Measurement of Mechanical and Electrical Properties of High-Purity Aluminum", Advances In Cryogenic Engineering 24, 1978 (1977)

[9] Hartwig, K.T., and Appius, P.G., "Strength and Electrical Resistance of Cold Drawn Al and Cu", Proceedings of the 8th International Cryogenics Conference, Genova, 720, IPC Science and Technology Press, England, 1980

[10] Baynham, E., et. al., "The Aluminum Stabilized Superconductor for the Delphi Magnet",Ninth International Conference On Magnet Technology MT9, Zurich, 639 (1985).

[11] Hartwig, K.T., Yuan, G.S., and Lehman, P., "The Effects of Low Temperature Fatigue and Strength of Pure Aluminum", IEEE Transactions on Magnetics MAG 21, 161 (1985).

[12] Yuan, G.S., Lehmann, P., and Hartwig, K.T., "The Effect of Prestrain on Low Temperature Fatigue Induced Resistivity in Pure Aluminum", Advances in Cryogenic Engineering 32, 413 (1986).

[13] Hartwig, K.T., Yuan, G.S., and Lehman, P., "Strain Resistivity at 4.2K in Pure Aluminum", Advances in Cryogenic Engineering 32, 405 (1986).

[14] Hartwig, K.T., and Yuan, G.S., "Energy Loss, Anisotropy, Magnetoresistivity and Recovery in Aluminum Strained at 4.2 K", IEEE Transactions On Magnetics MAG 23, 1409, (1987).

[15] Hartwig, K.T., and Yuan, G.S.,"Strength and Resistivity Changes Caused by Cyclic Strain at 4.2K in Pure Aluminum", International Cryogenic Materials Conference, Shengyang, 677, (1988).

[16] Huang, X., Eyssa, Y.M. and Hilal, M.A., "High Current Density Aluminum Stabilized Conductor Concepts for Space Applications", IEEE Transactions on Magnetics MAG 25, p 1532 (1989).

[17] Hartwig, K.T., Lumbis, A., and Roelli, J, "Cyclic-Strain Resistivity In Pure Aluminum at 20 K", Advances In Cryogenic Engineering 36, 725, (1990).

[18] Egan, J.P., and Boom, R.W., "Measurement of the Electrical Resistivity and Thermal Conductivity of High Purity Aluminum in Magnetic Fields", Advances in Cryogenic Engineering 36, 679, (1990).