The Eddy Current Method for RRR Measurement of Superconductive Materials

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Abstract

The development of the eddy current method for RRR measurement of superconductive materials is presented. The technique involves two concentric coils located close to the specimen. A current with a definite frequency is established in the primary coil, the magnetic field of this coil induces eddy current in the metal. The resulting magnetic field induces a signal in the pick up coil. This signal is a function of the material resistivity. For elimination of the inductive voltage, which is created by the primary coil in the pick up coil without sample, two identical pick up coils are used. The jump of the signal at Tc (Tc-the temperature of the superconductive transition) is measured for RRR identification.

Introduction

It is well known that the chemical purity and physical imperfections of metals can be indicated by low temperature resistivity. By practical applications the quality of materials can be characterized by RRR-residual resistivity ratio (ratio of the resistivity at the room temperature to the resistivity at 4,2 K). In this case it is possible to eliminate most of the geometrical dependencies.
The RRR is frequently measured by using of DC 4-point method, which involves the connections of two potential leads to the specimen. The disadvantage consist in the necessity of rather long sample which should be cut out from the sheet. Besides the effect of chemical pollution of the specimen and the effect of physical damage from mechanical strain in contact area may produce additional problems.
One of the important tasks of cavity production is the successive control of the RRR during different fabrication steps starting with the "as delivered" Nb sheet and finishing with the completed cavity. This is crucial to do by DC method and needs a nondestructive control method.
It seams, that the idea of the eddy current method may be in principle used for nondestructive RRR measurement of superconductive materials. First tests have shown that the devices fabricated at the moment by industry /1/ unfortunately are not suitable for this purpose at the low temperature. Our application of the eddy current method for RRR measurement of Nb is presented above.

Experimental Setup

Briefly the eddy current technique involves two concentric coils situated close to the metallic specimen (Fig. 1). A current with a definite frequency is established in the primary coil from the frequency generator. The alternating magnetic field in the primary coil induces eddy current in the metal the value and penetration depth of which depend on the electrical conductivity of the sample. This eddy current itself creates a magnetic field which interacts with the initial magnetic field. The resulting magnetic field induces a signal U in the secondary (pick up) coil. This signal is a function of the material's electrical conductivity and it can be registered on appropriate recording devices.
The density of eddy current is maximal on the metal surface in the contour with diameter close to diameter of the primary coil and decreases with deepening of the signal into the object. Generally for the electromagnetic field penetration depth into the nonmagnetic metal formula (1) is valid

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$$\delta = k \cdot \frac{503}{\sqrt{f \cdot \sigma}} \qquad (1)$$

with δ-penetration depth (cm), f-frequency (Hz), σ−electrical conductivity (MS/m), k<1 -the coil shape depending factor.
For definite value of the measuring electrical conductivity the maximum of the sensitivity can be achieved by proper choice of such parameters as coil radius, frequency, sample thickness, distance between sample and coils /2/.
The diagram of the eddy current apparatus is shown schematically in figure 2. The electronic equipment consists of a frequency generator, a lock in amplifier, a digital voltmeter and an oscillograph. Measurement is PC-controlled under the graphical programming language LabVIEW /3/. Two identical pick up coils with contrary directed magnetic fields were applied for elimination of the inductive voltage, which is created by the primary coil in the pick up coil without sample, .
From the traditional 4-point RRR measurement it is well known that firstly the resistivity of niobium with different purity remains nearly constant at room temperature and secondly the abrupt change of the resistivity at the temperature of the superconductive transition (Tc-jump) is the bigger the smaller the RRR value is. This behavior can be assumed as a basis for RRR eddy current measurement. In principle the measure of the superconductive jump in the signal amplitude would be enough for the RRR identification.
In practice it is reasonable to obtain the required RRR value from the previously created calibration curve. For that one some standard samples with well known RRR values are necessary. In this case a good accuracy can be achieved.
Figures 3 examples of U behavior first during cooling up and than during few cycles of additional heating up and cooling down. We can observe rather small temperature dependence of the signal, but the jump at Tc is expressed very good in every case and can be registered with a rather good accuracy and reproducibility (1-3%).

Influence on the Measuring Values

A row of factors can significantly disturb the measuring value in routine. The most important of them are:
a) distance between the pick up coil and the sample surface,
b) size of the measuring surface of the sample,
c) thickness of the sample,
d) curvature of the sample.
We have analyzed the mentioned factors from the point of view of our interest. This means the variations of the measurement parameters should be suitable for niobium cavity frame (RRR between 100 and 1000, sheet thickness between 1 and 3 mm and so on).
So the variation of the distance between pick up coil and sample's surface in limits of 0-0,6 mm has shown that the distance increment reduces the pick up signal, but the ratio ΔU/Unc (Unc=amplitude of the signal in normal conductive state at Tc) is roughly constant almost up to the distance 0,5 mm (figure 4).
It is desirable to have the sample surface, which would be in contact with the pick up coil, bigger than the coil surface by at least a factor of two. We used samples with a quadrangular shape. It turned out that the changing of the sample side length between 5 and 9 mm can produce rather big variations of the pick up signal. It is important to keep the sample sizes constant, in our case the sufficient size tolerance was about 0,1 mm. In this case the signal error stays within 1-3%.
It is desirable, too, that for all experiments the electromagnetic field completely remains inside the sample. This means the sample thickness is restricted by a definite minimum. The minimal thickness depends on the device parameters. In our case it was important to check the small frequencies of 50-500 Hz. When varying the niobium sheet thickness in the region of 1-3 mm we have observed only a rather small influence of the thickness on the pick up signal. The estimated skin penetration

depth for niobium near Tc is about 0,5-1 mm. This quantity is approximately the minimal sample thickness for our experiment.
There are some literature data concerning the influence of the sample curvature on the pick up signal /4/. For a pick up coil diameter of 13 mm which is bigger as in our case (our coil diameter is 6 mm) the differences of the measured values on a convex surface with a rather big curvature diameter (bigger than 50 mm) are not significant in comparison with a plane surface. These results allow to expect small curvature influence on the signal for the TESLA shape cavity in equator area (curvature diameter about 80 mm) but it probably needs additional correction in the iris area (curvature diameter about 40 mm).
After taking into account all of the mentioned aspects a rather good sensitivity and reproducibility of the measured values was achieved. For example figure 5 presents the frequency dependence of the ΔU/Unc signal. The experiment was carried out for both sides of the same sample. It can be seen that the reproducibility of the results is very good, in most case within 1-3%.
The RRR calibration curves are presented in figure 6. The distinguish between different RRR values can be done rather exactly. By the way one sample was cut out from the DORNIER cavity (RRR=240, DC method). This RRR quantity correlates very good with the calibration curve.
The signal ΔU/Unc should be proportional to δ. This conclusion is in agreement with figure 5 where the frequency dependence of ΔU/Unc was fitted by formula $\frac{A}{\sqrt{f}}$ (A-const.) describing the δ behavior by the constant σ, too.
Because of the proportionality between δ and ΔU/Unc the relation $\Delta U / U_{nc} \approx \frac{C}{\sqrt{RRR}}$ (C-const.) can be expected. It should be mentioned that the RRR is proportional to normal conductivity σ at Tc). The results of the analytical fitting can be seen in figure 6. The formula $\Delta U / U_{nc} = \frac{26}{\sqrt{RRR}}$ satisfactorily describes the calibration curve for the signal amplitude.

Summary

The application of the eddy current method for nondestructive RRR measurement of niobium, especially for RRR measurement in the TESLA cavity, has been developed. The RRR value can be obtained by means of the previously plotted calibration curve. The eddy current method does not need an electrical connection to the specimen.

Literature

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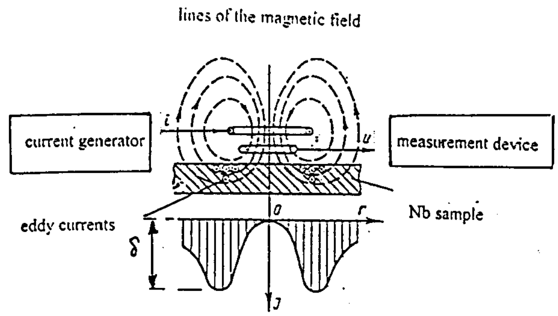

Fig. 1 Generalized schema of the eddy current method

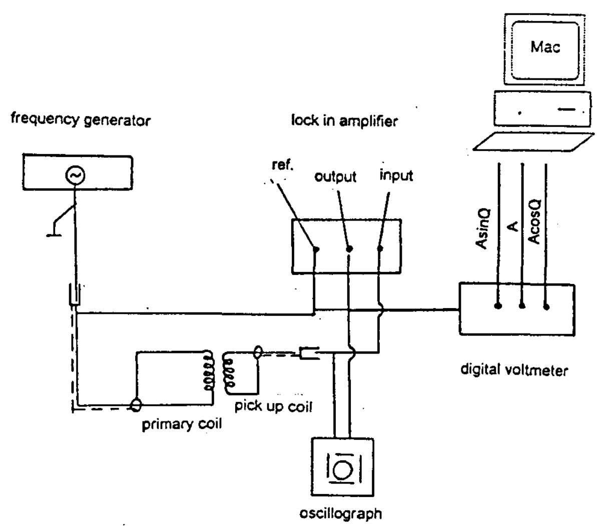

Fig. 2 Schematic diagram of the eddy current apparatus

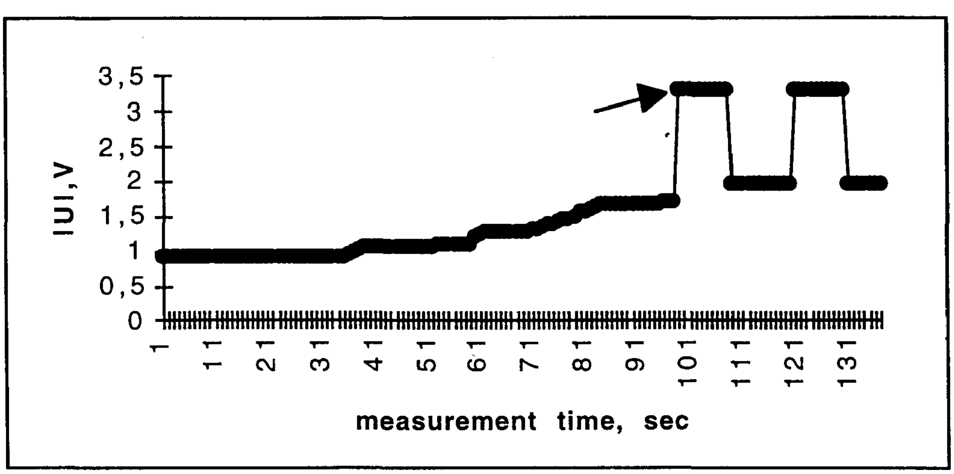

Fig. 3 Time dependence of the signal. A few cycles of heating up and cooling down was made up the 105th sec.

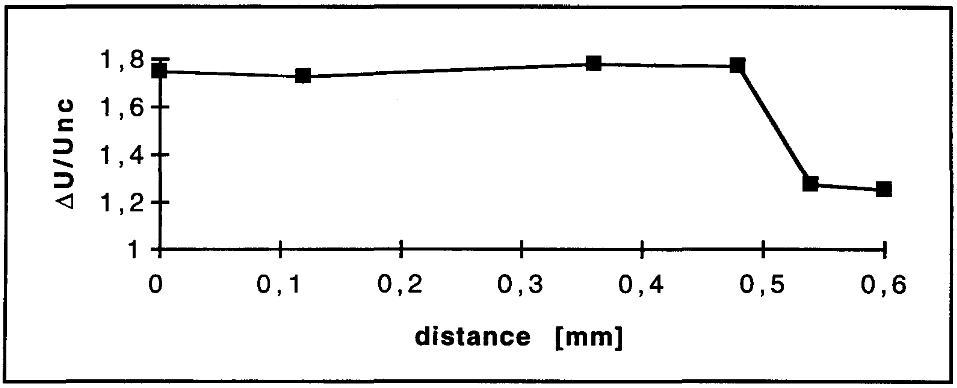

Fig. 4 Signal influence of the distance between pick up coil and the sample surface (RRR=265, f=113)

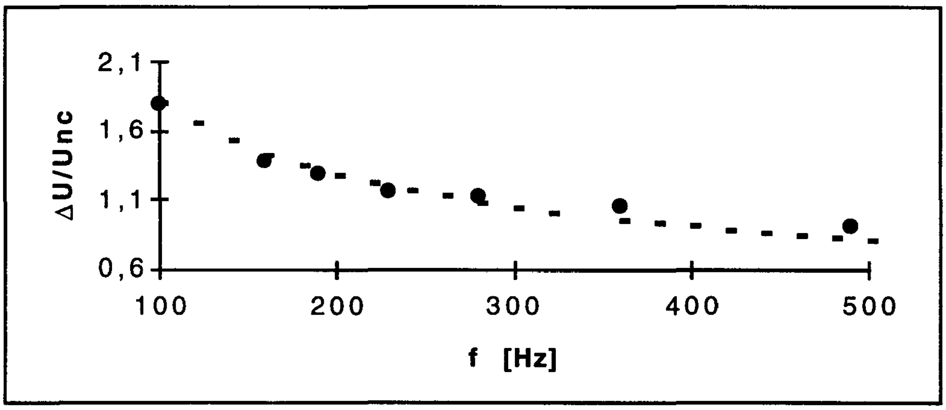

Fig. 5 Frequency dependence of ΔU/Unc (RRR=160)

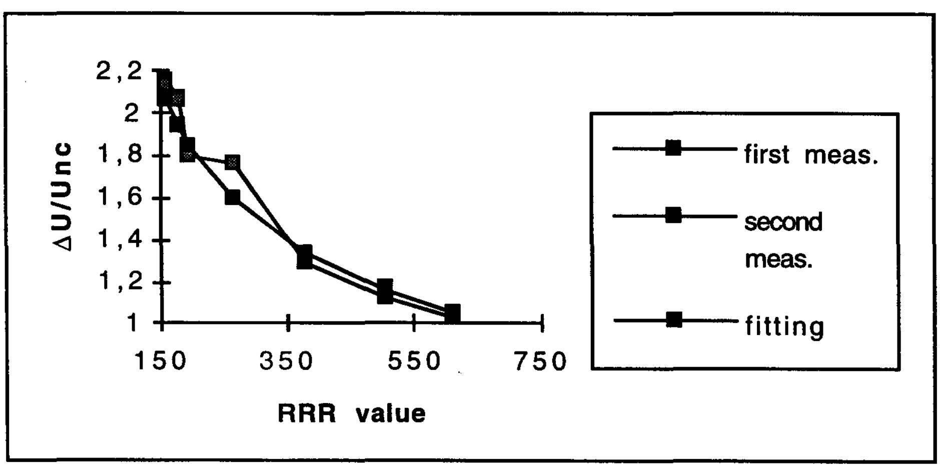

Fig. 6 Calibration curve for RRR measurement (f=113 Hz).