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[16]Interestingly enough, Smith and Gardner (Ref. 4) predicted a positive isotope effect for α-uranium, in fact $T_c \sim M^2$, on the basis of an empirical relation between the isotope effect and the pressure dependence of T_c [J. L. Olsen, E. Bucher, M. Levy, J. Müller, E. Corenzwit, and T. Geballe, Rev. Mod. Phys. 36, 168 (1964)]. Their model of superconductivity in uranium was somewhat similar to that described here. In a later paper, however (Ref. 5), they proposed a different model which apparently did not lend itself to a prediction of the isotope effect. Furthermore, the empirical relation used in Ref. 4 has subsequently been placed in doubt. [T. F. Smith, private communication. See also E. Bucher, J. Müller, J. L. Olsen, and C. Palmy, Cryogen. 5, 283 (1965).]
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LINEAR CURRENT-VOLTAGE CHARACTERISTICS IN TYPE-II SUPERCONDUCTORS UNDER CONDITIONS OF FLUX FLOW*

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The recent suggestion that the flux-flow current-voltage characteristics of Type-II superconductors can be described by the relation $\ln I \propto V^{1/2}$ is shown to be inadequate over an extended range of currents. The previously reported linear relationship between I and V is found to hold and the present ideas about flux flow remain unchallenged.

A number of investigations have been made on the current-voltage characteristics of superconducting foils in transverse magnetic fields. For all materials investigated the voltage has been reported to increase linearly with current for currents slightly larger than I_c, the minimum current required to produce a nonvanishing voltage.[1-4]

At currents intermediate between I_c and the linear I-V region, the voltage increases less rapidly with current. This intermediate region has remained puzzling, but Jones, Rhoderick, and Rose-Innes[5] have recently suggested that it is related to sample inhomogeneities which may produce flux-pinning centers with a range of pinning strengths.

The origin of a voltage in a Type-II superconductor has been explained by the dissipative motion of fluxoids.[1] In the presence of a transport current I, a Lorentz force F_L acts on a fluxoid. If this Lorentz force is sufficiently great to allow the fluxoid to overcome the sample pinning force F_P, the fluxoid moves with a constant velocity proportional to $F_L - F_P$. This viscous motion of flux leads directly to the linear current-voltage relationship.

Cladis[6] has recently reported that all published I-V characteristics follow a relation $\ln I \propto V^{1/2}$ over "the whole range of I" and that therefore "the division of the I-V curves into 'linear' and 'curved' parts is no more than an optical illusion." Clearly, if the Cladis relation provides a more adequate description of flux flow than the previously assumed linear relationship between current and voltage, our present understanding of flux-flow processes must be incorrect. It is therefore necessary to examine the Cladis relation with respect to other data, and preferably over an extended range of currents and voltages.

We have made such an examination on our own data on lead-bismuth and lead-thallium

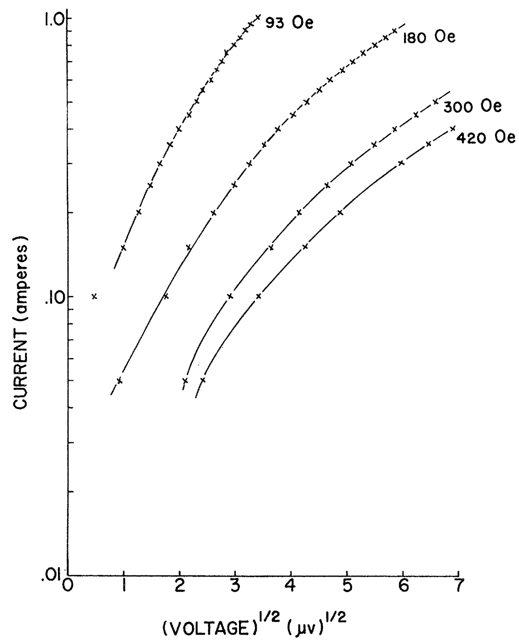

FIG. 1. Flux-flow data of French, Lowell, and Mendelssohn (Ref. 3) for nearly perfect $Ta_{80}Nb_{20}$ sample. Data are plotted as $\ln I$ vs $V^{1/2}$. Deviations from the Cladis relation $\ln I \propto V^{1/2}$ are apparent.

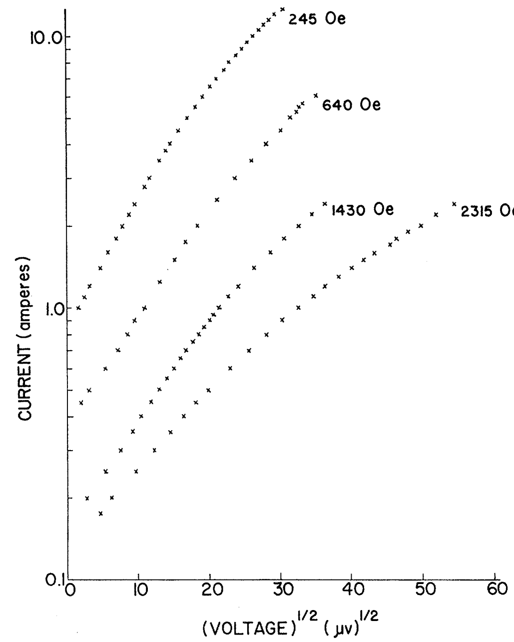

FIG. 2. Data of present work on $Pb_{60}Tl_{40}$ foil of intermediate critical current density and homogeneity level. The deviations from the Cladis relation at the larger values of I/I_c are again apparent.

alloys and also on other data which have appeared in the literature but which were unmentioned by Cladis.[6] Our conclusion is that the Cladis relation does not adequately describe the current-voltage characteristics, but rather sometimes provides a fortuitous fit when data are obtained over a limited range of currents. Linear flux-flow curves are therefore not optical illusions, and the existing theoretical descriptions of flux flow remain unchallenged.

In Fig. 1 we show the data of French, Lowell, and Mendelssohn[3] plotted as $\ln I$ vs $V^{1/2}$. The Cladis relation, $\ln I \propto V^{1/2}$, is clearly inadequate in describing the data. The flux-flow curves of this work are especially significant since the sample, a single crystal of $Ta_{80}Nb_{20}$, was prepared with a high degree of perfection so that the level of inhomogeneities and the resulting critical currents were very low. Cladis[6] also found data which did not fit the logarithmic relationship but dismissed it as being due to sample inhomogeneities. The data on which Fig. 1 is based cannot be so dismissed.

One feature of Fig. 1 which is especially relevant is that each flux-flow curve covers a larger range of currents ($I/I_c \gtrsim 10$) than was available in the data used in the Cladis analysis. The importance of using an extended range of currents in testing the Cladis relation became apparent in examining our own data. This is illustrated in Fig. 2 for a foil of $Pb_{60}Tl_{40}$. This sample was prepared by compressing the alloy ingot between glass plates to produce a foil with mirror-smooth surfaces. Samples thus prepared exhibit considerably lower critical current densities than those with rougher surfaces.[4,7] The foil was cut to dimensions of 3.8 cm × 0.5 cm × 0.018 cm and vacuum annealed at 340°C. Measurements were made at 4.2°K in a four-probe rig using knife-edge potential contacts. Continuous I-V curves were obtained with an x-y recorder after first amplifying the voltage signal. The resulting flux-flow characteristics were in every way well behaved, the flux-flow resistivity showing the same general field dependence as reported by others.[1]

This sample possesses higher critical current densities than the sample of Fig. 1, but about an order of magnitude lower than we obtained for unannealed rolled foils. We therefore may describe this sample as having an intermediate level of inhomogeneities. In this case the Cladis relation appears adequate at lower current levels, but inadequate for I/I_c

$\gtrsim 5$. It would not be possible to attribute deviations at these higher current levels to sample inhomogeneities in view of the even greater deviations shown in the more homogeneous sample of Fig. 1. Also we find that our rolled and unannealed foils with much higher critical currents and inhomogeneity levels show no greater deviations from the Cladis relation, provided the curves are taken to sufficiently high ratios of I/I_c.

Finally we point out that any ideal flux-flow characteristic showing an exactly linear current-voltage characteristic about I_c will show the same kind of deviations from the logarithmic relationship which Cladis attributes to inhomogeneities.

We conclude that the Cladis relation has limited validity. Specifically, it does not hold over an extended range of the linear portion of the flux-flow characteristic, regardless of sample inhomogeneity, and therefore this portion cannot justifiably be called an optical illusion. The present ideas about viscous motion of fluxoids remain unchallenged.

Mr. G. E. Kuhl obtained the data on the lead-bismuth alloys and Mr. C. J. Axt plotted the data of French, Lowell, and Mendelssohn.

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SUPERHEATING IN CYLINDERS OF PURE SUPERCONDUCTING TIN

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Magnetization measurements were carried out on cylindrical samples of pure tin with diameters of 7, 10, and 122 μm and very clean and smooth surfaces in the temperature range from 3.62 to 3.72°K. The magnetization was found to be reversible and linear with the applied field $H_0 < H_{sh}$. Considerable superheating up to fields $H_{sh} = 2.25 H_{cb}$ has been observed.

The theory of Ginsburg and Landau predicts superheated, i.e., metastable superconducting, states in magnetic fields above the thermodynamic critical field H_{cb}. Ginsburg[1] has calculated the maximum superheating field H_{sh}/H_{cb} as a function of the parameter κ for the superconducting half-space. A recent calculation for the same case by Matricon and Saint-James[2] gives the same curve as obtained by Ginsburg.

For a long time experiments showed superheating fields much lower than those given by theory using appropriate κ values estimated from other experiments.[3,4] Measurements on small spheres of indium[5] and tin[6] gave considerable superheating fields. In general, however, the application of the theoretical results for the half-space to experiments with small spheres seems to be uncertain unless $r\kappa/\delta_0 \gg 1$ (r = radius of the spheres, δ_0 = penetration depth).[1] An additional difficulty arises from the unknown actual field at the single spheres, which may differ from the applied field H_0 because of the susceptibility of the sample.

In our experiment we measured the magnetization of three cylindrical samples of pure tin (99.9999 %) with diameters of 7, 19, and 122 μm and equal lengths of 25 mm. The samples were extruded from glass capillaries at a temperature a few degrees below the melting point in helium atmosphere. The surfaces of the samples obtained by this procedure were found to be optically smooth. There were no defects which could be resolved by light microscope. Moreover, an x-ray investigation revealed the samples to be single crystals. Care was taken to avoid any harm to the surfaces, as well as oxidation and plastic deformation of the samples during the unavoidable