Superconducting Transition of Tin Alloys in an Alternating Field

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INTRODUCTION

If a rod of an "ideal" (or first-kind) superconductor is situated in a small alternating magnetic field $h_0 \cos \omega t$ superimposed on a steady field H, the signal induced in a coil closely wound on the rod is very small until H exceeds the critical field. Before the signal recovers its normal state value, however, it passes through a maximum. An example of this behavior is shown in Fig. 1. It has been observed that

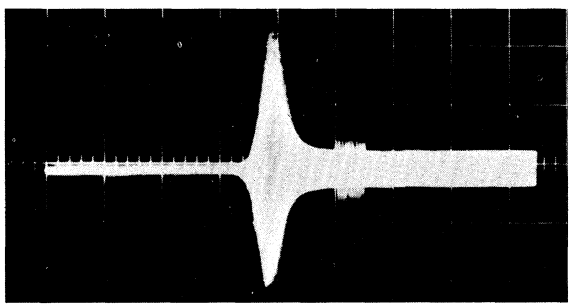


FIG. 1. The peak in signal amplitude for an ideal superconductor: 1.3% Sn–In at 3.53°K (critical field: 17 G; alternating field: 46 cps, 0.3-G amplitude; horizontal sensitivity: 0.42 G/small div).

this peak in amplitude disappears at concentrations above about 2% indium in tin–indium alloys, and Wipf[1] has suggested that the disappearance of the peak is associated with the onset of second-kind superconductivity.

In order to explore this suggestion further we have investigated the dependence of signal amplitude on applied field by sweeping the field through the superconducting transition at a constant rate and taking photographs of the oscilloscope screen as the spot has been deflected vertically by the signal, and horizontally by a voltage proportional to the field H. We have been able, at the same time, to record the magnetization and resistance as a function of field under the same conditions and displayed in the same way as the variations in signal amplitude.

It seems that most of the features of the behavior of the signal amplitude are a result of hysteresis. In particular, the separation of the peak (which disappears but may be made to reappear by increasing the sweep rate) from the recovery of the normal state signal, a characteristic of the more concentrated alloys, results from hysteresis in the tail of the transition.

[1] S. Wipf, Cryogenics (to be published).

EXPERIMENTAL DETAILS

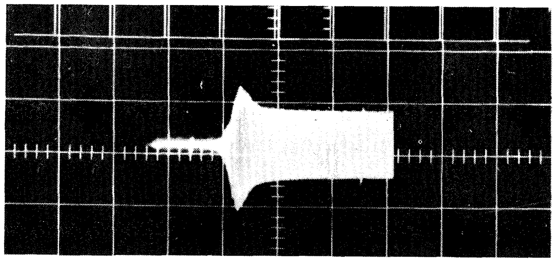
The specimens we have used are polycrystalline rods about 2 mm in diameter and 3 cm long. They have all been annealed for about 80 days at 212°C. Current and potential leads have been attached to the ends of the rods in order to measure their resistance through the superconducting transition. Usually a current of 40 mA was used and the potential difference applied to a Keithley millimicrovoltmeter. The magnetization curves were taken by integrating the output of the coil, after turning off the alternating field.

In order to display magnetization rather than induction curves, an identical coil to the one wound on the specimen is connected in series opposition to it in the same applied field.

The alternating field was usually provided by a separate coil, but in order to display the dynamic behavior of the magnetization, as in Fig. 6, where a voltage proportional to the *total* magnetic field $H + h_0 \cos \omega t$ rather than H was required to sweep the oscilloscope, it was produced by modulating the current controller feeding the Helmholtz coils. In most of the experiments the amplitude of the alternating field h_0 was 0.3 G and its frequency about 50 cps.

Behavior in an Alternating Field

Above about 2.5% indium, the behavior in an alternating field can be separated into two parts: (a) A peak in signal amplitude, which is absent when the field is swept slowly but can be made to reappear by increasing the sweep rate. This feature we call the "rate-dependent peak." (b) The recovery of the normal state signal. The separation of the two features becomes larger as the temperature is reduced, or as the concentration of indium is increased (Figs. 2–4). In the 1.95% and 2.2% alloys we can observe the transition to this kind of behavior from that of the "ideal" superconductors like the 1.3% alloy of Fig. 1. In a steady field there is still the trace of a peak in the 2.2% alloy (Fig. 2). The rate dependence of the peak is rather slight at 1.95%, whereas in the 2.2% alloy a rate-dependent peak is clearly visible. It also appears at a slightly lower field than the residual steady-field peak. As the temperature of the 2.2% alloy is reduced, the recovery of the normal state signal begins to separate itself from the peak, but in the 1.95% alloy we have observed no separation of the two features.



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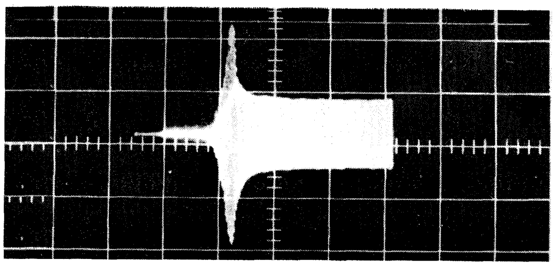

(b)

FIG. 2. The rate-dependent peak. 2.2% Sn–In at 3.53°K. Sweep rate: (a) 0.56 G/sec, (b) 2.26 G/sec. (Peak at 15 G, other details the same as Fig. 1.)

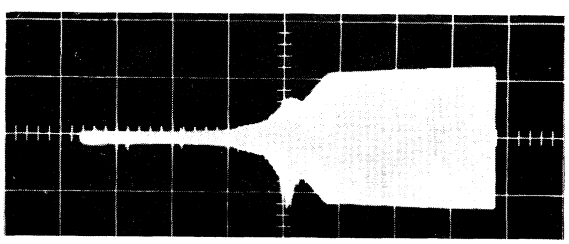

FIG. 3. The peak and the recovery of the normal state signal become separated. 2.2% Sn–In at 3.35°K. Sweep rate too slow for the rate-dependent peak to appear. (Peak at 42 G, other details the same as Fig. 1.)

Cause of the Behavior

The disappearance of the peak in signal amplitude and its reappearance when the rate of field sweep is increased is a result of hysteresis in the magnetic transition. Hein and Falge[2] have already shown this. Their results on a tantalum sphere show the same sort of behavior we have described above. We explain it again, in terms of the path followed by the magnetization M on a plot of $-4\pi M$ against H, because it can be done briefly, and especially in order to show what happens during the recovery of the normal signal. In Fig. 5 we have plotted imaginary magnetization curves taken in rising and falling fields (as indicated by the arrows) exaggerating the irreversibility in the tail. If, at a point such as A, the field is decreased slightly, $-4\pi M$ will not retrace the rising field curve but will travel along a line AB whose slope is unity, corresponding to a freezing of the flux at the value it had at A. If the field is raised again, $-4\pi M$ will retrace its path along BA until at A it will start down the rising field curve again. (Such behavior is shown in the magnetization curves of Fig. 6 where the field was modulated at 1 cps as it was swept through the transition.) If, therefore, at a steady field H, a modulating field, amplitude h_0, is applied, $-4\pi M$ will travel up and down between A and B, and no signal will be induced in the coil. The same will be true at H_2 or H_3. But at H_4, where the hysteresis in the tail has become small, $-4\pi M$ travels around a loop rather than along a straight line. The recovery of the normal state signal corresponds to the shrinking of this loop. We should expect from

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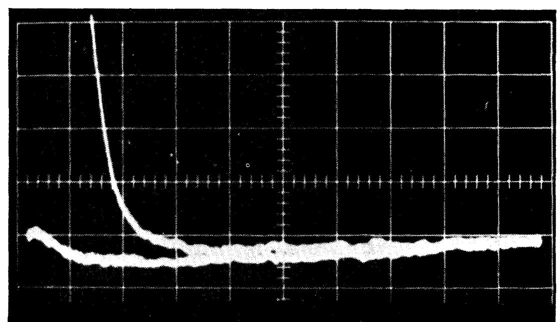

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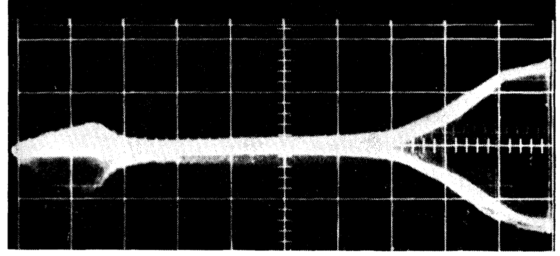

FIG. 4. (a) Part of the magnetization curves in rising (upper curve) and falling field (lower curve). The narrow irreversible tail of the transition can just be seen. (b) The last traces of the irreversible tail are revealed by the recovery of the normal signal, now clearly separated from the rate-dependent peak. 4.5% Sn–In at 3.335°K. (Peak at 49 G; alternating field: 65 cps, 0.3-G amplitude; horizontal sensitivity: 0.63 G/small div.)

[2] R. A. Hein, and R. L. Falge, Phys. Rev. 123, 407 (1961).

this that the waveform of the signal would be a distorted sine wave until the recovery is complete. This is indeed confirmed by our findings.

The recovery, then, is due to a separation of the rising and falling field magnetization curves in the tail of the transition, the disappearance of the peak to a separation of the curves in the region where $-4\pi M$ is changing rapidly with field. In steady field the peak can be made to reappear by increasing the amplitude of the alternating field until it becomes larger than the separation of the two magnetization curves. Even before it gets as large as that a small peak may be produced because, in practice, the paths such as EF between the magnetization curves are not straight so that a cycle such as ABA, as it becomes larger, will open out from a line into a loop as B approaches the falling field curve. We have observed such loops directly in our 2.2% alloy at 3.0°K ($H_c \simeq 100$ G) where the separation between the magnetization curves was about 1.8 G, and yet a

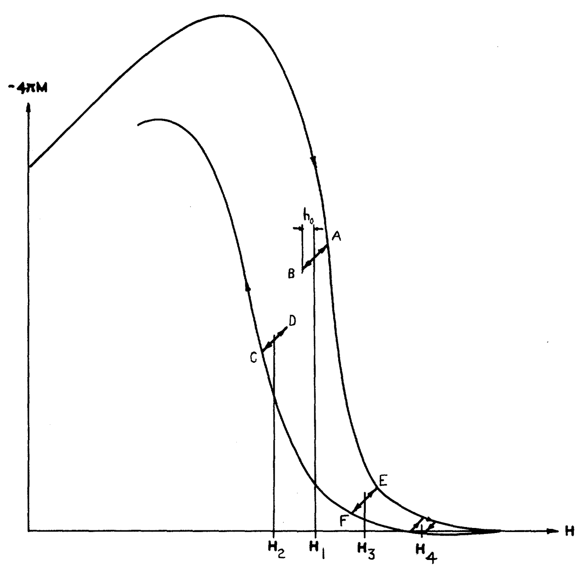

FIG. 5. Curves of magnetization versus applied field H for an irreversible superconductor, showing hysteresis. As indicated by the arrows, the upper curve is followed in rising field, the lower curve in falling field. On this plot of $-4\pi M$ against H, where M is the magnetization, a line of unit slope corresponds to constant magnetic flux. An alternating field amplitude h_0 swings $-4\pi M$ up and down AB at H_1, CD at H_2, EF at H_3, but at H_4 around the loop shown. Above H_3 the recovery of the normal state signal takes place.

small peak could be observed (as in Fig. 3) in an alternating field of amplitude 0.6 G peak-to-peak.

The rate-dependent peak reappears because, as the field is swept upwards (say), $-4\pi M$ will travel down a portion of the rising field magnetization curve between successive cycles of the type ABA. In a similar fashion it will appear also (at a lower field) when the field is being swept down.

We do not yet understand, however, why the rate-dependent peak appears more or less equally on both positive and negative cycles of the signal. We would expect it, according to the above explanation, to be made up of positive or negative pulses in a rising field, and of pulses of the opposite sign in a falling field.

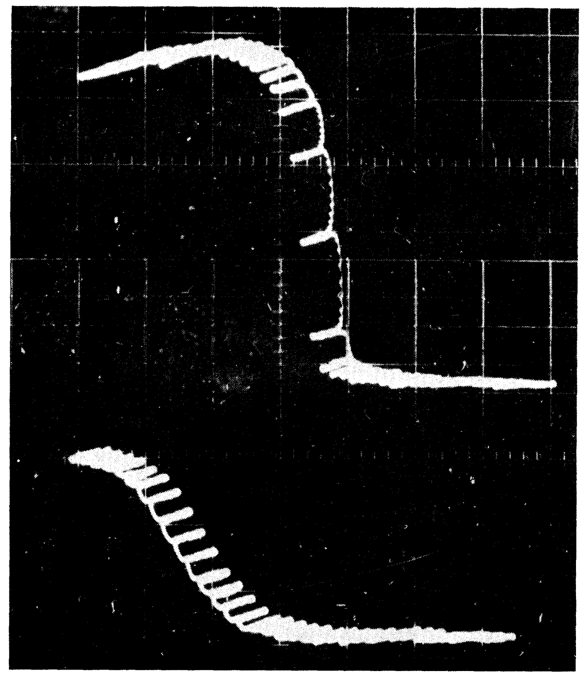

FIG. 6. The path of the magnetization of a superconductor showing hysteresis in a field modulated at low frequency (1 cps) while the field is swept at a constant rate upwards (upper curve) or downwards (lower curve). 3.0% Sn–In at 3.406°K. (Horizontal deflection provided by a voltage proportional to the total instantaneous field applied to the sample. Horizontal sensitivity 0.30 G/small div.)

DISCUSSION

The resistance transitions start to broaden in comparison with the width of the magnetic transition in the same circumstances of composition and temperature that the rising and falling field magnetization curves become separated. It seems likely that both are the result of second-kind superconductivity in our imperfect specimens. If that is so, then we must suppose that the regular way, qualitatively speaking, in which these properties vary with increasing indium concentration is a result of the increasing magnitude of the negative surface energy in specimens rather similar in whatever type of inhomogeneity these properties are most sensitive to. However, if these alloys are second-kind superconductors above some concentration depending perhaps on temperature (Wipf suggests 2.0% indium at about 3°K) one expects to find much larger tails on the magnetization curves of the more concentrated alloys than can be seen except at very high sensitivity. According to the theory of second-kind superconductors, the ratio of upper critical field H_{c2} to the thermodynamic critical field H_c for tin alloys would be

$$H_{c2}/H_c = K + 0.35\rho ,$$

where K is a constant and ρ is the resistivity in microhm-cm. Taking this ratio to be unity at 2.0% indium, one can calculate the separation between H_c and H_{c2}. If we neglect the difference between the lower critical field and H_c and assume H_c corresponds to the position of the rate-dependent peak in a rising field then we find that the calculated H_{c2} in each case (2.2%, 3.0%, 4.5%) is close to the end of the recovery of the normal signal. The recovery marks the end of the hysteretic tail, and thus provides a lower limit to the end of the tail if the hysteretic part is followed by a reversible region. The long shallow hysteretic tail is just visible in the part of the magnetization curve shown in Fig. 4 for the 4.5% alloy. It seems probable then that in our specimens of these alloys the tails due to second-kind superconductivity are present, but that they are very shallow indeed as compared with the height of the magnetization curve, and irreversible.

CONCLUSION

All the features of the behavior of our tin alloys (the same ones that were used by Wipf) in an alternating field can be related to hysteresis. To the extent that the appearance of hysteresis marks the onset of second-kind superconductivity, so (when the alternating field amplitude is very small) does the appearance of the peak in a steady field, as Wipf suggested. If, however, one believes that in a perfect specimen the transition would be reversible, then the criterion is not a very fundamental one, though in practice it may well work for specimens of attainable perfection as long as the amplitude is small enough. The rate-dependent peak phenomenon shows that the peak will reappear when the amplitude exceeds the separation of the steep parts of the magnetization curves, at any rate at low frequencies such as the 50 cps that we have used. As the sweep rate is raised there are signs of a slowing up of the maximum rate of change of flux in the transition of the 2.2% alloy, as shown both by the way in which the rate-dependent peak depends on sweep rate and by an increase in the hysteresis. This is the only alloy in which we have investigated this property. Whether it is a function of specimen quality, as we suppose the hysteresis and probably the shallowness of the tail on the magnetization curve to be, is a question we hope to answer by making carefully annealed single crystals of these alloys.

The Peak Effect in Substitutional and Interstitial Solid Solutions of High-Field Superconductors

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INTRODUCTION

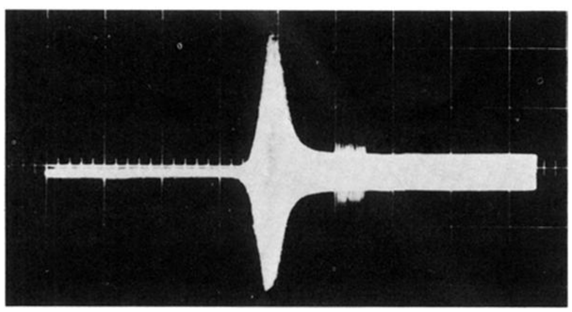
An anomalous behavior of high-field superconductors is the "peak effect." The data have been displayed principally in either of two ways: (1) a peak in J_c, the critical current density vs H_t, the transverse magnetic field and (2) a dip in R, the resistance, vs H_t. The anomaly has been reported in cold-worked transition metal alloys[1] as well as in impure niobium[2] and in interstitial solid solutions.[3] In the latter case it has been associated with H_{c2}, the upper critical field for a "negative surface energy" superconductor (type II). The results, summarized here, show that the anomaly [the anomaly is to be distinguished from that observed in J_c vs H (longitudinal)[4]] is more readily observed in interstitial than in substitutional solid solutions of transition metals. In both materials, when the anomaly occurs, it takes place at H_{c2} as determined magnetically. The results sug-

[1] For earlier references on the peak effect, see T. G. Berlincourt and R. R. Hake, Phys. Rev. **131**, 140 (1963).

[2] S. H. Autler, E. S. Rosenblum and K. H. Gooen, Phys. Rev. Letters **9**, 489 (1962).

[3] W. DeSorbo, Bull. Am. Phys. Soc. **8**, 294 (1963).

[4] See for example, S. T. Sekula and R. W. Boom, Appl. Phys. Letters **2**, 102 (1963).



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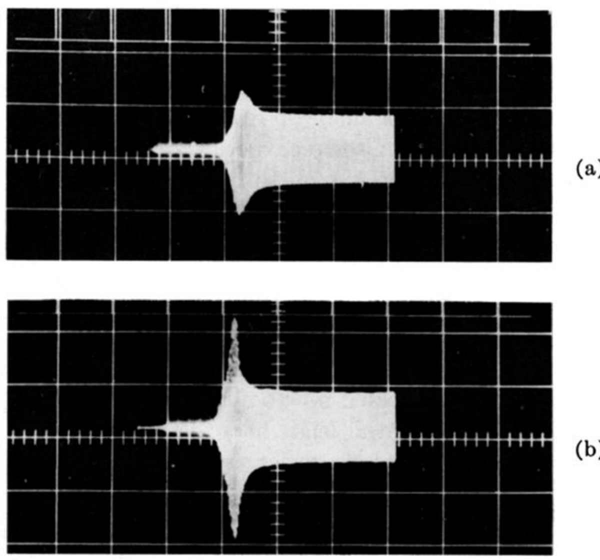

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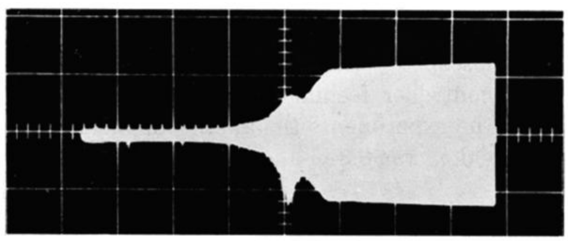

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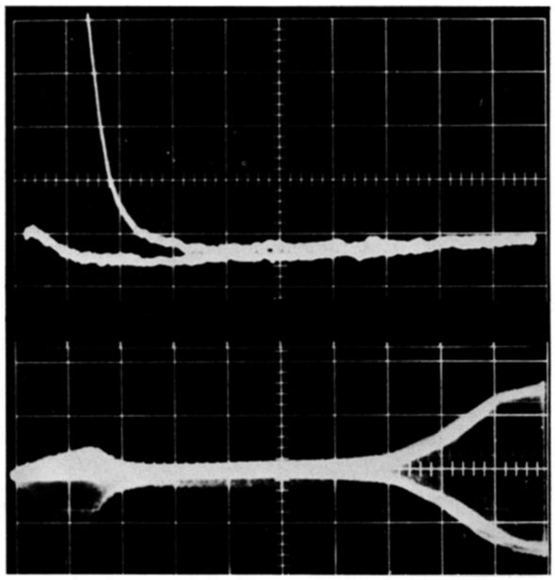

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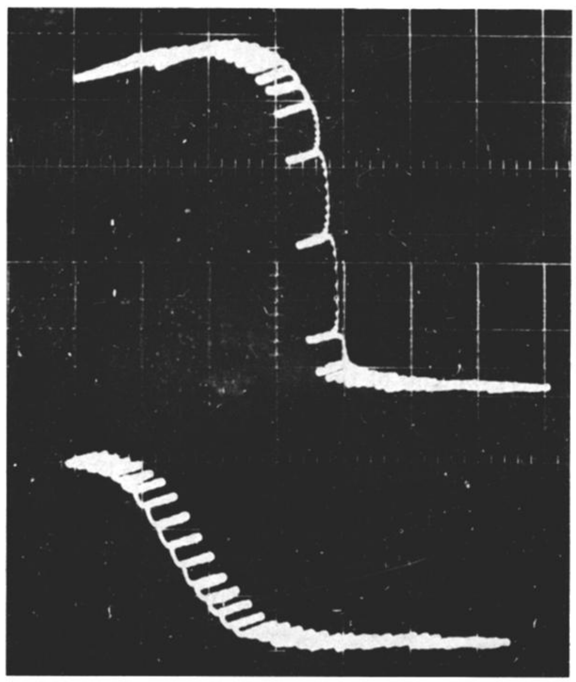

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