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Superconducting Lead Pressure Contacts

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ABSTRACT

The electrical properties of pressure contacts between superconductors is being investigated to obtain information needed for the design of high-current superconducting switches. It has been concluded from the study of pure lead contacts that a practical switch would utilize clean, roughened surfaces operating under a large mechanical load and at reduced temperatures. The current capacity, as well as the reliability, of the switch can be improved by applying a high-current pulse before use or by paralleling contacts. The voltage-current characteristic exhibits two types of transition differentiated by their abruptness, a nonohmic linear region, and is symmetrical with respect to the current direction.

Generally, the critical current can be increased by increasing the load, decreasing the temperature, or roughening the contact surfaces. In addition, highly oxidized contacts have a reduced critical temperature and a correspondingly reduced critical current.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

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SUPERCONDUCTING LEAD PRESSURE CONTACTS

INTRODUCTION

A mechanical superconducting switch capable of carrying high currents (e.g., 100 A) would be useful for many power applications of superconductivity. Although superconducting contacts have been studied, most of the work has been done with small contact areas and light loads ($\lesssim$100 g) for which the critical currents are at most a fraction of an amp. In 1932 Holm and Meissner (1) studied lead and tin junctions at various temperatures and magnetic fields. Later, in 1952, Dietrich (2) studied superconducting contacts with interposed insulating barriers. More recently, Meissner extended the early work on contacts significantly by studying the contact resistance between normal and superconducting metals, with Bedard (3), and between a large number of superconductors and plated superconductors (4,5). Simons (6) has considered sliding as well as stationary superconducting contacts.

About the only work oriented toward the design of a high-current switch has been that of Gaulé et al. (7). In 1964 they reported that their best results had been obtained with pure lead contacts coated with a very thin layer of tin for which a reproducible critical current of 13.5 amp was found at a load of 800 g. Recently this group claimed to have done considerably better with niobium-plated lead contacts (8).

As a first step in our search for a high-current superconducting switch we investigated pure lead pressure contacts. We found that the critical current of such contacts tends to increase as the load increases or as the temperature decreases, that it is greater for contacts with freshly cleaned surfaces than for contacts with heavily oxidized surfaces, and that contacts with roughened surfaces have higher critical currents than contacts with polished surfaces.

Although voltage-current characteristics were not necessary for the design of a superconducting switch, these characteristics were measured for completeness. Voltage-current characteristics show two types of transition, a linear nonohmic region, and symmetry with respect to the current direction.

CALCULATIONS

Before considering the experiment it is instructive to attempt to predict the behavior of the contacts. Given the contact geometry, Fig. 1, and assuming that the contact material has a Poisson ratio of 0.45, the classic formulas of Hertz (9) for an ideal elastic deformation give the radius b of the load-bearing contact area as

$$b = 1.1 \left(\frac{Lr}{E}\right)^{1/3}, \tag{1}$$

where r is the radius of curvature of the upper contact member, E is Young's modulus for the contact material, and L is the load on the contact. The maximum pressure occurs at the center of the contact area and is given by

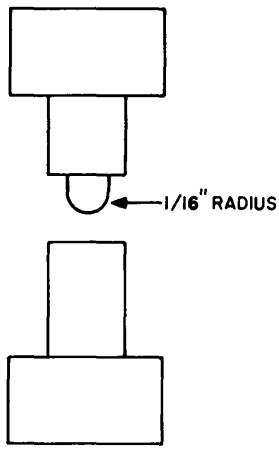

Fig. 1 - Geometry of the superconducting contacts

$$p_{max} = 1.5 \frac{L}{\pi b^2} . \tag{2}$$

When p_{max} reaches a value equal to the material's hardness H, the deformation can no longer be purely elastic but must become plastic. Using the value of the hardness for lead at 4.2°K given by Holm and Meissner (1), 1.49×10^6 g/cm^2, one finds that the load at which the elastic-to-plastic deformation change occurs is about 13.5 g. Since 250 g is the smallest load encountered in this experiment, an elastic deformation with the original geometry is unlikely.

For a plastic deformation the relationship between the load L, the load-bearing area A_b, and the hardness H is (9)

$$L = \xi H A_b , \tag{3}$$

where, usually, $0.2 < \xi < 1$, although ξ may be considerably less than 0.2 if the contact surfaces are highly polished.

If it is assumed that the contact surfaces mate perfectly and that the superconducting contact area has radius a, then Silsbee's hypothesis (10) predicts that

$$I_{cr} = 5a\mathcal{H}'_{cr} , \tag{4}$$

where I_{cr} is the critical current and $\mathcal{H}'_{cr}$ is the critical field of the contact. Assuming that the temperature dependence of $\mathcal{H}'_{cr}$ (11) is

$$\mathcal{H}'_{cr} = \mathcal{H}'_0 \left(1 - \frac{T^2}{T'^2_c}\right) , \tag{5}$$

where $\mathcal{H}'_0$ is the contact's critical field at absolute zero and T'_c is the contact's critical temperature at zero field, the critical-current equation becomes

$$I_{cr} = 5a\mathcal{H}'_0 \left(1 - \frac{T^2}{T'^2_c}\right) . \tag{6}$$

Primes were placed on $\mathcal{H}_0$ and T_c because they are functions of the contact pressure. Garfinkel and Mapother (12) have reported that, for lead,

$$\mathcal{H}'_0 = \mathcal{H}_0 - 7.65 \times 10^{-6} \text{ gauss/g-cm}^2 (p - p_{std})$$

and

$$T'_c = T_c - 3.72 \times 10^{-8} \text{ °K/g-cm}^2 (p - p_{std}) ,$$

where $\mathcal{H}_0$ and T_c are the usual standard pressure values (p_{std}) of the critical field at absolute zero and the critical temperature, i.e., 805 gauss and 7.22°K, respectively (11). Substituting in Eq. (6) and using the fact that the pressure for a plastic deformation is ξH, we obtain

$$I_{cr} = 2.31 \times 10^{-3} a \sqrt{L/\xi} (805 - 11.4\xi) [1 - T^2/(7.22 - 5.54 \times 10^{-2}\xi)^2] , \tag{7}$$

where the terms with p_{std} included have been dropped because of their small size with respect to the other terms. A factor α has been inserted in Eq. (7) to account for the fact that the Silsbee hypothesis is rarely strictly valid. For a wire the critical current is usually only 50% to 80% of the predicted value (10). As an example, if $\xi = 1$, $\alpha = 0.6$, and $T = 4.2°K$, then $I_{cr} = 0.72\sqrt{L}$.

In the above derivation it was assumed that there is a single contact area. In practice one might expect to find several discrete superconducting contact regions. If there are n superconducting contact regions, Eq. (4) must be rewritten as

$$I_{cr} = 5\mathcal{H}'_{cr} \sum_{i=1}^{n} a_i . \tag{8}$$

To complete the calculation assume that the n contact regions are identical and that they share the load equally; then

$$L = \sum_{i=1}^{n} L_i = \sum_{i=1}^{n} \xi H \pi a_i^2 = \xi H \pi n a_i^2 . \tag{9}$$

If we further assume no magnetic interaction between the various current paths, we have

$$I_{cr} = 5\mathcal{H}'_{cr} n \sqrt{L/\xi H \pi n} = 5\mathcal{H}'_{cr} \sqrt{nL/\xi H \pi} . \tag{10}$$

Now, if $\xi = 1$, $\alpha = 0.6$ and $T = 4.2°K$, then

$$I_{cr} = 0.72 \sqrt{nL} . \tag{11}$$

Thus, roughly, the more contact regions there are within a given nominal contact area, the greater will be the critical current.

EXPERIMENTAL APPARATUS AND METHOD

The experiments were performed with the apparatus shown in Fig. 2. The weight support assembly can be raised or lowered by rotating knob K. Lowering this assembly deposits the weights one at a time upon the upper contact by means of stop S, and, conversely, raising this assembly removes the weights. Contact can be broken by raising the weight support assembly until plate P engages stop S. The load which remains upon the contact after all the weights are removed is 250 g; thus, the load can be varied between 250 g and 1150 g in increments of 100 g.

The contacts were made by casting lead of 99.999% purity in plaster molds. Originally all contact pairs had the forms shown in Fig. 1; however, loading flattened the round contact members and indented the flat contact members. The contacts were extensively cleaned with solvents and dilute acids after they were removed from the molds. To keep the contacts especially clean, they were placed in alcohol immediately after the final surface preparation and were kept covered with the alcohol during transfer to the dewar.

To eliminate frost formation on the contacts, the dewar was sealed and then evacuated immediately after the contacts had been installed. The vacuum was maintained during the liquid nitrogen cooling period. Next, the dewar was filled with helium gas, and a slightly positive pressure was maintained during the liquid helium transfer and the experiment.

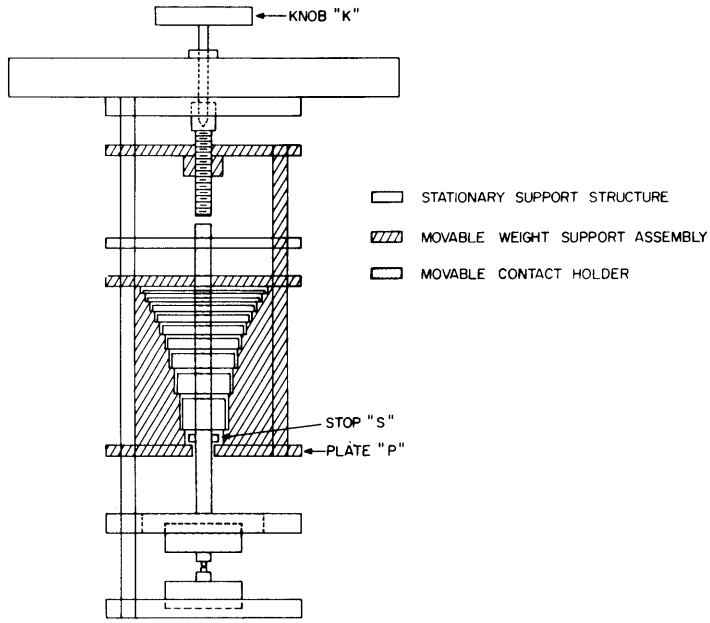

Fig. 2 - The experimental apparatus

Separate voltage and current leads were attached to each contact. Current was supplied by storage batteries, controlled by circuitry similar to that described by Fietz (13), and was measured with an ammeter. The voltage across the contact pair was detected and measured with a Leeds and Northrup 2430-C galvanometer calibrated to read in volts. The minimum detectable voltage was 0.1 μV, and, by using a resistance-switch network, voltages up to 1.0 V could be continuously measured. To increase the speed of taking data an X-Y plotter was used to record some of the voltage-current characteristics.

The temperature of the contacts could be lowered to 2.5°K by reducing the vapor pressure above the liquid helium.

DATA

Contact Set 1

The load versus the critical current for a clean, polished, new contact pair (set 1) is shown in Fig. 3. After the contact was carefully broken and then remade, the critical current was found to be constant at 8.7 amp, even though the load was increased from 250 g to 550 g.

At this point liquid helium was added to the system, and the measurements were repeated (third run of Fig. 3). The liquid helium filling operation jarred the system and probably shifted the contact point. This may explain why the load becomes important again. This third run is somewhat smoother than the initial run, although many of the same features are still apparent.

After the experiment was completed the diameter of the indentation left on the flat contact was measured and was found to be 0.1526 cm. When Eq. (3) is used, this diameter is found to correspond to a value of 0.0422 for ξ. This value is a minimum value, since the load-bearing area can be no larger, and is usually smaller, than the apparent

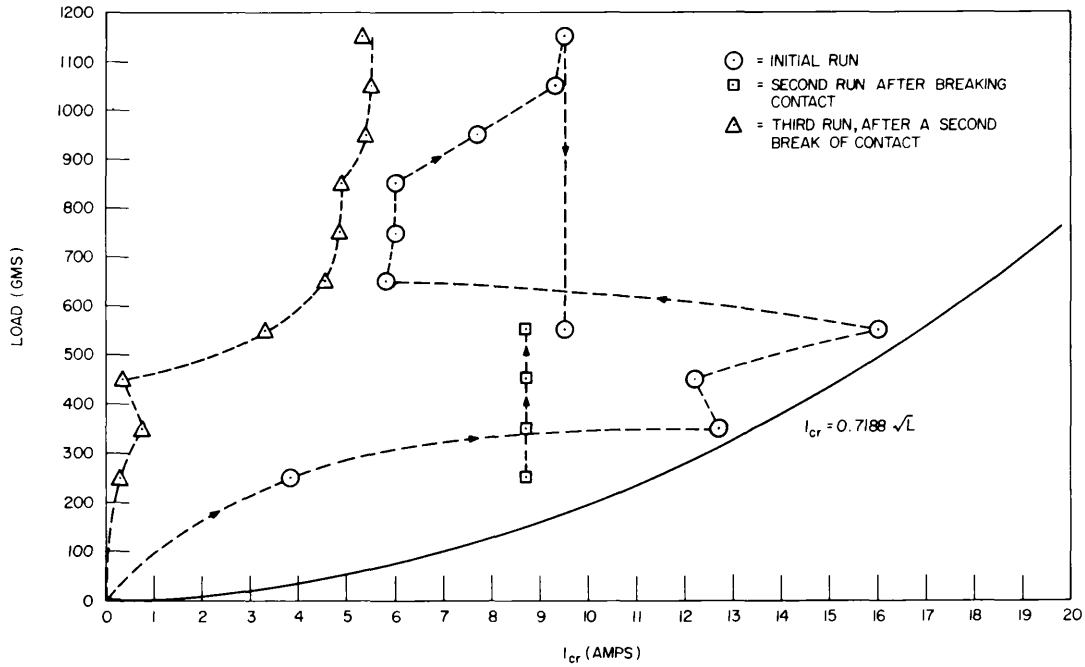

Fig. 3 - Load vs critical current for a clean, polished, new contact pair (set 1)

contact area. In any case, for $\xi = 0.0422$, $\alpha = 0.6$, and $L = 1150$ g, the maximum critical current is 122 amp, an order of magnitude greater than the largest measured critical current. This could mean that only a very small part (about 1.7%) of the apparent contact area can support a superconducting current or that the junction behaves as a weak superconducting link with a reduced critical field (about 70 gauss) due to an insulating surface layer. The second possibility appears to be ruled out by the fact that there was no corresponding reduction of the critical temperature. The smallest critical current that can be calculated by varying ξ (for $\xi = 1$) is 24.4 amp, which is still substantially greater than any of the measured values.

A second experiment was performed with this set of contacts after they had been exposed to the atmosphere for several days. The plot of L versus I_{cr}, Fig. 4, shows breaks as before, but the critical currents are smaller than those shown in Fig. 3.

Next, this same contact pair was cleaned and repolished but was not reformed to the original shapes. Figure 5 shows L versus I_{cr} for these contacts. Notice that the breaks occur similarly to those shown in Fig. 3 and that the critical currents have increased over those of Fig. 4. After we added liquid helium we obtained the curves shown in Fig. 6. The critical currents at 1150 g for these curves agree better with the initial run data of Fig. 3.

In addition to determining the load versus the critical current for the data obtained at 4.2°K, the critical current versus the temperature at constant load was also measured. Most of the temperature data were taken at a constant load of 1150 g; however, the data taken at smaller loads were consistent with the 1150-g data. Since the critical current varied with the temperature in an apparently parabolic manner, as expressed in Eq. (6), a critical temperature for the contact could be determined by extrapolation. For the newly cleaned contacts of Fig. 3 this critical temperature was found to be about 10°K; for the heavily oxidized contacts of Fig. 4 the critical temperature had dropped to about 5.8°K, and for the recleaned and repolished contacts of Figs. 5 and 6 the critical temperature had increased to about 8.1°K.

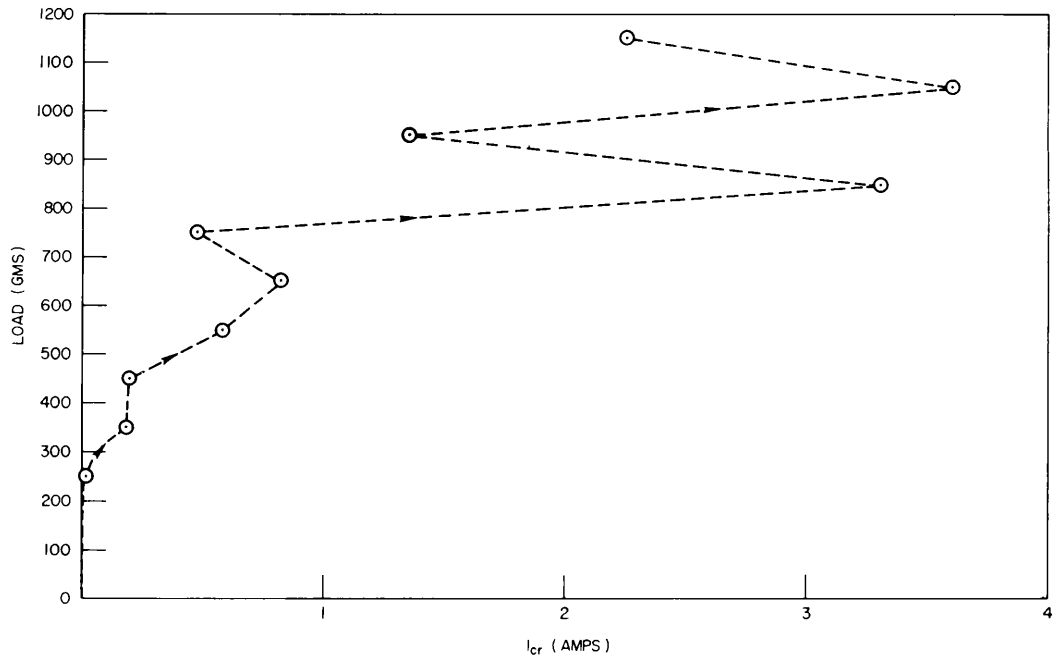

Fig. 4 - Load vs critical current for set 1 after it was exposed to the atmosphere for several days

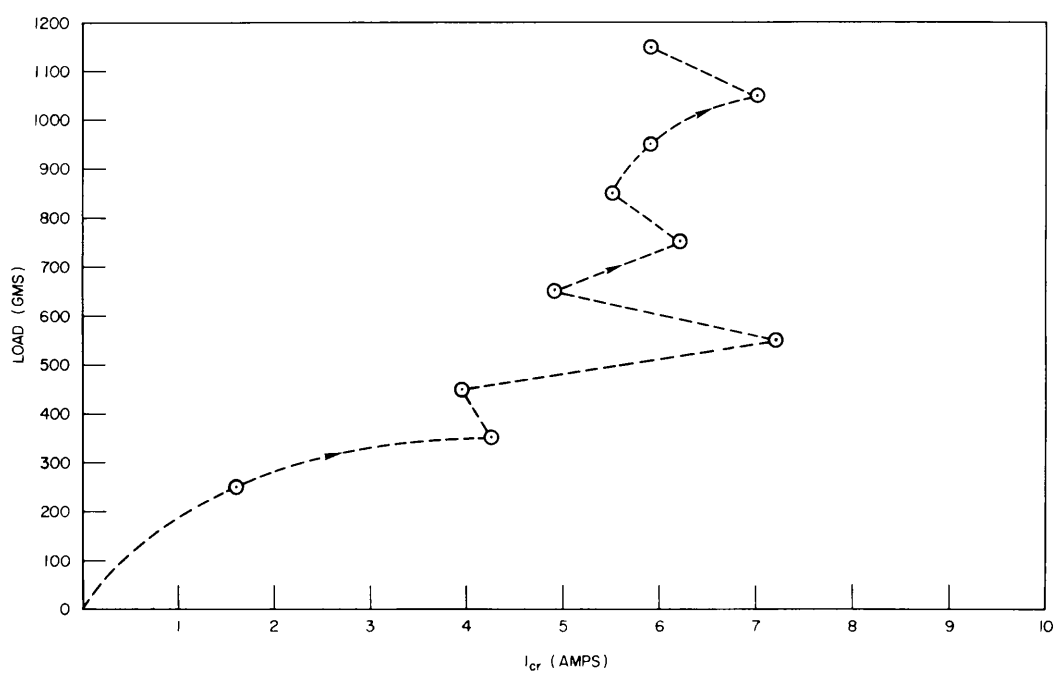

Fig. 5 - Load vs critical current for set 1 after it was cleaned and repolished

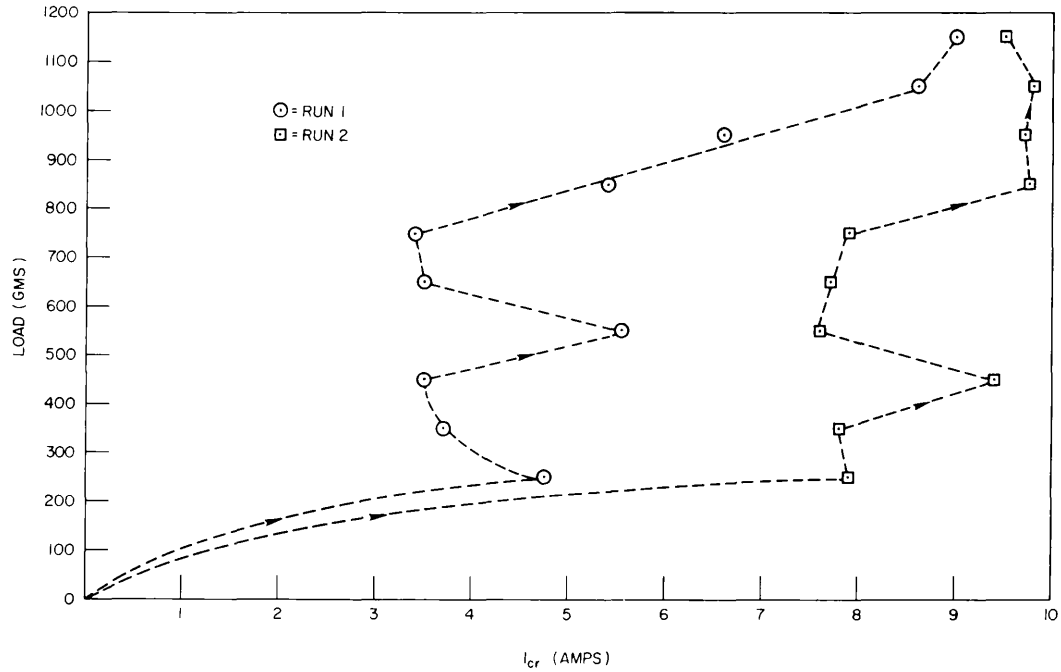

Fig. 6 - Continuation of the data of Fig. 5

Contact Set 2

A second set of contacts was used which should have been comparable in all other respects to set 1 except that it was unpolished (the surfaces were slightly etched). Upon initial contact at a load of 250 g the critical current was found to be 9.1 amp. Contact was broken and remade, and it was found that the critical current had dropped to 1.4 amp. The load was then increased and the remainder of the curve obtained is shown as Exp. 1 in Fig. 7. This curve is somewhat smoother than the initial-run and the third-run curves of Fig. 3, and even at a load of 1150 g the critical current seems to be increasing significantly, in contrast to set 1. The temperature versus the critical current is shown as Exp. 1 in Fig. 8 where extrapolation gives a critical temperature of 6.48°K.

The following day (after exposure to the atmosphere for several hours) the contacts were cleaned and a second experiment was performed. The plot of the load versus the critical current for this second experiment is similar to the curve for the first experiment (see Fig. 7), except that the critical currents are slightly smaller. The critical temperature (see Exp. 2, Fig. 8) had dropped to 6.05°K. This is consistent with the general change in the critical currents shown in Fig. 7.

Contact Set 3

Roughened contacts were investigated next, since increasing the number of superconducting contact points within a nominal contact area should increase the critical current. Such contacts were obtained by passing 600-grit silicon carbide paper over the contact surfaces two times at right angles. A typically roughened surface is shown in Fig. 9. Experiments were performed with the upper contact smooth and the lower contact rough, and with both contacts rough.

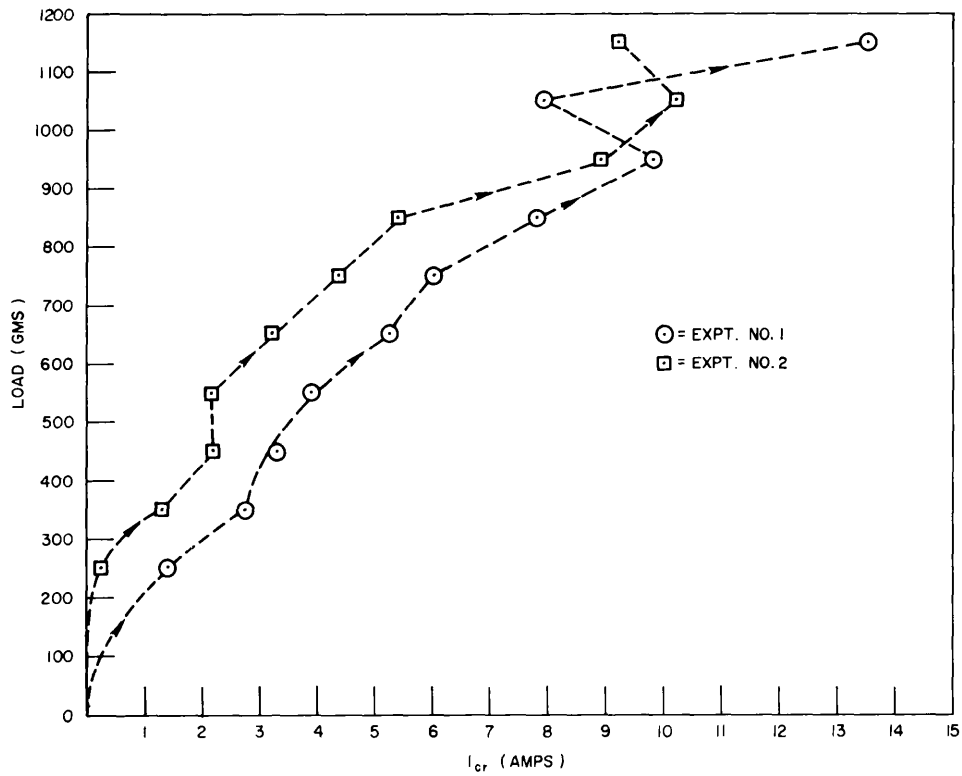

Fig. 7 - Load vs critical current for a clean, etched pair of contacts (set 2)

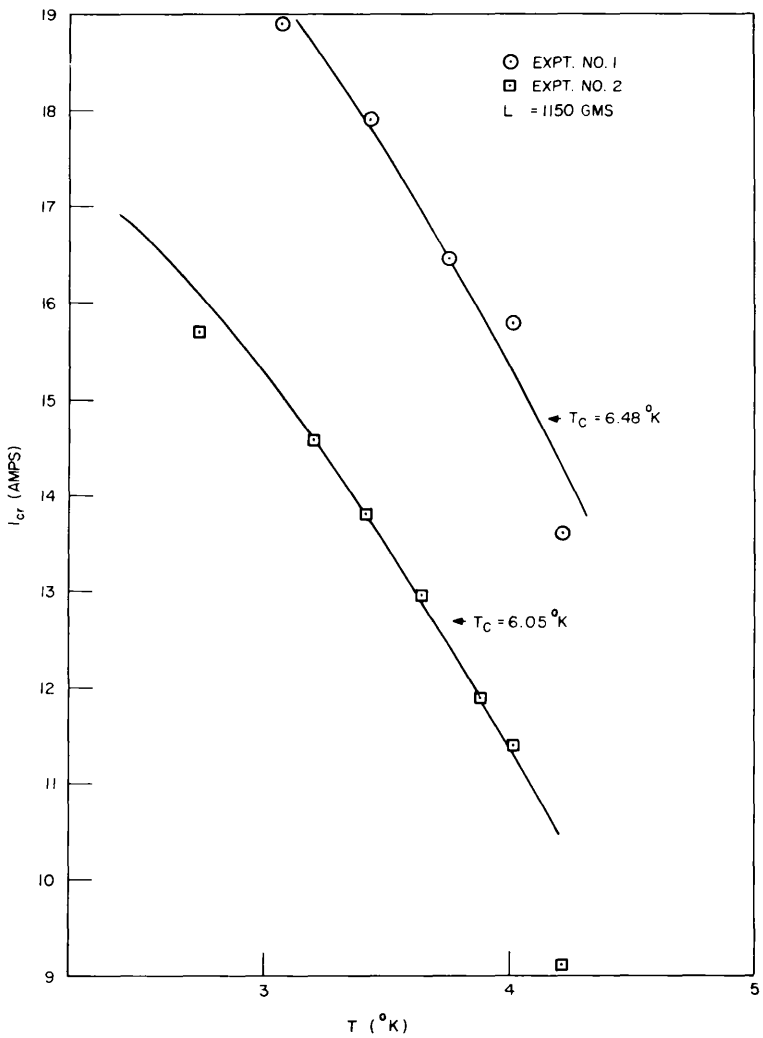

Fig. 8 - Critical current vs temperature for set 2

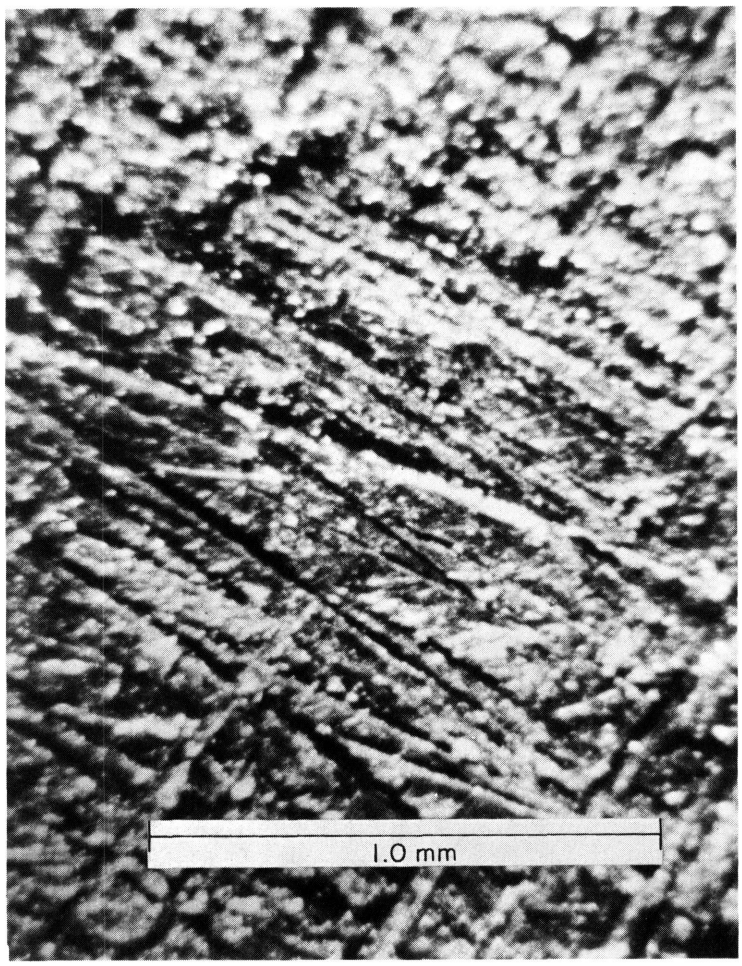

Fig. 9 - Flat contact surface roughened with 600-grit silicon carbide paper

As expected, the critical currents were greater for the rough contacts than for the smooth contacts and were anywhere from 2 to 3-1/2 times greater. Contact pairs having one smooth and one rough contact surface exhibited smoother curves and slightly higher critical currents than contacts having both surfaces rough. This indicates that the number of contact points was greater and that the points remained more stable for the rough-smooth contact pair than for the rough-rough contact pair, which seems plausible. The data are given in Figs. 10 and 11.

DISCUSSION

The most important property of a superconducting switch is its current capacity. As a function of load, the critical current tends to increase as the load increases; however, practically every experiment shows current jumps from higher to lower critical currents as the load increases. It is difficult to imagine a mechanism that would decrease the superconducting contact area under these conditions. Indeed, one would expect the contact area to increase, either because the contacts deform or because tarnish films on the surfaces are ruptured. The most likely explanation for the observed decreases seems to

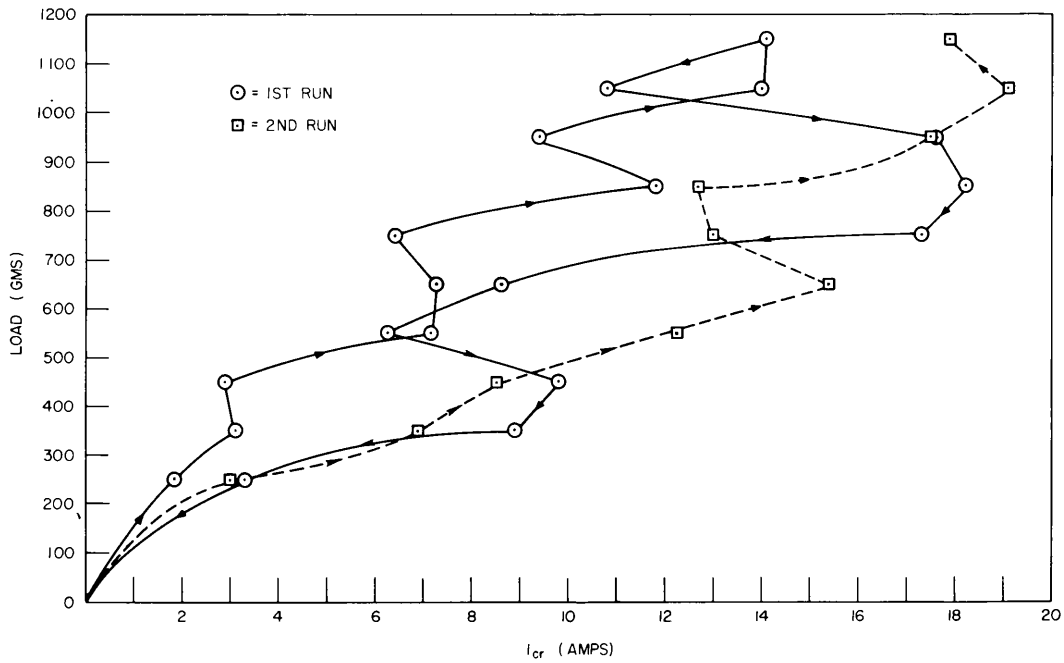

Fig. 10 - Load vs critical current for contacts with both surfaces roughened

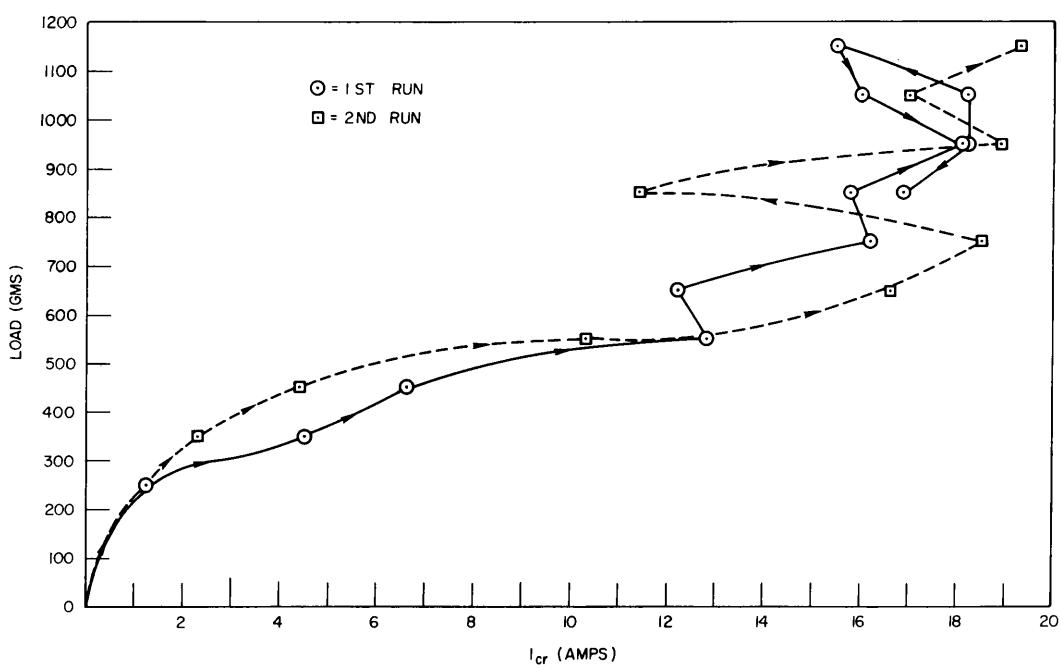

Fig. 11 - Load vs critical current for contacts with one rough surface and one smooth surface

be that when a contact region expands it coalesces with other contact regions and reduces the number n in Eq. (9).

Also, in general, when the load on a contact is reduced there is little if any change in the critical current. This indicates that the contact deformation is plastic (permanent) and that the pressure (at least over the present experimental range) has essentially no effect upon the superconducting properties of the contact. This is consistent with the magnitude of the pressure coefficients given by Garfinkel and Mapother (12), especially if ξ is small.

As a function of temperature the critical current always increases as the temperature decreases. It is also found that the contacts with higher critical temperatures are invariably capable of sustaining higher critical currents. In fact, calculated changes in the critical current based upon the measured critical temperature change are generally rather accurate.

The surface condition of the contacts is quite important in determining the critical current. Exposure of the contacts to the atmosphere decreases the critical current and also the critical temperature. The critical current can then be increased by physical cleaning or even by extended storage in a vacuum. This latter phenomenon may be due to a self-cleaning effect related to the self-annealing property of lead at room temperature.

The increase in the critical current for roughened contacts is quite significant and is believed to be due to an increased number of superconducting contact regions within the nominal contact area. Although a similar observation can be made with normal contacts, that is, a slightly roughened contact has a greater conductance than a very smooth one (14), the explanations for these two effects are believed to be fundamentally different. For normal contacts the conductance is essentially proportional to the total area of electrical contact, and, because a slightly roughened surface provides more points of contact, the contact area is usually increased. On the other hand, the critical current of a superconducting contact region is proportional to the radius rather than to the area of the region, so that the critical current is increased by increasing the number of contact regions, even at the expense of contact area. As noted before, this explains the decreasing current jumps observed with increasing load, since an increase in load could cause a decrease in the critical current if the contact regions coalesce.

If the critical current of a contact pair is reached and the current is then increased, a subsequent measurement on the contact pair will indicate a higher critical current. This effect might have practical application for high-current switches. For example, in one experiment the critical current was found to be 6 amp. The current was increased to 30 amp for 2 or 3 sec and was then reduced to zero, after which the critical current was found to be 14 amp. This increase of critical current can be explained by Joule-heat melting the lead and joining the two contact members by a continuous metal bridge. Figure 12 shows a minute portion of a contact surface in which it appears that such welding has occurred. The critical current of this spot, found using Silsbee's hypothesis, is about 13.5 amp. These spots could also be produced by opening a superconducting contact with current flowing. To use this effect with a switch, a high-current pulse could be applied to the contacts just before using them. Since roughened contacts improve the current capacity, such "priming" would not necessarily reduce the lifetime of the contacts.

For a practical switch, one last point should be mentioned. If, at a given load, contact is broken and remade many times, the scatter of the critical-current values may be considerable. To illustrate, one such set of data is shown in Fig. 13. If high reliability is desired, then the maximum current carrying capacity must be chosen below the minimum critical current. The capacity of the switch would then be severely limited because of a few exceptionally low critical-current values. This problem might be eliminated by

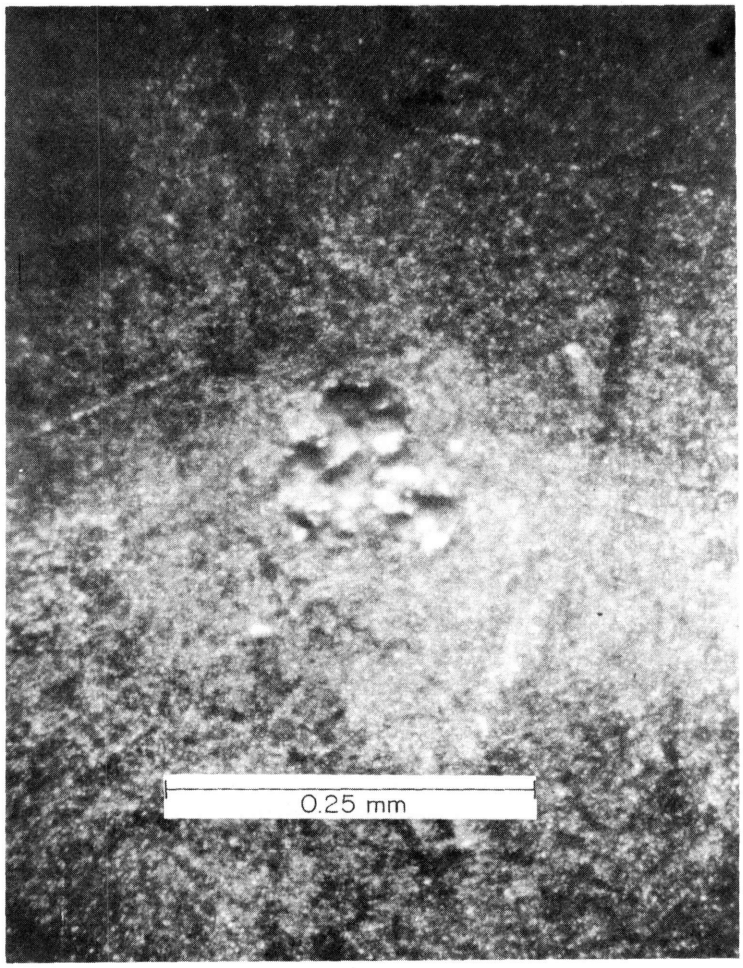

Fig. 12 - Pitting believed to be due to a micro weld between a contact pair

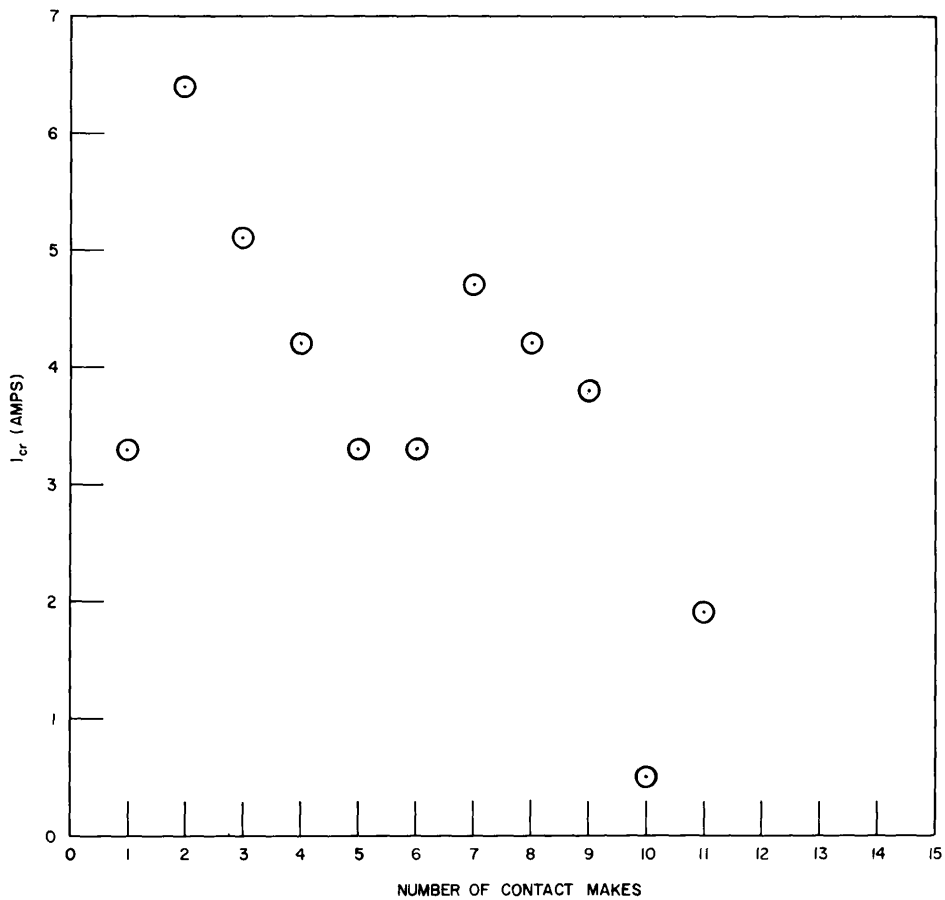

Fig. 13 - A set of data in which the variation of the critical current with the number of contact makes was large

paralleling the contacts and by taking advantage of a more uniform average as well as increased current capacity and/or by using a large initial current pulse to increase the reliability and the current capacity.

There remain two general properties of the superconducting lead pressure contacts that should be mentioned. The first property is the apparent unpredictability of when the two essentially different transition curves (also reported by Meissner (5)) will occur. Typical examples of the transition curves are in Figs. 14 and 15. The two types of transition are easily differentiated by observing the initial deflection of the galvanometer. For curves of type A this initial deflection is very abrupt, whereas for curves of type B the voltage increases gradually, making it difficult to pinpoint the beginning of the transition. In both cases, however, after an initial power-law increase in voltage with current, the characteristic appears to become linear, although for comparable critical currents the slope for a type-A transition is greater than the slope for a type-B transition (see Fig. 14). This linear region is not ohmic, however, since it does not extrapolate through zero current at zero voltage but passes through a positive current value. This effect has been previously reported for oxidized junctions by Pankove (15) who believes that part of the current through the contact is a supercurrent, even though there is a voltage across the junction.

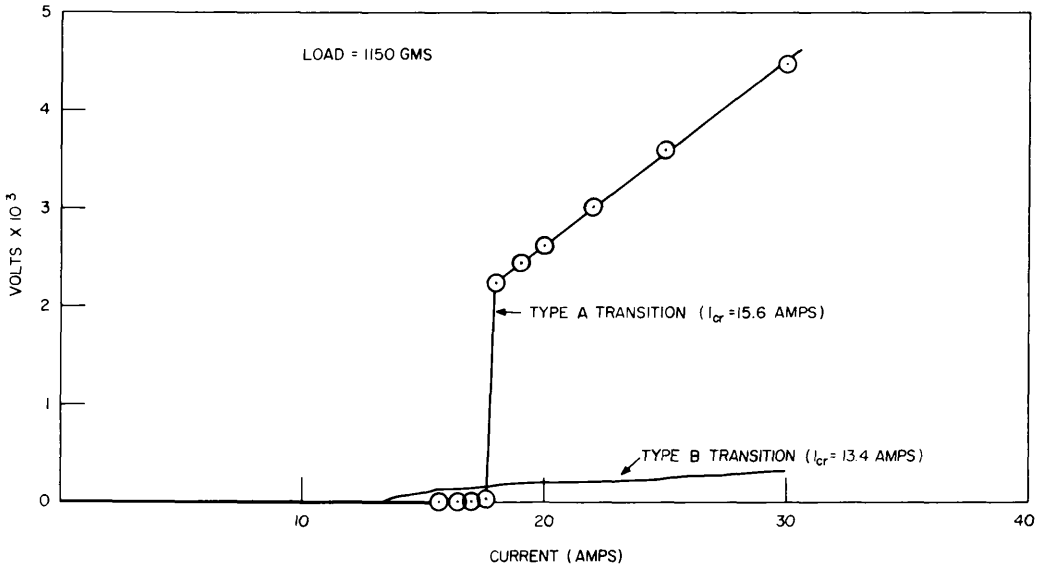

Fig. 14 - Voltage-current characteristics of type A and type B for which the critical currents are comparable

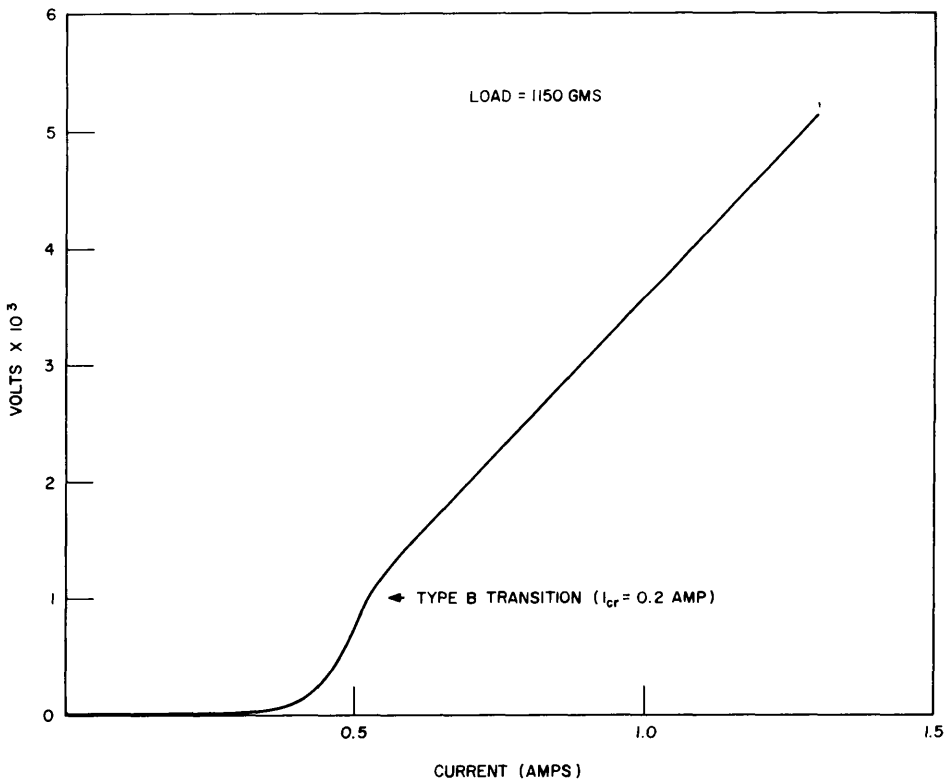

Fig. 15 - A typical type-B characteristic

The second property is the symmetry of the voltage-current characteristic of the contact, the critical current being independent of the direction of the applied current.

SUMMARY

The properties of superconducting lead pressure contacts have been studied for the purpose of designing a superconducting switch. Generally, the critical current can be increased by increasing the load, decreasing the temperature, or roughening the contact surfaces. In addition, highly oxidized contacts have a reduced critical temperature and a correspondingly reduced critical current. In practically every experiment there are critical current jumps from higher to lower values as the load increases. This is believed to be due to coalescence of the superconducting contact regions. If after reaching the critical current of a contact pair the current is increased further, a repeat critical-current measurement shows a larger critical current which is probably due to the formation of a metallic bridge caused by Joule heating. The scatter of the critical current at a given load can be considerable and limits the reliable design current capacity of a switch.

The voltage-current characteristic exhibits two types of transition, abrupt and gradual, and a nonohmic linear region. The characteristic is symmetrical with respect to the applied current.

Present knowledge indicates that a practical switch would utilize clean, roughened contacts, low temperatures, application of a high-current pulse before use, and paralleling of several contact pairs to average the scatter of the critical current.

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13. ABSTRACT

The electrical properties of pressure contacts between superconductors is being investigated to obtain information needed for the design of high-current superconducting switches. It has been concluded from the study of pure lead contacts that a practical switch would utilize clean, roughened surfaces operating under a large mechanical load and at reduced temperatures. The current capacity, as well as the reliability, of the switch can be improved by applying a high-current pulse before use or by paralleling contacts. The voltage-current characteristic exhibits two types of transition differentiated by their abruptness, a nonohmic linear region, and is symmetrical with respect to the current direction.

Generally, the critical current can be increased by increasing the load, decreasing the temperature, or roughening the contact surfaces. In addition, highly oxidized contacts have a reduced critical temperature and a correspondingly reduced critical current.

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