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SUMMARY

An experimental investigation was performed to determine the effect of tension on the critical current of niobium-zirconium (NbZr) wire and niobium-tin (Nb_3Sn) ribbon at liquid-helium temperature, 4.2° K. The critical currents of the Nb_3Sn samples were measured at 4.14 teslas from zero tension to the breaking point. The critical currents of the NbZr samples were measured at zero magnetic field from zero tension to the breaking point. Critical current characteristics were investigated with the Nb_3Sn sample length both parallel and transverse to the magnetic field. The experimental samples consisted of commercially available NbZr wire and Nb_3Sn vapor deposited on stainless steel ribbon.

The experimental procedure was to increase the stress by a discrete amount and then increase the current until the sample made a transition to the normal state. Copper-plated Nb_3Sn reached a maximum in critical current density at low values of stress. A maximum in the curve of critical current density against stress was observed when the ribbon was oriented transversely to the magnetic field with the field perpendicular to the ribbon surface. The maximum was typically 20 to 44 percent higher than the critical current density of the initially unstressed ribbon. The critical current density of all the other samples was nearly constant up to a value of stress slightly below the breaking point and then dropped off sharply. For all the samples tested, the changes in the critical current density with tension were irreversible.

INTRODUCTION

Since 1961, when Kunzler and his associates first announced their observation of superconductivity in a high magnetic field for niobium-tin (Nb_3Sn) (ref. 1), a considerable amount of work has been done to utilize the high-field superconductors in the fabrication of magnets. As the technology of magnet building has advanced, the field intensity and working volume have correspondingly increased. Since the hoop stress in the conductor of a magnet is a function of the current, the magnetic field, the diameter of the turn, any effect of stress on the critical current becomes important. The critical current is determined experimentally as the current which causes a transition to the normal state at a specific magnetic field. Investigations of the mechanical properties of niobium-zirconium (NbZr) and Nb_3Sn are reported in references 2 and 3. The effect of tensile stress on the superconducting properties of Nb_3Sn-core wire (with a Nb sheath surrounding the powder core) is reported in reference 4.

In an effort to obtain an insight into critical current degradation caused by stress in some of the widely used magnetic materials, an experimental study was initiated. The critical currents of the NbZr wire samples were measured at zero magnetic field from zero tension to the breaking point. The critical currents of the Nb_3Sn samples were measured at a magnetic field of 4.14 teslas from zero tension to the breaking point. (The magnetic field was needed to cause a transition of the Nb_3Sn samples to the normal state with the available current supply.) In some cases when the samples could not be returned to the normal state, even in a magnetic field, it was necessary to reduce their cross-sectional area by cutting them in half lengthwise.

Experiments were performed with the sample length oriented both transversely and parallel to the magnetic field. In the transverse tests of the ribbon samples, both orientations of the ribbon plane with respect to the magnetic field were investigated. The NbZr experimental samples consisted of commercially available 2.54×10^{-4}-meter-diameter, copper-plated Nb-0.25Zr and Nb-0.33Zr wire. The ribbon samples were Nb_3Sn vapor deposited on stainless steel ribbon as described in reference 3. The sample thickness of both the silver- and the copper-plated ribbon ranged from 0.736×10^{-4} to 1.30×10^{-4} meter, and the width ranged from 0.920×10^{-3} to 2.33×10^{-3} meter.

APPARATUS AND TESTS

All the tests were performed in a 5.0-tesla, 5.08-centimeter-bore superconducting solenoid which has a uniformity corresponding to a variation in the field of less than 1 percent within a 2.54-centimeter-diameter spherical volume. The magnet was calibrated by using a rotating-coil gaussmeter with an accuracy to within 0.001 of the full-scale reading. During experimental runs, the magnetic field was monitored by measuring the potential drop across a shunt in series with the magnet.

The device used to apply tension and to provide the high current contacts to the superconducting samples in the bore of the 5.08-centimeter-diameter magnet is shown in figures 1 and 2. The device, including the magnet, was submerged in liquid helium.

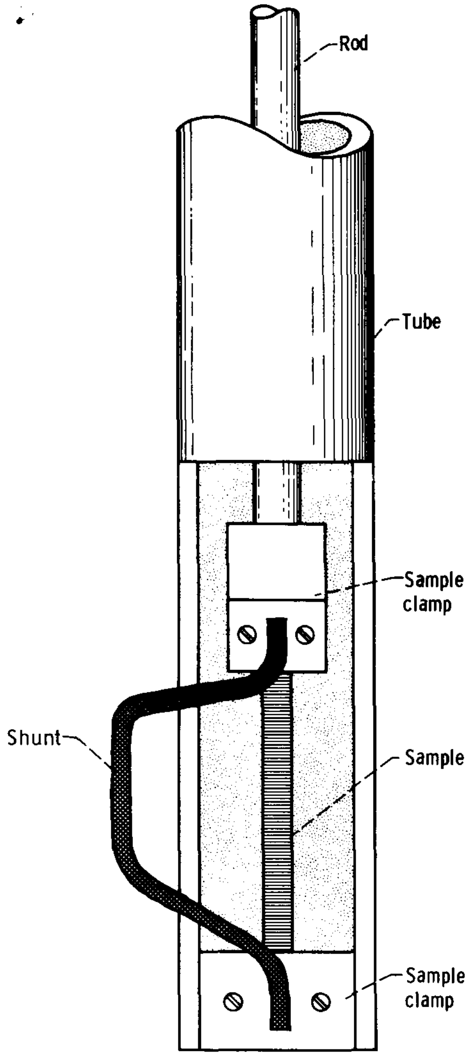


Figure 1. - Longitudinal tension device.

Two different devices were used since it was intended to apply tension to samples when they were both parallel and transverse to the magnetic field. Furthermore, two variations of the horizontal tension device were necessary to investigate both possible transverse orientations of the ribbon samples; the ribbon could be oriented so that the magnetic-field vector was either in the plane of the ribbon or perpendicular to it.

Figure 1 shows the device used to apply tension to the samples parallel to the magnetic field. One end of the sample is clamped to the end of the tube, which in turn is bolted to the top of the magnet Dewar. The other end of the sample is clamped to the rod, through which tension can be applied to the sample from outside the Dewar. Current leads are soldered to the sample clamps, and the samples are shunted electrically by a number 20 copper wire which is also soldered to both sample clamps. A pair of potential leads is soldered to the shunt for the purpose of measuring the shunt current.

The device used to apply tension to the samples perpendicular to the magnetic field is shown in figure 2. Here again the mechanism for applying tension to the sample is a rod with a concentric tube. The longitudinal force is converted to a transverse force by a cone on the end of the rod which rides between a pair of wheels and axles. The wheels and axles are mounted on a pair of opposing lever arms between which the sample is clamped. An upward movement of the rod spreads the lever arms apart and thus applies tension to the sample. The mechanical advantage of the complete mechanism at ambient temperature was determined by, first, measuring the change in resistance of a stainless steel ribbon as a function of tension, and second, stressing the same ribbon with the transverse tension device and then determining the resistance variation with the applied force. The resulting curves of resistance against tension and resistance against applied force were both linear. The ratio of the slopes of the two curves is the desired mechanical advantage; its value was 1.63. (It was assumed that the mechanical advantage of the mechanism remained constant when the mechanism was placed in liquid helium.) Two pairs of lever arms were used in the experiment, each pair corresponding to one of the two ribbon orientations tested. Again current leads were sold-

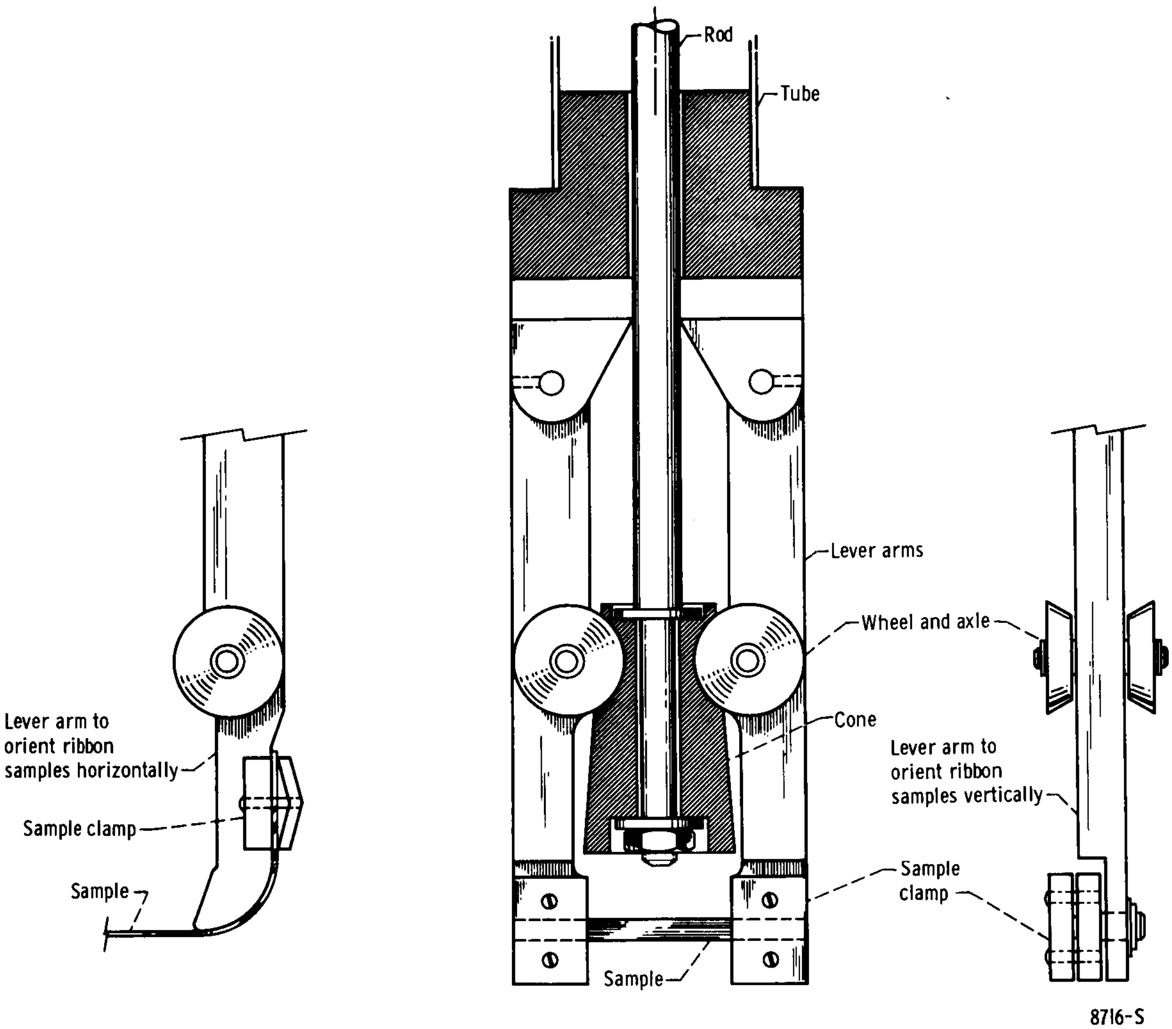


Figure 2. - Transverse tension device.

ered to the sample clamps, and the samples were shunted electrically by a number 20 copper wire that was also soldered to both sample clamps.

Figure 3 shows the apparatus used to apply external force to the rods in both of the tension devices previously described (figs. 1 and 2). This apparatus consisted of a manual hydraulic loader, a hydraulic cylinder, and a strain-gage load cell. The hydraulic loader and the associated valve system were connected so that the hydraulic cylinder could be driven in either direction or held at any specific point. The load cell was mounted between the hydraulic cylinder shaft and the force application rod. In an experimental run, the tension in the sample was obtained from the load cell output. For longitudinal tension runs, the load cell indicated the force on the sample directly. When the transverse tension device was used, the values of force (indicated by the load cell) were multiplied by the mechanical advantage of the device.

Critical current was measured in the same manner for all the different sample ori-

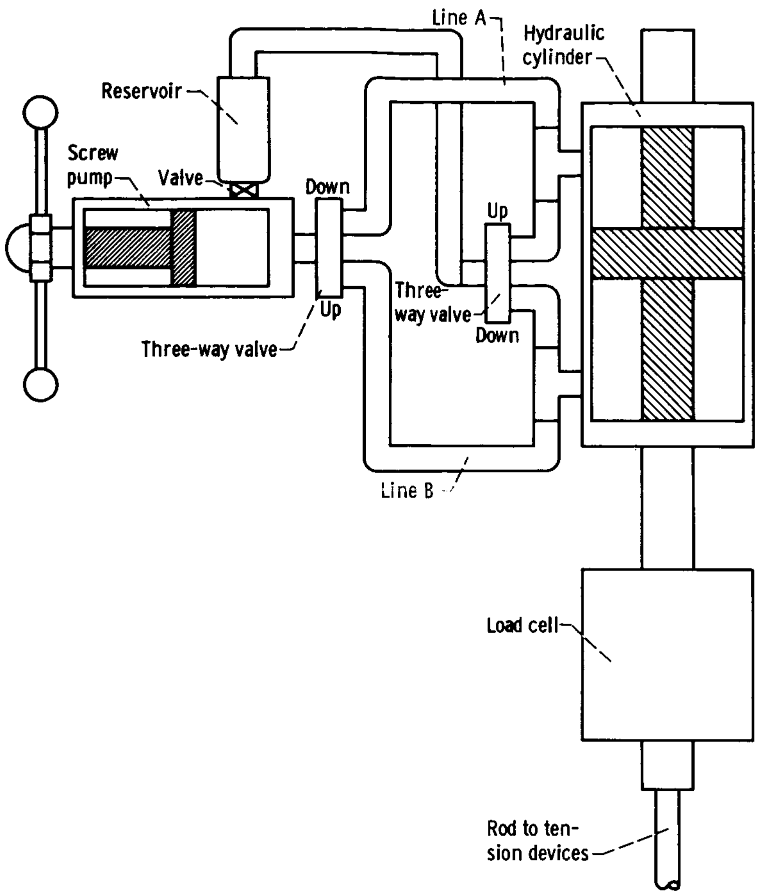


Figure 3. - Hydraulic system. Three-way valves are marked to denote direction hydraulic cylinder will move if line A or B is open.

entations investigated. Current shunts were provided to prevent damage to the sample during the superconducting to normal transition. The necessary shunt was one whose resistance was much greater than the resistance of the current contacts to the superconducting sample so that almost all the current would go inititally through the sample. In addition, the resistance of the shunt had to be much less than the normal resistance of the sample so that the current would be transferred to the shunt and not burn out the sample when a transition from the superconducting to the normal state occurred. The shunt was also used to measure the critical current indirectly. By monitoring the shunt voltage as a function of the total current to the sample and shunt, the normal transition of the sample could be observed as a sharp increase in the shunt voltage. The sample critical current was then determined by subtracting the shunt current from the total current at the transition point. The shunt current was determined from the shunt voltage since the shunt resistance was known.

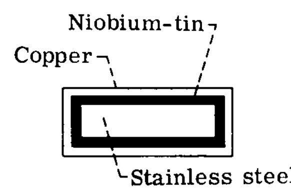
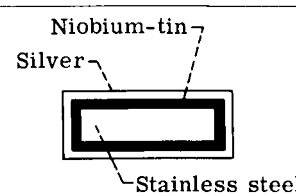
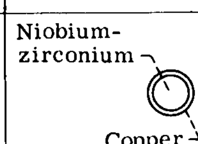
Frequently, several measurements of the critical current were taken at each value of stress as the stress was increased from zero to the breaking point. When the critical current varied with the application of stress, the samples were investigated to determine if reducing the stress would return the critical current to the values previously measured at that stress level. Two X, Y-plots were made during a typical run; they were load cell output against strain and shunt voltage against total current.

The values of critical current density were calculated on the basis of the total cross-sectional area of the unstressed sample. The tensile stress values were calculated on the basis of the cross-sectional area of the substrate only in the Nb_3Sn ribbon samples and on the basis of the total cross section for the NbZr samples.

RESULTS AND DISCUSSION

For the purpose of discussion, the presentation of results is divided between the two major types of samples, Nb_3Sn and NbZr. The discussion of Nb_3Sn ribbon samples is further divided for each of the three orientations: ribbon transverse to the magnetic field with the ribbon plane perpendicular to the magnetic-field direction, ribbon transverse to the magnetic field with the ribbon plane parallel to the magnetic-field direction, and ribbon length parallel to the magnetic-field direction. End-effect considerations and ulti-

TABLE I. - EXPERIMENTAL SAMPLE PARAMETERS

Sample	Width or diameter, m	Total thickness, m	Substrate thickness, m	Material description	Cross Section
1	1.18×10^{-3}	7.36×10^{-5}	4.57×10^{-5}	Niobium-tin (Nb_3Sn) vapor deposited on stainless steel ribbon, copper plated	
2	1.04				
3	1.38				
4	2.21				
5	2.21				
6	2.21				
7	0.922				
8	0.920				
9	1.71				
10	1.34×10^{-3}	0.130×10^{-3}	6.35×10^{-5}	Niobium-tin (Nb_3Sn) vapor deposited on stainless steel ribbon, silver plated	
11	1.14	117			
12	1.12	.117			
13	2.33	.130			
14	2.33	.130			
15	2.33	.130			
16	2.33	.130			
17	2.54×10^{-4}	----------	---------	Niobium-0.25 zirconium wire, copper plated	
18	2.54	----------	---------	Niobium-0.33 zirconium wire, copper plated	

mate strengths of the sample materials at both ambient temperature and at 4.2° K are presented. The sample parameters and schematic representations of the sample cross-sectional areas appear in table I. The most pronounced effect was observed when the Nb_3Sn ribbon samples with copper plating were oriented transversely to the magnetic field with the field perpendicular to the ribbon surface. Typical curves are shown in figure 4. Note that, as the stress increases, the critical current density initially increases to a value as much as 20 to 44 percent above the critical current density of the unstressed samples. Further increases in the stress cause the critical current density to decrease well below the critical current density of the unstressed sample, and finally the sample becomes entirely resistive just before it reaches the breaking point. The silver-plated Nb_3Sn ribbon samples (fig. 5) did not have a pronounced maximum at low values of stress. For several samples at points in the critical-current-density - stress curve, the stress was reduced and subsequently increased again. The critical currents that were measured before the stress was reduced and those measured after it was re-

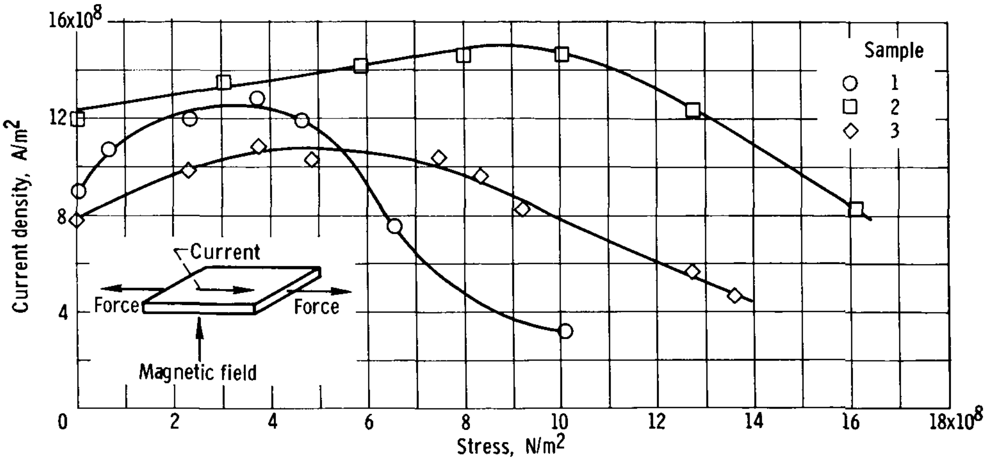


Figure 4. - Effect of stress on critical current density of copper-plated niobium-tin ribbon oriented with magnetic field perpendicular to current and plane of ribbon.

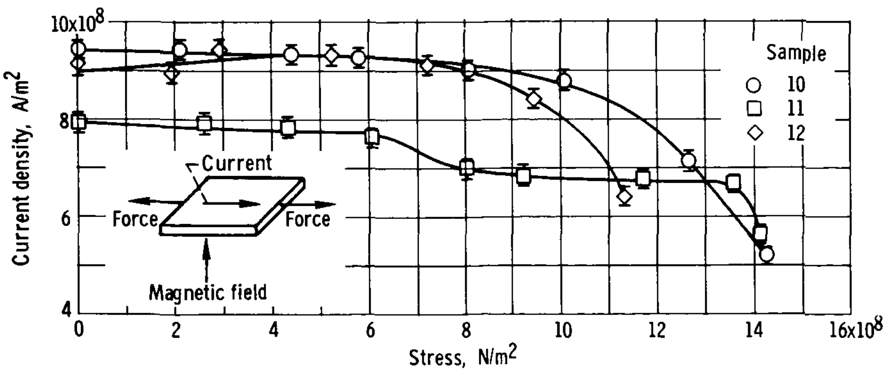


Figure 5. - Effect of stress on critical current density of silver-plated niobium-tin ribbon oriented with magnetic field perpendicular to current and plane of ribbon.

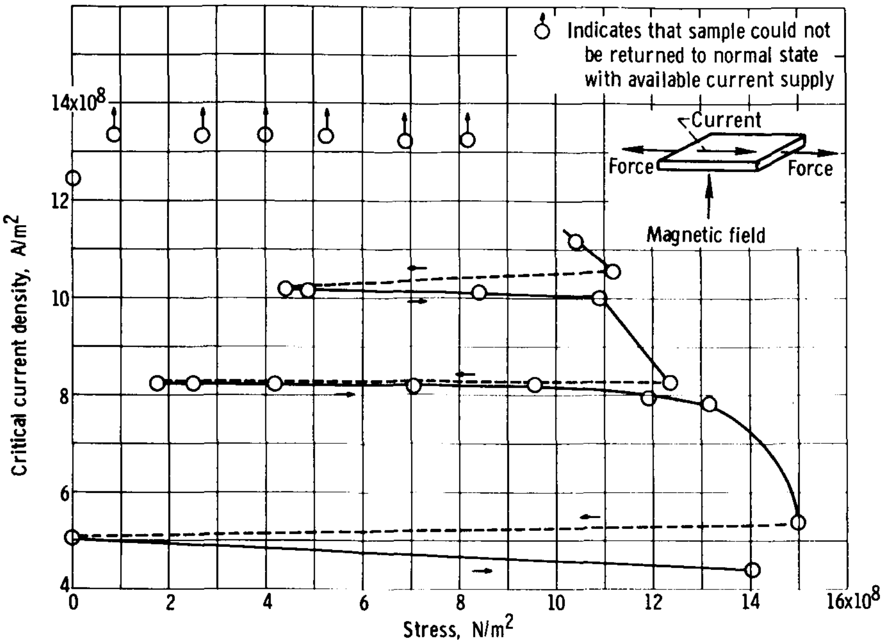


Figure 6. - Effect of stress on critical current density of copper-plated niobium-tin ribbon oriented with magnetic field perpendicular to current and plane of ribbon.

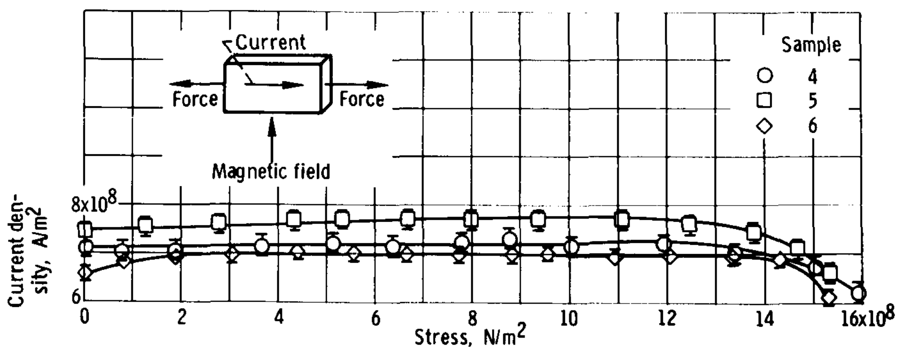


Figure 7. - Effect of stress on critical current density of copper-plated niobium-tin ribbon oriented with magnetic field perpendicular to current in plane of ribbon.

applied differed only slightly. Figure 6 shows a typical result of this study in the region of high-stress values. The same effect was observed also in the region of low-stress values.

The results reported in reference 4 are qualitatively similar to those obtained in this experiment; increases in critical current density with applied stress were observed up to some level of stress where the critical current density decreased abruptly. Reference 4 reported that in the region of low values of applied stress, when the stress was removed, the critical current densities returned to the level measured prior to stressing. This differs from the results obtained in this experiment, where the critical current density remained relatively constant when the applied stress was decreased to zero. Figures 7 and 8 show typical curves of critical current density against stress for Nb_3Sn

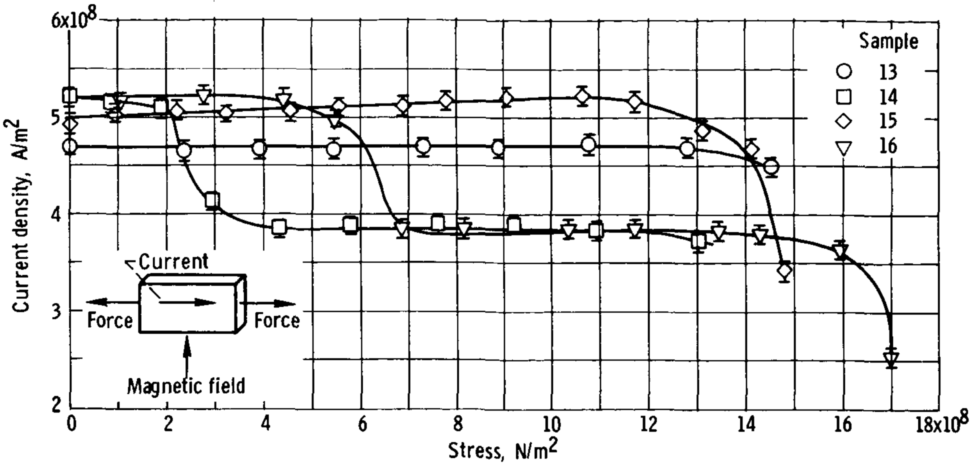


Figure 8. - Effect of stress on critical current density of silver-plated niobium-tin ribbon oriented with magnetic field perpendicular to current in plane of ribbon.

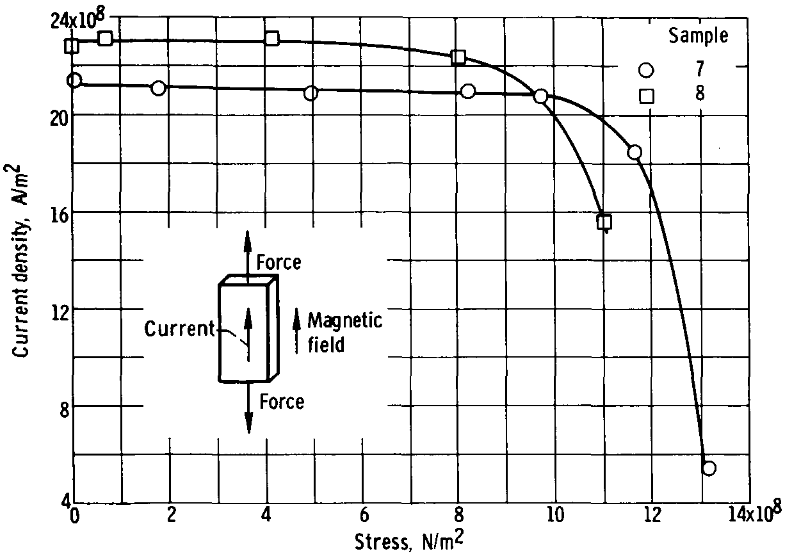


Figure 9. - Effect of stress on critical current density of copper-plated niobium-tin ribbon oriented with magnetic field parallel to current and ribbon.

ribbon samples, copper- and silver-plated, respectively, oriented transversely to the magnetic field with the field parallel to the plane of the ribbon. The critical current density as a function of stress was relatively constant for both types of platings, with the exception of some silver-plated samples that exhibited an abrupt drop in critical current density at low values of stress (fig. 8, samples 14 and 16). The drop was about 25 percent of the zero-stress critical current density. After the initial decrease, the critical current density remained constant with further increases in stress until just before the breaking point. The critical current density of the copper-plated ribbon increased slightly with stress. Generally the increase was less than 5 percent. With all the samples, the current density dropped off sharply and the sample became resistive just before

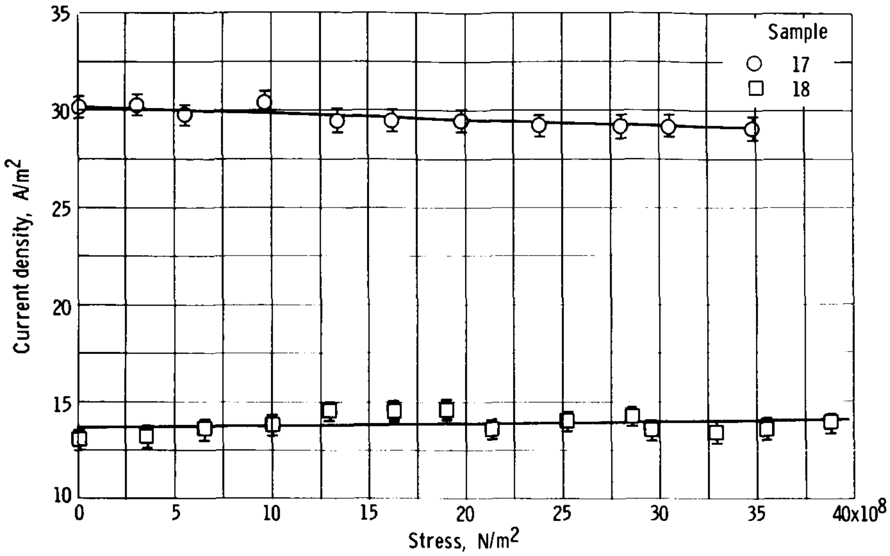


Figure 10. - Effect of stress on critical current density of niobium-zirconium wire.

the breaking point.

Figure 9 shows results for Nb_3Sn ribbon samples oriented with their length parallel to the direction of the magnetic field. Again the critical current density was relatively constant with respect to changes in the stress.

Since the NbZr wire could be returned to the normal state without applying a magnetic field, it was studied at zero magnetic field. Figure 10 shows typical curves for both Nb-0.25Zr and Nb-0.33Zr. Both types of samples exhibited negligible variation in critical current density until just prior to the breaking point, when the samples became resistive.

Two attempts were made to ensure that the changes in critical current density were not due to changes in the resistance of the current contacts. The contact resistance was measured during typical runs, and no correlation with changes in critical current was found. In addition, remounting the sample after critical current degradation was observed did not result in any critical current change.

End effects and the effect of splitting the ribbon in order to return the sample to the normal state with the available current supply must be taken into consideration also. Either clamping of the samples or misalinements of the samples in the clamp could cause a compressive or shear stress in them, which might affect the critical current density. The region of the sample adjacent to the clamps, which is under the combined compressive, shear, and applied tensile stress, could be the first to be returned to the normal state. This effect is contrary to the observation that unshunted samples generally burn out near the center. In the transverse orientation with the ribbon plane perpendicular to the magnetic-field direction, the clamps are oriented so that the ribbon adjacent to the clamp is parallel to the magnetic field. Since the critical current density is greater in the longitudinal orientation, any clamping effects tend to be minimized. Where reduction of the cross-sectional area of the samples was necessary to return them to the normal state, an additional shear stress was introduced when the samples were cut in half lengthwise. Reducing the cross-sectional area was necessary when the ribbon samples were oriented either longitudinal to the field direction or transverse with the ribbon plane perpendicular to the field direction. Splitting the ribbons also resulted in a change in geometry in that, after they were split, the superconducting material of the sample was no longer surrounded by either copper or silver shunting material.

These findings can be applied to superconducting magnet construction. The stress that can be sustained by unreinforced magnet windings without current degradation is limited. In magnets that have combinations of field intensity, current levels, and geometry resulting in forces large enough to cause current degradation, additional structural material will become necessary. In those samples where critical current enhancement results from increasing stress, magnets wound from these materials might be designed to use this characteristic to advantage. The abrupt decrease in the critical current density at low values of stress of the silver-plated ribbon samples indicates that the designer should be cautious in using this material in magnet applications where high axial fields are present.

The ultimate strengths of Nb_3Sn ribbon and NbZr wire were measured at 300° and 4.2° K. As expected, the ultimate strengths of both materials increased at the lower temperature. The ultimate strength of the Nb_3Sn ribbon increased from 10.6×10^{8} to 12.5×10^{8} newtons per square meter. Similarly, the ultimate strength of NbZr wire increased from 20.8×10^{8} to 55.0×10^{8} newtons per square meter.

CONCLUDING REMARKS

The critical current density of several commercial superconductors was affected by tensile stress. Copper-plated niobium-tin ribbon exhibited a maximum in critical current density at low values of stress when the ribbon was oriented transversely to the magnetic field with the field perpendicular to the ribbon surface. The maximum typically had a value of 20 to 44 percent of the initially unstressed critical current density. For all the samples tested, changes in the critical current density were irreversible. In high-field, large-bore magnets, critical current degradation caused by stress will be a significant design factor.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 8, 1966,
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