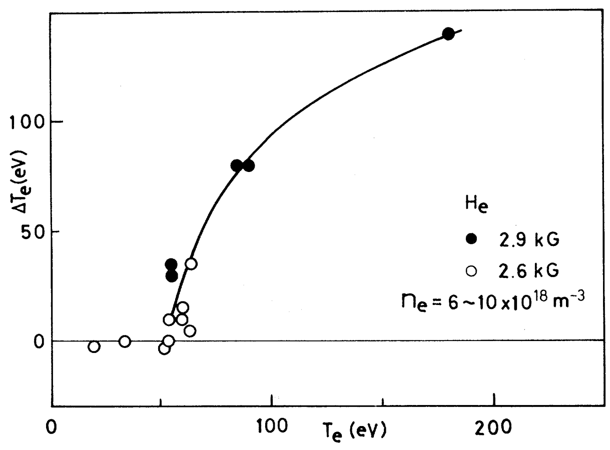

FIG. 4. Temperature increments of the electron vs background electron temperature.

of neutral particles and the excitation of the kinetic Alfvén wave becomes difficult, and presumably there are no significant heatings. These facts are in good agreement with the theory.[1]

Another possible and important mechanism for plasma heating is a nonlinear process[8] for the kinetic Alfvén wave. The efficient heating of the plasma and the enhancement of the loading resistance (Fig. 2) may be attributed to the nonlinear process. A further experiment is necessary and under preparation to give clear account for this process.

In conclusion, it has been shown that the shear Alfvén wave is excited in the toroidal plasma and is effective to heat the entire plasma. The remaining problem is to investigate the decay of the temperatures during the rf pulse.

The authors wish to thank Dr. A. Hasegawa for his detailed discussions and members of Heliotron group for their discussions and assistance in the experiment.

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Plastic Deformation of Free-Standing Crystals of hcp ^{4}He

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(Received 8 August 1977)

A method has been developed for producing free-standing crystals of hcp ^{4}He. Stress-strain relations have been measured for such crystals plastically deformed under conditions of unconstrained shear. An upper bound for the flow stress of 5×10^4 dyn/cm^2 is determined. Comparison is made with experiments on constrained crystals.

We have studied the plastic properties of solid ^{4}He and report the first measurements of stress-strain relations for single crystals deformed under conditions of uniaxial stress, i.e., unconstrained shear. These experiments are aimed at investigating the migration and generation of dislocations and point defects in solid helium, which in turn is motivated by the possibility of quantum effects in the motions of these defects. It has been pointed out[1] that point defects in solid helium may exist as delocalized excitations that can move practically freely through the crystal. In addition, dislocations, and particularly kinks on dislocations, may be treated in a similar fashion.[2] One might expect, therefore, that the response of such a dislocation to an applied stress may be much larger than in a classical solid.

Several investigations[3-7] of plastic deformation in solid ^{4}He have been reported in recent years. All of these experiments have involved measurements of the force required to displace a solid object imbedded in the solid helium, which filled the sample cell. Keshishev, Mezhov-Deglin, and Shal'nikov[4] used a glass rod displaced by a magnetic yoke, Suzuki[5,7] has employed a steel ball or a brass rod pulled by a thin wire, while Tsymbalenko[6] has used two metal plates attracted by a large electrical-potential difference applied between them. While these experiments have yielded interesting results, they all suffer from the following complications. Firstly, any displacement of the object requires the transport of solid helium from one side of the object to the other. It is not clear that this is accomplished by the displacement and generation of dislocations alone, or if other processes, such as local melting, for example, are also involved. Secondly, because of the very complicated flow pattern around the moving object, neither the conventional stress nor the corresponding strain can be directly determined from the force-displacement measurements. Finally, since the solid helium is constrained by the rigid walls of the container, movement of the object may require the operation of additional slip systems which would not be activated if the solid were unconstrained and free to shear.

The present experiment was designed to produce plastic deformation of solid helium under conditions resembling as closely as possible those conventionally used in the case of ordinary solids. Since the gross features of the deformation appear to be very similar to those of classical solids, such an experiment is essential if the detailed characteristics of point defect and dislocation motion in solid helium are to be examined. The experiment involved the production of a crystal of solid helium which could be strained along one direction by the movement of a flat piston, but which was unconstrained and free to shear in the other two directions. This obviously requires that the crystal be surrounded by a fluid medium which does not resist shear. Since the only fluid which can exist in contact with solid helium is liquid helium, this was accomplished by the imposition of a temperature gradient to melt a thin layer of solid on four sides of the crystal. In order to compare our results with those of previous studies, we have also conducted experiments on crystals constrained by the walls of the container.

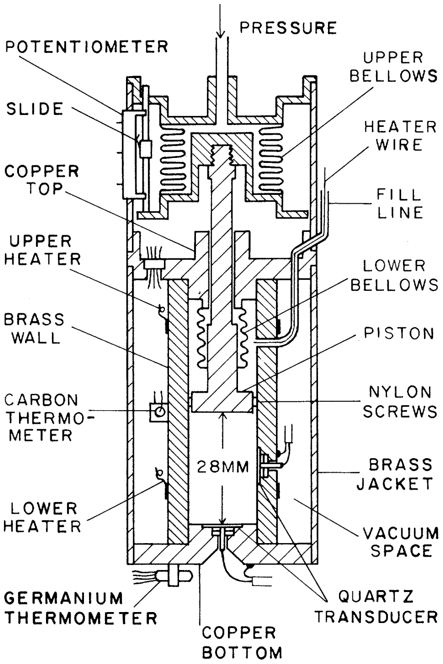

FIG. 1. Sample cell with movable piston.

The apparatus is shown in Fig. 1. The freezing cell is square in cross section with a copper top and bottom, and brass side walls. A copper piston passes through the top of the cell using a bellows as a flexible pressure seal. The cell is surrounded by a brass jacket enclosing a vacuum space, which thermally insulates the side walls from the pumped helium bath. The apparatus shown in the diagram is contained inside a can which may be filled with liquid helium from the main bath through a needle valve.

Crystals of solid helium were grown at a constant pressure P_0 of 32.5 atm, which corresponds to a molar volume[8] of 20.5 cm^3/mole. The fill line was kept open throughout the experiment by a resistance heater wire passing down the center of the stainless-steel capillary.

To begin growing a crystal, the bath helium was allowed to fall to a level about half way down the cell, and current was supplied to the upper heater wound on the cell wall. Since the top was no longer in contact with the bath, a temperature gradient could be created of approximately 50 mK down the length of the cell. By slowing reducing the bath temperature from 1.85 to 1.75 K, a crystal was grown up from the cell bottom. Two $\frac{3}{8}$-in. 10-MHz X-cut coaxially plated quartz transducers were mounted in recesses in the cell walls. Crystal growth was monitored by the ultrasonic echoes from the solid-liquid interface that were received by the bottom transducer. When the interface reached the side transducer, two sets of echoes corresponding to propagation across the cell through solid and through liquid could be seen simultaneously, indicating that the interface was quite flat. After $1\frac{1}{2}$–2 h when the solid reached the piston, the upper heater was turned off and the needle valve opened to refill the can and surround the cell with 1.75-K liquid helium.

An attempt was made to determine the angle θ between the crystallographic c axis and the vertical axis of the cell from measurements of the longitudinal velocity of sound and the known elastic constants of hcp ^{4}He.[9,10] Unfortunately, the velocity of sound is double valued for $\theta > 40°$, and it was not always possible to resolve this ambiguity. Out of twelve crystals investigated in detail, velocities in the vertical direction ranged between 560 and 500 m/sec, corresponding to θ between 20° and 70°. Since in almost all cases there was a measurable difference between the velocities in the two directions, and no spurious echoes were seen, it is felt that single crystals were grown. Attenuation values at 10 MHz ranged from 2 to 4 dB/cm, which are comparable to other measurements on single crystals.[11]

With solid filling the cell, the bath temperature was slowly raised to 1.80 K. Current was supplied to the upper heater to melt the solid near the walls above the piston, and ensure that the pressure on the solid in the cell was equal to the pressure P_0 measured outside the cryostat. If an unconstrained crystal was to be studied, current was then supplied to the lower heater to melt a thin layer of solid around the walls below the piston. This was indicated by the onset of uncontrolled "ringing" of the side transducer and the disappearance of the side echoes. Typically this required a dissipation of approximately 50 mW in each heater, producing a wall temperature of 1.87 K. Since the inside of the lower bellows was filled with bath helium, and the piston was thermally insulated from the side walls by four nylon screw heads, the piston and the bottom of the cell remained at the bath temperature of 1.80 K. By way of reference, the melting temperature of solid helium under 32.5 atm is 1.85 K.[8] Therefore, a free-standing helium crystal existed between the piston and the cell bottom, as evidenced by the fact that there was no degradation of the echoes received by the bottom transducer.

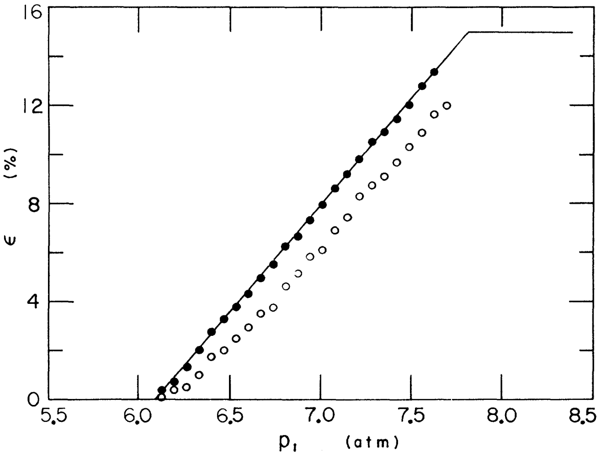

FIG. 2. Piston displacement as a function of applied pressure. The calibration with the sample cell filled with liquid helium is shown by the solid line. The open circles are for solid helium constrained by the cell walls. The closed circles are for a free-standing helium crystal.

After the temperatures had been stabilized, the crystal was deformed by slowly increasing the pressure P_1 of helium gas supplied to the upper bellows. The displacement of the piston was measured using a $10\text{-k}\Omega$ "cermet" potentiometer. The resistive element was rigidly attached to the upper bellows housing and the slide attached to a shaft fixed to the lower flange. Resistance readings were initially calibrated against the piston movement using the arrival times of echoes from the bottom transducer at 2.0 K with liquid helium under 32.5 atm filling the cell. Relative positions of the piston could be measured with an accuracy of ±0.05 mm.

The resulting calibration curve is shown as the solid line in Fig. 2. The piston could move a total of 4.3 mm, producing a maximum deformation of 15%. The combined spring constant of the two bellows was approximately 2 kg/mm, and their cross sectional areas were such that with liquid in the cell, an initial P_1 of 6.1 atm was required to begin the downward movement of the piston.

Typical results are also shown in Fig. 2 for the deformation of an unconstrained and a constrained crystal, i.e., with and without melted sides, as a function of P_1. No significant dependence on orientation was noted for the crystals investigated to date. In all cases as the deformation proceeded, the attenuation of the ultrasonic echoes increased rapidly, and the echoes disappeared for deformations greater than about 2%.

For a given strain, the stress is proportional

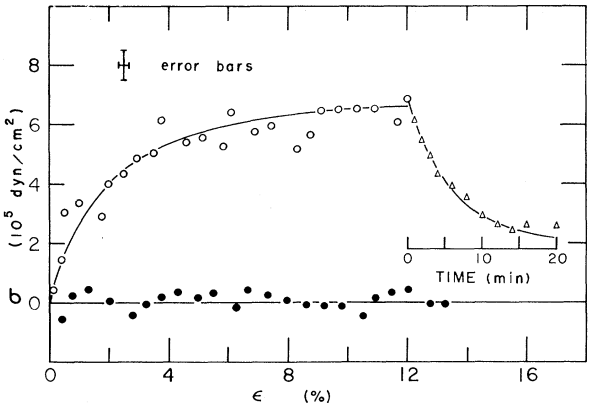

FIG. 3. Stress-strain relations for the constrained and unconstrained crystals of Fig. 2. The open triangles indicate the stress relaxation for the constrained crystal. The line through the triangles is an exponential decay with a time constant of 6 min. The line through the open circles has been hand drawn as a guide for the eye.

to the difference in the pressures P_1 required to produce that strain, with and without a solid under the piston. The proportionality constant equals the ratio of the area of the upper bellows to that of the piston, which is 2.8. The resulting stress-strain relations are shown in Fig. 3.

In the case of the constrained solid, the stress required for plastic deformation approaches a constant value of approximately 6×10^5 dyn/cm^2. While an exact quantitative comparison is not possible, this is the same order of magnitude that has been measured in other experiments. For example, Suzuki[7] finds that a force of about 3×10^5 dyn is required to displace a steel ball, 0.3 cm^2 in cross section through solid helium at 1.77 K and 32 atm. The present results, however, show no indication of the very large yield drop noted by Suzuki.[5,7]

The results shown in Fig. 3 were measured for a strain rate of approximately 0.01%/sec. After the constrained solid had been deformed by 12%, the pressure P_1 was kept constant and the time dependence of the stress was measured. The stress relaxed exponentially with a time constant of 6 min to a residual stress of 2×10^5 dyn/cm^2. Similar effects have been noted by Suzuki.[5,7]

The most striking result, however, is the large reduction in the flow stress that occurs when the helium crystal is unconstrained and free to deform in shear. We can only conclude that the stress is less than the uncertainty in the measurement, 5×10^4 dyn/cm^2, although the scatter of the data in Fig. 3 indicates that it may be considerably less than this value. Measurements were also carried out for an unconstrained crystal deformed at a strain rate of 0.1% sec. Again, the flow stress was found to be less than the uncertainty, i.e., less than 5×10^4 dyn/cm^2. The results also indicate that, contrary to what has been hypothesized by Suzuki,[5,7] there is no large Peierls stress for dislocation movement in hcp ^{4}He.

In conclusion, we have developed a method for studying the plastic properties of free-standing crystals of solid ^{4}He. While we have not established the detailed nature of the dislocation dynamics governing the deformation, we have found that the flow stress is at least an order of magnitude smaller than has been previously suspected. The experimental results also point out the importance of using unconstrained crystals in future studies of the plastic deformation of solid helium.

This research was supported by the National Science Foundation through the Materials Research Laboratory of Brown University and under Grant No. DMR75-14761. One of us (D.J.S.) wishes to acknowledge a fellowship from the National Research Council of Canada.

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