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Plastic Deformation of bcc ⁴He

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Measurements have been made of the stress-strain relations and the changes in ultrasonic attenuation during plastic deformation of free-standing and constrained crystals of bcc ⁴He. Comparison is made with measurements for hcp ⁴He. During plastic deformation, bcc crystals are found to behave much like a viscous liquid. The results suggest a large concentration of highly mobile vacancies in the bcc phase.

We report here the first studies of the plastic deformation of bcc solid ⁴He. While plastic deformation in solid helium has been the subject of several investigations,¹⁻⁷ these have all been confined to the hcp phase of ⁴He. Since the discovery of the bcc phase in 1961,⁸ many of its properties have been measured, including its specific heat,^{9,10} thermal conductivity,¹¹ and elastic constants.¹² However, the information to be gained from these measurements, especially with regard to the nature, concentration, and behavior of crystal defects, is severely limited by the small temperature range of about 50 mK over which the bcc phase exists. This is in contrast to solid ³He for which extensive specific-heat measurements,¹³ along with x-ray¹⁴ and NMR studies,¹⁵ have demonstrated that there is a much larger concentration of vacancies in the bcc phase than in the hcp phase. So far, the limited NMR data^{16,17} and specific-heat analysis¹² have been insufficient to show if this is also the case in solid ⁴He. If a large concentration of vacancies does exist in bcc ⁴He, one might expect this to be reflected in its behavior during plastic deformation.

In a previous report,⁷ we outlined a method for producing and deforming free-standing single

crystals of solid helium. We also pointed out the importance of using free-standing crystals for measurements of the stress-strain relations. In the present experiments, we have extended these investigations to the bcc phase of solid ⁴He, and have found significant, qualitative differences in the behaviors of the two phases.

The experimental apparatus has been described previously.⁷ A large ballast volume of 44 liters was added to the high-pressure system at room temperature to aid in maintaining a constant pressure during crystal growth and deformation. Crystals of bcc ⁴He were grown at a pressure of 27.6 atm, corresponding to a freezing temperature of 1.65 K and a molar volume of 21.0 cm³/mole,^{10,18} by slowly reducing the bath temperature from 1.67 to 1.63 K over the course of about $\frac{1}{2}$ h. In growing crystals from liquid He II, it was found that the heat leak due to the superfluid was sufficient to keep the fill line open without the use of the fill-line heater.

The completed crystal filled the sample cell, 16 mm×16 mm in cross section, and 28 mm between the cell bottom and the movable piston. Crystal growth and quality were monitored by ultrasonic waves (pulse-echo method) generated

by 10 MHz X-cut quartz transducers mounted in the cell bottom and in one side wall. The crystallographic orientation¹² could not be determined unambiguously from the two longitudinal-sound-velocity measurements; however, the anisotropy of the velocities and the regular echo patterns indicated that the solid probably formed as a single crystal. Among the twelve crystals investigated, attenuation values ranged from 1.5 to 2.5 dB/cm, which are somewhat less than those measured for 20.5-cm³/mole hcp crystals⁷ [hereafter referred to as hcp(I)]. Moreover, for bcc crystals, 3 to 4 times as many ultrasonic echoes could be detected as for hcp(I) crystals. This may indicate that solid grown from the superfluid forms a better bond to the transducer.

In order to produce an unconstrained crystal, use was made of the heaters incorporated in the cell⁷ to melt a layer of solid around the side walls. This melting was indicated by instability of the ultrasonic echoes and "ringing" of the side transducer, but in contrast to the case of hcp(I) crystals, the side echoes did not disappear completely. This strongly suggests that only a very thin layer was melted. Since the liquid layer thus formed was superfluid He II, it constituted a thermal short circuit to the cell bottom, and any further increase in heat supplied to the cell walls did not significantly raise the wall temperature, or increase the thickness of the liquid layer. The echoes received by the bottom transducer were essentially unchanged by this process.

To deform the resulting free-standing crystal,

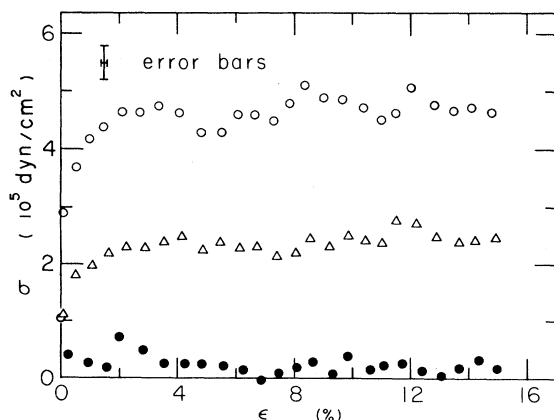


FIG. 1. Typical stress-strain relations for 21.0-cm³/mole bcc ⁴He. Solid circles, unconstrained crystal deformed at a strain rate of 0.06%/sec; open triangles, constrained crystal at 0.01%/sec; open circles, constrained crystal at 0.08%/sec.

the pressure P_1 of helium gas supplied to the driving bellows⁷ was increased linearly in time in order to push the piston down at an approximately constant rate. The piston displacement, and hence the strain ϵ , was measured continuously up to the maximum value of 15% by the change in resistance of a 10-k Ω potentiometer attached to the driving bellows. In addition, any change in the attenuation of the echoes received by the bottom transducer was monitored during the deformation by an automatic attenuation read-out unit (Matec model AARA III). After each experiment, the solid was melted by raising the bath temperature to 1.67 K, and a calibration curve of ϵ vs P_1 , with liquid helium filling the cell, was obtained. By comparing the curves for solid and liquid, the stress σ exerted on the solid was determined as a function of ϵ .

A typical stress-strain curve for an unconstrained bcc crystal is shown by the solid circles in Fig. 1 for a strain rate of 0.06%/sec. The flow stress is very small, approximately $(3 \pm 1) \times 10^4$ dynes/cm². This is the same order of magnitude that was found for hcp(I) crystals. The results reported previously⁷ for these crystals, plus subsequent measurements at higher strain rates, are summarized in Fig. 2. There is an indication that the flow stress increases somewhat with increasing strain rates, but as far as the macroscopic stress-strain relation is concerned, there is no apparent difference between the two phases.

The changes in ultrasonic attenuation, however,

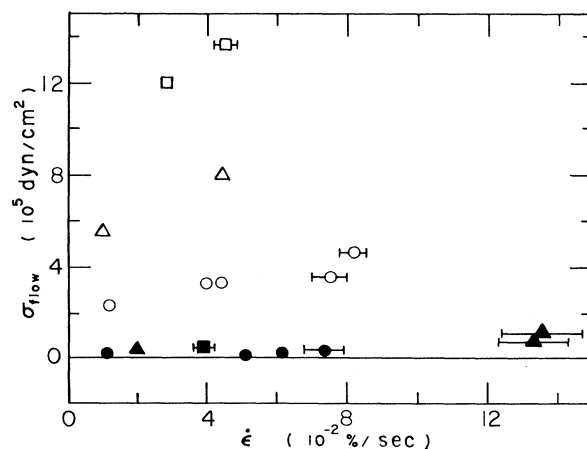


FIG. 2. The flow stress at various strain rates. Closed symbols indicate unconstrained crystals, and open symbols, constrained crystals. Circles, 21.0-cm³/mole bcc ⁴He; triangles, 20.5-cm³/mole hcp ⁴He; squares, 20.95-cm³/mole hcp ⁴He.

are dramatically different. For bcc crystals, the attenuation measured in the vertical direction, α_v , increased during deformation by at most 3.5 dB/cm. Moreover, most of this apparent increase is accounted for by purely geometrical effects. These are due to the piston reflecting surface becoming increasingly nonparallel to the bottom transducer as the piston descends, as determined from attenuation measurements at 1.67 K with liquid ^4He filling the cell. The apparent increase in attenuation due to this effect is 2 dB/cm, so that the actual increase in α_v for bcc crystals is at most 1.5 dB/cm, even for the highest strain rate investigated (0.08%/sec). This is in contrast to the case of hcp(I) crystals for which α_v increased by more than 7 dB/cm (the maximum that could be measured) within the first 1% of deformation, followed by the complete disappearance of the echoes as the deformation increased. Moreover, if the hcp crystals were allowed to anneal for $\frac{1}{2}$ h or more following deformation, the echoes, in some cases, reappeared, but with a different vertical velocity than for the undeformed solid, indicating recrystallization to a different orientation. Crystals of bcc ^4He showed no measurable changes in velocity during or after deformation.

In order to determine whether the relatively small change in attenuation was a property of the bcc phase, or whether it depended on the solid being in contact with superfluid liquid He II, rather than normal He I, several hcp crystals were grown from the superfluid just below the bcc phase.¹⁹ These crystals were grown at 1.43 K and 25.9 atm, corresponding to 20.95 cm³/mole¹⁸ [hereafter referred to as hcp(II)]. The flow stress for an unconstrained hcp(II) crystal is shown in Fig. 2. The behavior of α_v was essentially identical to that of hcp(I), with a rapid disappearance of the echoes at the onset of deformation.

Experiments were also performed for all three types of crystals without producing a liquid layer around the side walls. Since the solid is constrained by the walls of the cell, movement of the piston results in the transport of solid through the 0.8-mm-wide space between the piston and the cell wall. In this configuration, the attenuation, α_h , of the echoes received by the side transducer, which is located 13 mm above the cell bottom, could also be monitored. This allowed us to determine how far the effect of deformation on ultrasonic attenuation extends into the solid.

Typical results for the stress-strain (actually force-displacement) relations for constrained bcc crystals are shown in Fig. 1. The curves are qualitatively similar to those found for constrained hcp(I),⁷ with the stress approaching a constant value for deformations greater than about 2%. However, as indicated in Fig. 2, this stress is less for bcc crystals than for either hcp(I) or hcp(II), at any strain rate investigated. Upon deformation, constrained hcp crystals also displayed a large increase in the vertical attenuation, resulting in a disappearance of the echoes within the first 1% of deformation. In addition, the horizontal attenuation increased by 3 to 5 dB/cm. In contrast, constrained bcc crystals showed a small increase in α_v of less than 1.5 dB/cm, similar to the unconstrained case, and essentially no increase (less than 0.3 dB/cm) in α_h .

In view of these results, we offer the following hypothesis for the processes involved in plastic deformation of the two phases of solid ^4He . In the case of hcp ^4He , the results are consistent with a process of classical slip on crystal planes. For an unconstrained crystal, the stress is uniaxial, and slip takes place throughout the crystal. For a constrained solid, many slip systems must be activated to produce a complex flow pattern³ which can transport solid around the moving piston. This requires a larger flow stress than for an unconstrained crystal. Furthermore, the slip process extends down into the crystal, at least as far as the level of the horizontal transducer. In both the constrained and unconstrained cases, plastic deformation is accompanied by a large increase in the dislocation density, producing a large increase in the attenuation measured in the vertical direction. This increase in dislocation density may be large enough for the solid to recrystallize to a different orientation following deformation.

For bcc crystals, the fact that the change in α_v is essentially the same for both constrained and unconstrained crystals suggests that the deformation process is the same for both cases; furthermore, since there is essentially no increase in α_h , the deformation takes place only near the piston. This, combined with the fact that the increase in α_v is very small, indicates that bcc ^4He , undergoing plastic deformation, behaves more like a viscous liquid than an ordinary crystalline solid. This behavior could be explained by a large concentration of highly mobile vacancies in the bcc phase. Plastic deformation (and transport of matter) takes place by rapid

diffusion via these vacancies, and since there is little or no increase in dislocation density, there is also little increase in the attenuation.

In conclusion, we have investigated the plastic deformation of bcc solid ^4He , and we have found its behavior to be distinctly different from that of the hcp phase. The results are consistent with a process of rapid diffusion of matter in bcc crystals, possibly via a large concentration of highly mobile vacancies, although we cannot, at this point, determine if this process is classical or quantum mechanical in nature.

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Intrinsic Surface Phonons in Porous Glass

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Raman scattering and infrared reflectivity measurements have been performed on samples of porous Vycor glass. Three features in the spectra are due to intrinsic surface phonons. This identification is supported by a simple new theory for the surface.

Recently, there has been considerable interest in surfaces, particularly in their electronic properties. Very little attention has been given to surface vibrations, however, because it is virtually impossible to detect surface phonons in

most samples using conventional phonon-sensitive spectroscopic techniques. A promising method¹ of overcoming this problem is to perform low-energy electron-energy-loss spectroscopy on the surface. Measurements of this kind are scarce,