

Plastic Deformation of Alkali Halide Crystals at High Pressure: Work-Hardening Effects*

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The influence of hydrostatic pressure on the plastic deformation of alkali halide single crystals at large strain has been observed. The rates of work hardening in stages I and II are approximately independent of pressure in LiF, NaCl, and KCl, but both are doubled at 4.3 kbar in KI. In stage II the fractional increase of plastic flow stress at high pressure in an interrupted compression test, $\delta\sigma/\sigma$, is accounted for by the pressure-induced increase in elastic constants in all the alkali halides examined. Evidently, the strength in stage II is controlled by elastic interactions. The stress at the onset of stage III, σ_{III} , in the deformation of NaCl at 4.3 kbar is about half that at 1 atm; it is reduced slightly in KCl and is unchanged in KI. Deformation proceeds at lower stresses in stage III in NaCl and KCl under 4.3 kbar, and if compression at 1 atm in this stage is interrupted and reinitiated at 4.3 kbar, pronounced work softening is observed. The dependence of flow stress on pressure in stage III at constant structure, $(\delta\sigma/\sigma)_s$, is small and less than that expected from the pressure-induced change of elastic constants. The negative pressure dependence of σ_{III} and the small $(\delta\sigma/\sigma)_s$ in stage III may be explained in terms of thermally activated cross slip of screw dislocations when stacking faults on the primary slip plane cause a strong local dilation of the lattice.

INTRODUCTION

Alkali halide single crystals with the NaCl structure exhibit the three-stage stress-strain (σ - ϵ) curve shown schematically in Fig. 1. Stages I and II are approximately linear, with the rate of work hardening, $d\sigma/d\epsilon$, as much as ten times greater in stage II. Stage III exhibits a rate of work hardening which is smaller than in stage II and which decreases slowly with continuing strain. The onset of stage II is taken as the intersection of the linear extrapolations of stages I and II; stage III begins, by definition, when the σ - ϵ curve deviates by 1% strain from the linear extrapolation of stage II. We examine here the influence of hydrostatic pressure on the plastic deformation of several of the alkali halides in an attempt to identify the strength controlling mechanisms. Two types of experiments are conducted: (1) continuous σ - ϵ curves are recorded at 1 atm and 4.3 kbar, and (2) interrupted tests are performed in which the deformation of a crystal at pressure P_1 is halted, the pressure changed to P_2 , and the deformation then continued at P_2 , perhaps with a change of flow stress or rate of work hardening. Intercomparison of these two types of experiments enables one to determine the separate dependence of flow stress and dislocation structure on pressure after the method used by Cottrell and Stokes¹ in their experiments with temperature changes. The authors have previously reported results for the fractional change of flow stress with pressure in interrupted tests in stage I for annealed and radiation-hardened alkali halides²; interrupted tests here will be limited to stages II and III.

EXPERIMENTAL PROCEDURE

Plastic deformation of alkali halide single crystals at 4.3 kbar is achieved in the *minilester*, previously described,^{2,3} which permits uniaxial stress-strain compression testing of samples held under hydrostatic pressure. The uniaxial force is measured by a strain-gauge-type load cell. In the present work both a previously used load cell (L.C. #4)⁴ and a second load cell having similar properties (L.C. #6; 1 atm calibration = $1.8 \times 10^{-6}/N$) are used. The materials tested are LiF, NaCl, KCl, and KI. Compression samples are cleaved from large blocks themselves cleaved from annealed crystals by the Harshaw Chemical Company. Sample dimensions are usually about $1.3 \times 0.5 \times 0.4$ cm, which is approximately half the size of those previously used; for the compression rate used (0.009 cm/min), the compressive strain rate is $\sim 1 \times 10^{-4}/\text{sec}$. The ends of the samples are lubricated with 0.05-mm-thick sheets of Teflon to minimize the formation of cleavage cracks parallel to the compression direction. Except at very large strains, where they become catastrophic, these cracks have no effect on the σ - ϵ curve. After heavy deformation (~ 2 mm in a 12.7-mm-long sample) the sample ends remain parallel to within about 0.08 mm. Stress birefringence observations of lightly deformed samples indicate that slip occurs on both possible slip planes of one orthogonal $\{110\}$ $\langle 1\bar{1}0 \rangle$ set; the two oblique systems may operate simultaneously at low deformations in LiF. After heavy deformation, the specimens assume a shape characteristic of a predominance of slip on a single

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¹ A. H. Cottrell and R. J. Stokes, Proc. Roy. Soc. (London) **A233**, 17 (1955).

² L. A. Davis and R. B. Gordon, J. Appl. Phys. **39**, 3885 (1968).

³ R. B. Gordon and L. F. Mike, Rev. Sci. Instrum. **38**, 541 (1967).

⁴ An error in the 1 atm calibration of L.C. #4 has been detected. The load calibration of L.C. #4 noted in Ref. 2 is low by a factor of 1.4, i.e., it is $1.89 \times 10^{-6}/N$ rather than $1.35 \times 10^{-6}/N$. Consequently, the stresses calculated in Ref. 2 are too high by a factor of 1.4. However, the absolute value of the stress is not important in Ref. 2.

TABLE I. Work-hardening parameters (1 atm).

	σ_0 (bars)	$N_{\theta I}^a$	θ_I bars/u.s.s. ^b	$\frac{\epsilon_{II}}{\%}$ (shear)	$N_{\theta II}^a$	θ_{II} bars/u.s.s.	σ_{III} bars	$\frac{\epsilon_{III}-\epsilon_{II}}{\%}$ (shear)	K_s Mbar	θ_{II}/K_s $\times 10^3$	θ_I/K_s $\times 10^3$
LiF	7 \pm 1	10	120 \pm 10 ^a	10 \pm 3	1	1000 (4.3 kbar)	0.46	2.2	0.3
NaCl	3 \pm 1	12	170 \pm 50	5 \pm 2	4	550 \pm 30	90 \pm 10	15 \pm 5	0.15	3.7	1.1
KCl	4 \pm 1	5	280 \pm 40	3 \pm 2	6	340 \pm 40	45 \pm 8	11 \pm 3	0.10	3.4	2.8
KI	5 \pm 1	11	180 \pm 40	4 \pm 2	6	270 \pm 25	25 \pm 5	6 \pm 3	0.065	4.2	2.8

^a N = number of measurements averaged in computing slopes; $N_{\theta I}$ includes some samples studied previously (Ref. 2).

^b Bars/unit shear strain.

^c Limits are average deviation for θ_I and θ_{II} and maximum deviation for other parameters.

slip system, in agreement with the observations of Davidge and Pratt⁵ and Hesse⁶ on NaCl. To remove effects due to varying specimen geometry, the lengths of crystals whose σ - ϵ curves at 1 atm and 4.3 kbar are to be compared are carefully matched to within ± 0.02 mm and their areas, to within $\pm 4\%$.

RESULTS

Typical 1 atm, room-temperature σ - ϵ curves observed for LiF, NaCl, KCl, and KI are given in Fig. 2. The stress and strain are calculated as $\sigma_s = \sigma_c/2$ and $\epsilon_s = 2\epsilon_c = 2\Delta l/l_0$, where subscript s and c refer to shear and compression respectively. Work-hardening parameters are listed in Table I. A systematic decrease in θ_{II} , the slope of stage II, ($\epsilon_{III} - \epsilon_{II}$), the range of stage II, and σ_{III} is observed in the order of decreasing K_s , where $K_s = \{\frac{1}{2}(c_{11} - c_{12})/c_{44}\}^{1/2}$ is the stress-field elastic constant for a screw dislocation in the NaCl structure.⁷ The critical resolved shear stress, σ_0 , and ϵ_{II} , the range of stage I, are greatest in LiF while θ_I , the slope of stage I,

is smallest, but variation of these parameters in the other alkali halides does not appear systematic. The value of θ_{II} listed for LiF is obtained from one experiment at 4.3 kbar as, due to the intervention of cracking, stage II does not fully develop at 1 atm. It is probable that θ_{II} is comparable at 1 atm and 4.3 kbar in LiF. To account for differences in elastic properties, θ_I and θ_{II} may be divided by K_s . The ratio θ_{II}/K_s is roughly constant at $(3 \pm 1) \times 10^{-3}$; θ_I/K_s varies by a factor of 10.

The effect of 4.3-kbar pressure on the σ - ϵ curves for LiF, NaCl, KCl, and KI is shown in Figs. 3-6. The typical reproducibility of the deformation curves is indicated in Fig. 4 for NaCl. Figure 5 for KCl represents data for six specimens, with three each run at 1 atm and 4.3 kbar. In Fig. 6, for KI, the curves are averages for four crystals at each pressure. In each case, the error bars represent the maximum spread of the data.

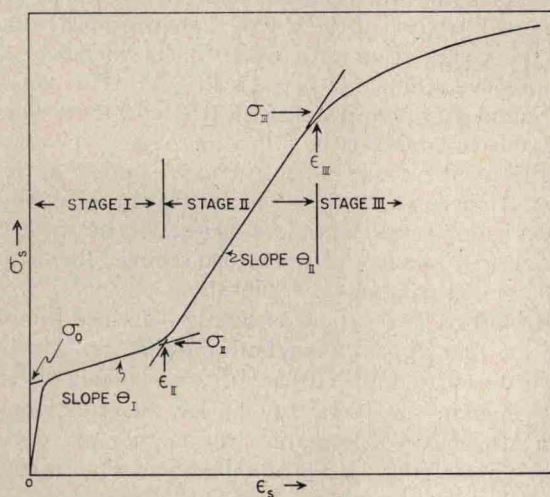


FIG. 1. A schematic, single-crystal stress-strain curve showing three stages of work hardening.

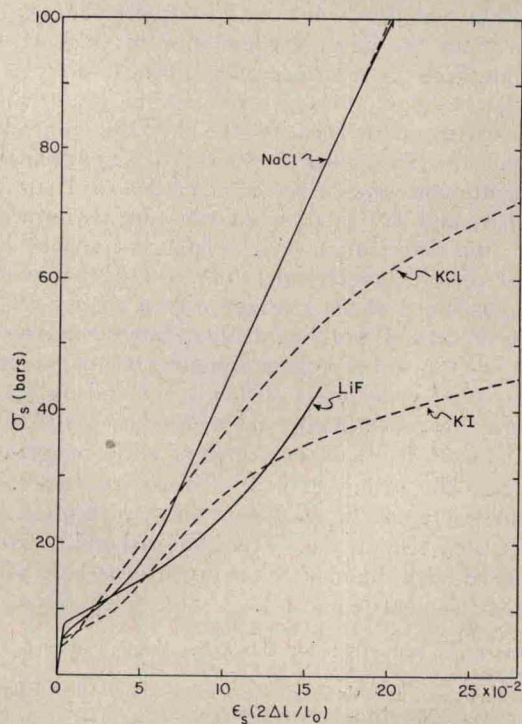


FIG. 2. Typical compression stress-strain curves at 1 atm and room temperature for NaCl, KCl, LiF, and KI. Dashed line for NaCl is extrapolation of stage II.

⁵ R. W. Davidge and P. L. Pratt, Phys. Status Solidi 6, 759 (1964).

⁶ J. Hesse, Phys. Status Solidi 9, 209 (1965).

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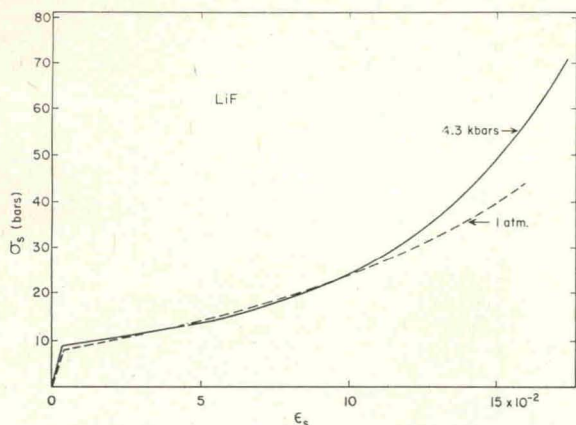


FIG. 3. Shear-stress-shear-strain curves for LiF at 1 atm and 4.3 kbar.

A pressure-induced shortening of stage I is observed for LiF, NaCl, and KI and the same is probably true for KCl, where the scatter in the data is such that a single curve can represent the deformation in stages I and II at both pressures. The rate of work hardening in stage I appears little changed by the application of pressure except in KI where it is increased by roughly a factor of 2. The range of stage II, $(\epsilon_{III} - \epsilon_{II})$, is decreased by about a factor of 2 at 4.3 kbar in NaCl and KI and it is reduced slightly in KCl. The slope θ_{II} appears unchanged except in KI where it is doubled at 4.3 kbar. The length of stage II is reduced in extent in NaCl and KCl because σ_{III} is decreased by pressure; in NaCl σ_{III} decreases from ~ 90 bars at 1 atm to ~ 45 bars at 4.3 kbar and in KCl the reduction is from ~ 45 bars to ~ 40 bars. In KI, σ_{III} appears unchanged by pressure; $(\epsilon_{III} - \epsilon_{II})$ is reduced because of the increased slopes of stages I and II. Figure 4, for NaCl, shows that the 4.3-kbar σ - ϵ curve lies close to the 1-atm curve in stage I and above the 1-atm curve in stage II; it then crosses the 1-atm curve so that deformation proceeds in stage

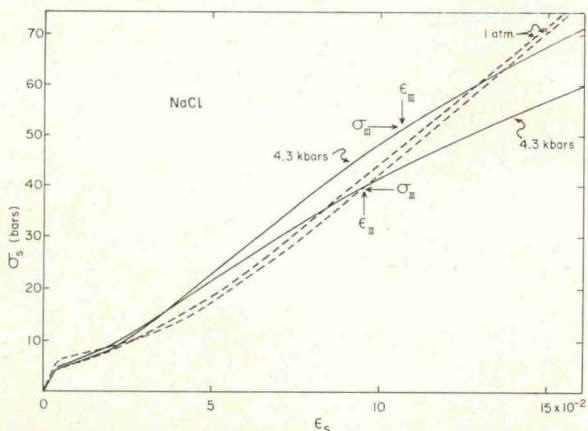


FIG. 4. Shear-stress-shear-strain curves for NaCl at 1 atm and 4.3 kbar. σ_{III} and ϵ_{III} are noted for the 4.3 kbar curves; σ_{III} at 1 atm is ~ 90 bars.

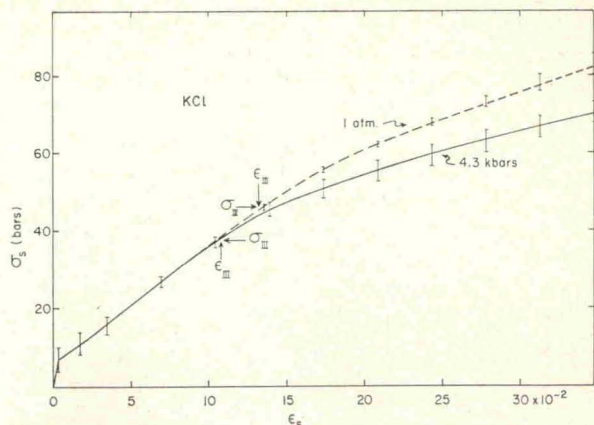


FIG. 5. Deformation of KCl at 1 atm and 4.3 kbar; the curve at each pressure represents an average for three specimens (average stress for a given strain). The error bars represent the maximum spread of the data; σ_{III} and ϵ_{III} are noted for each pressure.

III at 4.3 kbar when stage II is still the stable deformation mode at 1 atm. At a strain where stage III is stable at both pressures, the rate of work hardening in KCl is less at 4.3 kbar (Fig. 5). The stage III curve for KI always lies at higher stress at 4.3 kbar (Fig. 6) and the rates of work hardening in stage III at 1 atm and 4.3 kbar are nearly the same.

Figure 7 shows an interrupted stress vs plastic strain, σ - ϵ_p , curve (the elastic strain is subtracted out) for NaCl deformed into stage II. The fractional change of flow stress with pressure (measured to the upper yield point on pressure application) is $\sim 3 \times 10^{-2}$, equivalent to the change which obtains in lightly deformed but heavily irradiated samples of NaCl.² A change of this magnitude may be accounted for by the change with pressure of the edge (K_e) and/or screw (K_s) dislocation stress-field constant in the NaCl structure. Figure 8 shows a 1-atm σ - ϵ_p curve for KCl interrupted twice in stage II and twice in stage III by deformation under pressure. For the first 4.3-kbar interruption in stage II, $\delta\sigma/\sigma \sim 6 \times 10^{-2}$ (on pressure application) and for the second, $\delta\sigma/\sigma \sim 4 \times 10^{-2}$, which is the same range of values found for γ -irradiated crystals and is approximately

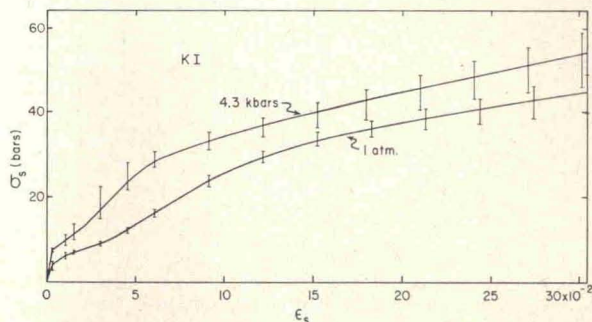


FIG. 6. Deformation of KI at 1 atm and 4.3 kbar; the curve at each pressure is an average for four samples. The error bars represented the maximum spread of the data.

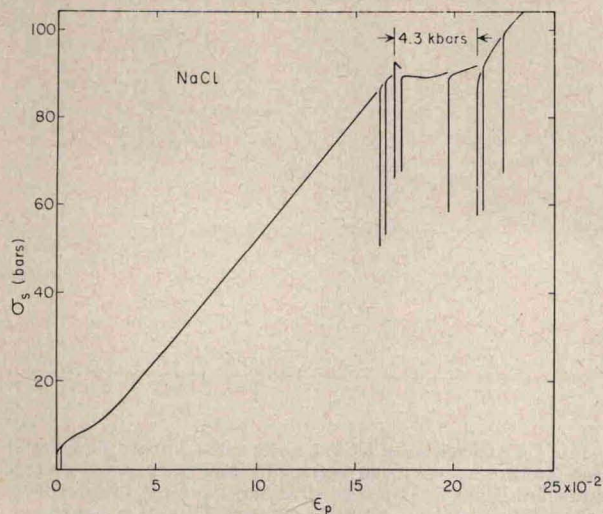


FIG. 7. An interrupted-stress-plastic-strain curve for NaCl prestrained well into stage II; $\delta\sigma/\sigma \approx 3 \times 10^{-2}$ on pressure application.

equal to $\delta K/K$.⁸ Figure 9, for KI, shows $\delta\sigma/\sigma \approx 15 \times 10^{-2}$ in stage II; in LiF stage II yields $\delta\sigma/\sigma \approx 1.5 \times 10^{-2}$. In all cases, $\delta\sigma/\sigma$ appears to be independent of strain in stage II, within experimental accuracy. Figure 10 shows a plot comparing $\ln(\sigma_2/\sigma_1)$ and $\ln(K_2/K_1)$ for alkali halides hardened by stage II deformation (or γ -irradiation²). These data are listed in Table II also.

The σ - ϵ curve for NaCl in Fig. 7 shows a pronounced yield point and reduced work-hardening rate when deformation is initiated at 4.3 kbar. This appears to be the same type of work softening as that observed by Cottrell and Stokes¹ in Al single crystals when deformation at low temperature was interrupted and then re-initiated at a higher temperature. Figure 8 for KCl, shows even more pronounced work softening in stage III, with the addition of a decrease of flow stress at high pressure; $\delta\sigma/\sigma$ is -6% on the second pressure interruption in stage III. Although some small-scale recovery

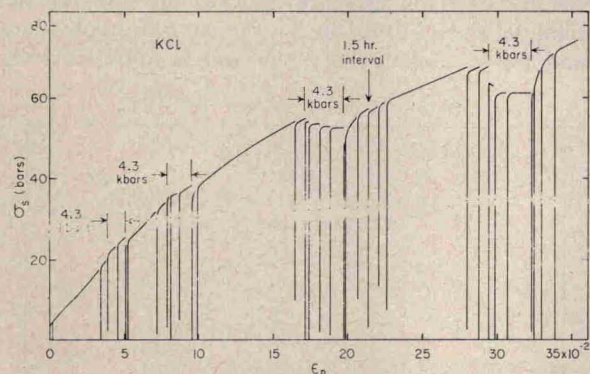


FIG. 8. An interrupted-stress vs plastic-strain curve for KCl. Two regions of high-pressure deformation obtain in both stage II and stage III.

⁸ Further experiments on irradiated crystals beyond those in Ref. 2 indicate a value of $\delta\sigma/\sigma \approx 5 \times 10^{-2}$ for KCl, slightly lower than the value previously reported ($\delta\sigma/\sigma \approx 8 \times 10^{-2}$).

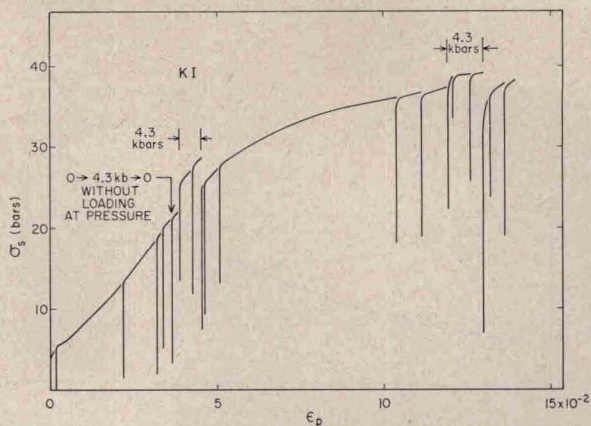


FIG. 9. A σ vs ϵ_p curve for KI interrupted once each in stage II and stage III where $\delta\sigma/\sigma$ (on pressure application) is $\approx 15 \times 10^{-2}$ and 4×10^{-2} respectively. Note that a pressure cycle without loading at pressure causes no significant change of flow stress.

is evident in the loading cycles just prior to pressure application, the observed decrease of flow stress at 4.3 kbar cannot be due to recovery because on pressure release the flow stress increases to its former value. The previous rate of work hardening also obtains after a short region of high work hardening rate. The occurrence of work softening in NaCl and KCl is evidence of plastic instability, i.e., the dislocation structure developed at 1 atm late in stage II or in stage III is unstable during deformation at 4.3 kbar because both σ_{III} and the rate of work hardening are less at this pressure. (Examination of the heavy strain regime in LiF is precluded by severe cracking.)

In an interrupted test there is apparently no significant irreversible, i.e., structure dependent, change in flow stress in stage II in NaCl and KCl. Within experi-

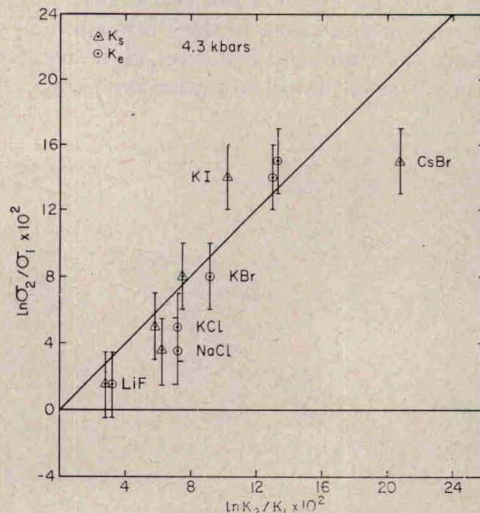


FIG. 10. A comparison of $\ln\sigma_2/\sigma_1$ and $\ln K_2/K_1$ for edge and screw dislocations, where subscript 2 refers to 4.3 kbar and 1 to 1 atm. $\ln\sigma_2/\sigma_1$ data for CsBr² and KBr (unpublished) are for γ -irradiation hardened samples. $\ln\sigma_2/\sigma_1$ data for the other materials are for stage II hardened samples; for γ -irradiation hardened samples $\ln\sigma_2/\sigma_1$ is virtually identical.

TABLE II. Pressure dependence of work-hardening characteristics.

	Stage II				Stage III			
	N_{II}^a	$(\delta\sigma/\sigma)_s$ $\times 10^2$	$\delta K_s/K_s$ $\times 10^2$	$\delta K_\epsilon/K_\epsilon$ $\times 10^2$	N_{III}^a	$(\delta\sigma/\sigma)_s$ $\times 10^2$	$\frac{\Delta\epsilon^b}{\%}$ (shear)	$\delta\sigma_{III}/\sigma_{III}$ $\times 10^2$
LiF	3	1.5 ± 2^c	2.8	3.2
NaCl	3	3.5 ± 2	6.5	7.5	2	0 ± 2	33 to 40	-50 ± 10
KCl	5	5 ± 2	6.0	7.5	4	-1.5 ± 2	28 to 45	-11 ± 5
KI	3	15 ± 2	10.8	13.9	3	6 ± 2	16 to 24	0 ± 5

^a Number of determinations of $\delta\sigma/\sigma$.^b The range of strain covered in stage III in determining $\delta\sigma/\sigma_s$.^c Estimated average deviation (see Ref. 2).

mental error, $\delta\sigma/\sigma$ is the same, with or without the occurrence of work softening on initiation of deformation at high pressure. The flow stress increment shown in Fig. 7 thus is $(\delta\sigma/\sigma)_s$, the "structure independent" change of flow stress. To determine $(\delta\sigma/\sigma)_s$ in stage III in NaCl and KCl it is necessary to prestrain at 4.3 kbar (to eliminate subsequent work softening) and then measure the flow stress at 1 atm; this yields $(\delta\sigma/\sigma)_s \sim 0$ and -1.5×10^{-2} for NaCl and KCl, respectively, independent of ϵ_s in the range covered (see Table II; a negative change corresponds to higher σ at 1 atm). Comparing $\delta\sigma/\sigma$ in Fig. 8 for KCl (-6% , second pressure cycle, stage III) to $(\delta\sigma/\sigma)_s \sim -1.5\%$, shows that work softening in stage III entails a structure dependent decrease of σ . To obtain $(\delta\sigma/\sigma)_s$ for KI, one must prestrain at 1 atm because the 4.3 kbar σ - ϵ curve always falls at higher stresses (Fig. 6); $(\delta\sigma/\sigma)_s \sim +6\%$ (Fig. 9).

The difference in the 1 atm and 4.3 kbar σ - ϵ curves in Figs. 3-6 includes the pressure dependence of the structure and the pressure dependence of the flow stress at constant structure $(\delta\sigma/\sigma)_s$. In stage II or III the stress for a given strain at 1 atm or 4.3 kbar varies by as much as 20% or more. On comparison of this difference with the small values of $(\delta\sigma/\sigma)_s$ listed in Table II, it is apparent that the continuous σ - ϵ curves at the two pressures differ primarily because the structure, i.e., the amount of work hardening for a given plastic strain, is pressure dependent.

DISCUSSION

Stage I

Stage I work hardening in LiF is believed to be controlled by elastic dislocation interactions ($\delta\sigma/\sigma \sim \delta K/K$), which may be long range according to a Taylor mechanism⁹ or short range according to the debris mechanism of Gilman and Johnston¹⁰ and Gilman.¹¹

Davidge and Pratt⁵ found for stage I in NaCl that the

shear stress, σ , and the dislocation density, N , are related by

$$\sigma = \alpha b \mu N^{1/2}, \quad (1)$$

where b is the Burgers vector, μ , the shear modulus and α is a constant. Equation (1), with $\alpha \sim 0.2$ (in reasonable agreement with $\alpha \sim 0.4$ from their etch-pit experiments) is a well-known consequence of the Taylor¹² elastic work-hardening mechanism and Davidge and Pratt conclude that this mechanism controls stage I in NaCl. However, Nabarro, Basinski, and Holt¹³ show that work-hardening mechanisms other than the Taylor mechanism, such as jog dragging, cutting the dislocation forest, and attractive intersections lead to Eq. (1) with approximately the same value of α . Thus, confirmation of Eq. (1) by etch-pit data does not prove the operation of the Taylor mechanism.

In Ref. 2 we report values for $\delta\sigma/\sigma$ in NaCl, KCl, and KI which are two to four times $\delta K/K$. These values lead to activation volumes on the order of 0.5 to 0.9 of the anion volume, suggesting control (or partial control) of work hardening by a mechanism involving the creation and/or diffusion of point defects. The value of $\delta\sigma/\sigma$ decreases in stage I with increasing ϵ , apparently as a result of an increasing contribution to the flow stress from the elastic interaction of dislocations, until it reaches the value which obtains in stage II. Hence, elastic effects play a role in stage I but point defect formation and/or diffusion appears important also. The decrease in the range of stage I during deformation under pressure may result from the pressure induced increase in elastic constants.

Figures 3-6 indicate that the pressure dependence of σ_0 is no larger than the values of $\delta\sigma/\sigma$ which obtain after light deformation in stage I (see Ref. 2). Consequently, one would not expect to find larger $\delta\sigma/\sigma$ in an etch-pit experiment, where the pressure induced change in stress necessary to maintain a given dislocation velocity is determined at essentially zero strain. Etch-pit experiments on LiF confirm this conclusion.¹⁴

⁹ P. Haasen and J. Hesse, Nat. Phys. Lab. G. Brit., Proc. Symp. No. 15, 1, 137 (1963).

¹⁰ J. J. Gilman and W. G. Johnston, Solid State Phys. 13, 147 (1962).

¹¹ J. J. Gilman, J. Appl. Phys. 33, 2703 (1962).

¹² G. I. Taylor, Proc. Roy. Soc. (London) A145, 362 (1934).

¹³ F. R. N. Nabarro, Z. S. Basinski, and D. B. Holt, Advan. Phys. 13, 193 (1964).

¹⁴ W. L. Haworth, L. A. Davis, and R. B. Gordon, J. Appl. Phys. 39, 3818 (1968).

Stage II

In an earlier paper² the authors emphasize the close correspondence of $\delta\sigma/\sigma$ and $\delta K/K_{e_0}$ for alkali halide crystals hardened by γ irradiation, where the flow stress is presumably controlled by the elastic interaction of radiation-produced defects and dislocations.¹⁵ The present work shows that for crystals deformed into stage II the same correspondence holds (Fig. 10), indicating that the flow stress is controlled by elastic dislocation-dislocation and/or dislocation-point defect interactions.

Further evidence that stage II is controlled by elastic effects is the approximately constant value of θ_{II}/K , for the materials listed in Table I. The variation in the influence of pressure on θ_{II} (and θ_I) in the various alkali halides, i.e., no significant effect in NaCl or KCl but a factor of 2 increase in $\theta_{I,II}$ at 4.3 kbar in KI, is perhaps associated with the greater influence of pressure on the elastic constants of KI (see Table II).

Davidge and Pratt³ have studied stage II work hardening in detail in NaCl. They report that the important deformation feature for the second stage is limited slip on the third and fourth (oblique) slip systems and suggest that work hardening is controlled by the cutting of dislocation dipoles on the primary slip plane by oblique dislocations. Assuming there is ample thermal energy available for the cutting process, the pressure dependence of this mechanism could be through the change in elastic constants only. Other mechanisms involving the motion of oblique dislocations, where the interaction with dislocations on the primary system is purely elastic, are compatible with the NaCl work of Davidge and Pratt as well. For example, Saada¹⁶ considers the attractive junction reaction between primary and oblique dislocations which converts a fourfold node to two threefold nodes; the greater stability of this configuration strengthens the crystal. Seeger *et al.*¹⁷ propose that stage II in fcc metal single crystals is controlled by the elastic interaction of parallel or nearly parallel dislocations on the planes of the primary slip system, according to a modified Taylor mechanism. The role of oblique dislocations in this case is to increase the density of obstacles to the motion of the primary dislocations resulting in a reduced slip distance. These mechanisms should also yield $\delta\sigma/\sigma \approx \delta K/K$. Our data does not allow choice of a particular "elastic" mechanism.

Stage III

The onset of stage III in NaCl and KCl occurs at a lower stress and strain during deformation at 4.3 kbar

(Table II; $\delta\sigma_{III}/\sigma_{III}$). In KI σ_{III} is unchanged at high pressure even though the elastic constants of KI are some 11%–14% higher at 4.3 kbar. Thus a mechanism for stage III hardening must have a negative dependence on pressure. Hesse⁶ has examined the temperature and strain rate dependence of σ_{III} in NaCl. His data fit the equation

$$\ln(\sigma_{III}/\mu) = \ln(\sigma_{III}/\mu)_{T=0} - (kT/A) [\ln(\dot{\epsilon}_0/\dot{\epsilon})], \quad (2)$$

where T is absolute temperature, $\dot{\epsilon}$ is the strain rate, k is Boltzmann's constant, and A and $\dot{\epsilon}_0$ are also constants. For conditions of constant strain rate

$$\ln(\sigma_{III}/\mu) \propto -T,$$

i.e., σ_{III} decreases rapidly with increasing temperature. Thus the onset of stage III is favored by both high temperature and high pressure in NaCl and KCl; this eliminates any diffusion controlled process such as thermally activated dislocation climb¹⁸ as the rate controlling mechanism in stage III, because diffusion is suppressed by high pressure.¹⁹

Stage III develops when the elastic work-hardening mechanism of stage II is interrupted by a process of dynamic recovery, leading to a reduced rate of work hardening. For fcc metal single crystals the recovery process is thought to require the thermally activated, stress assisted, cross slip of screw dislocations; cross slip enables the screw dislocations to circumvent barriers to slip on the primary slip plane. According to the model of Seeger and co-workers,^{20,21} stage III begins when the stress rises high enough to cause recombination of extended dislocations on the primary slip plane, thus allowing cross slip to begin. The large stresses necessary for recombination are thought to be generated by the stress amplification caused by dislocations piled up against barriers. The temperature and strain-rate dependence of this process, in terms of σ_{III} , are given by Eq. (2). Because data for NaCl also fit this equation, Hesse⁶ has suggested that the Seeger model for thermally activated cross slip may apply to the alkali halides also. Fontaine^{22,23} has recently calculated the stacking fault energy (γ) for the $\{110\}$, $\{111\}$, and $\{100\}$ planes of the alkali halides. It is found that dislocation dissociations of the order of $5b$ may exist on $\{110\}$ and $\{111\}$ but not on $\{100\}$.^{22–24} An important feature of the cross slip model, i.e., extended dislocations on the primary slip plane, is thus present in alkali halide crystals. Fontaine²³ also proposes a

¹⁸ S. Mader, Ref. 16, p. 183.

¹⁹ D. Lazarus and N. H. Nachtrieb, in *Solids Under Pressure*, W. Paul and D. M. Warschauer, Eds. (McGraw-Hill Book Co., New York, 1963), p. 43.

²⁰ A. Seeger, J. Diehl, S. Mader, and H. Rebstock, *Phil. Mag.* **2**, 323 (1957).

²¹ A. Seeger, R. Berner, and H. Wolf, *Z. Phys.* **155**, 247 (1955).

²² G. Fontaine, *J. Phys. Chem. Solids*, **28**, 2553 (1967).

²³ G. Fontaine, *J. Phys. Chem. Solids*, **29**, 209 (1968).

²⁴ G. Fontaine and P. Haasen, *Phys. Status Solidi* **31**, K67 (1969).

¹⁵ R. L. Fleischer, *Acta Met.* **10**, 835 (1962).

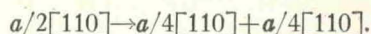
¹⁶ G. Saada, in *Electron Microscopy and the Strength of Crystals*, G. Thomas and J. Washburn, Eds. (Interscience Publishers, Inc., New York, 1963), p. 651.

¹⁷ A. Seeger, S. Mader, and H. Kronmuller, Ref. 16, p. 665.

mechanism for the formation of barriers to block active sources. The observed variation in σ_{III} at 1 atm in the alkali halides appears compatible with Fontaine's model, i.e., for roughly equal dislocation extensions on the primary slip plane ($\sim 5b$) the value of σ_{III} in the alkali halides should reflect a change in elastic constants; indeed σ_{III} for NaCl, KCl, and KI varies approximately in proportion to K_s (see Table I).

Direct experimental evidence to support the suggestion that cross slip controls stage III in the alkali halides is due to Matucha and Haasen²⁵; they found that surface cross slip traces on NaCl are observed only after deformation enters the third stage. These traces differ from those in metals, however, in that cross slip occurs consecutively on two different planes; from the primary $\{110\}$ plane, it proceeds to $\{111\}$, then to $\{100\}$ before returning to $\{110\}$. Matucha and Haasen suggest that cross slip first occurs on $\{111\}$ because dissociation is energetically favorable on this plane. The driving force for transfer of cross slip to $\{100\}$ cannot be increased dissociation, but rather must occur because slip over large distance on $\{111\}$ would lead to charged surface steps.

The proposed dissociation on $\{1\bar{1}0\}$ is²³



The stacking fault brings unlike ions into juxtaposition across the fault plane, and thus, it is favored by a strong Coulombic energy contribution. It is opposed by an exchange contribution which is relaxed by a strong local dilation of the lattice perpendicular to the fault plane ($\delta d_{110}/d_{110} \approx 0.3$).²³ Consequently application of high pressure should result in an increase in stacking-fault energy, as proposed by Fontaine and Haasen.²⁴ The reduction in σ_{III} under pressure occurs because cross slip of screw dislocations depends on recombination of the partial dislocations. When γ is increased at high pressure the stacking-fault ribbon is narrowed and less stress is required to bring about recombination and, hence, cross slip. The stage III structure should thus begin to develop at lower stress (σ_{III}) at 4.3 kbar. The stacking-fault partials will also repel one another more strongly at pressure due to an increase in elastic constants. If this effect is significant it could forestall a decrease in σ_{III} and this perhaps explains the results for

KI. As $\delta K/K_{e,s}$ are about the same for NaCl and KCl, the reason for the different values of $\delta\sigma_{III}/\sigma_{III}$ for these materials is unclear. Possibly the stacking-fault dilation differs significantly in the alkali halides (greater in NaCl than in KCl or KI); presumably $\delta\sigma_{III}/\sigma_{III}$ would be more negative for greater dilation.

As noted in the results section, the work softening which occurs at high pressure in NaCl and KCl after prestrain at 1 atm is evidence of plastic instability. In light of the mechanism discussed here for stage III, it presumably occurs because, due to the increase in γ , some dislocation configurations stable at 1 atm are unstable at higher pressures. When deformation is re-initiated under pressure, cross slip occurs in a catastrophic fashion and a yield point develops. Experiments show that the rapid cross slip must be driven by external stress: If deformation in stage III at 1 atm is interrupted, the pressure increased to 4.3 kbar and then returned to 1 atm without loading at 4.3 kbar, there is no transient or permanent change of flow stress or work-hardening rate at 1 atm. Thus there is no motion of dislocations due to application of pressure alone.

A change in σ_{III} due to applied pressure means that cross slip must begin from a different stage II structure, or that the structure developed by cross slip must be in some way different, i.e., $d\sigma_{III}/dP$ is not a measure of the change of flow stress at constant structure. The flow stress increment $(\delta\sigma/\sigma)_s$, as determined in an interrupted test, is a measure of the latter quantity and at large strains one can expect a contribution to $(\delta\sigma/\sigma)_s$ from the change in elastic constants with pressure. For NaCl, KCl, and KI, however, $(\delta\sigma/\sigma)_s$ in stage III appears significantly less than $\delta K/K_{e,s}$; in fact, $\delta\sigma/\sigma_s$ for KCl may be slightly negative (Table II). Thus, besides causing the negative pressure dependence of the dislocation structure, i.e., negative $\delta\sigma_{III}/\sigma_{III}$, the cross-slip mechanism also makes a negative contribution to $(\delta\sigma/\sigma)_s$. A negative $d\sigma_s/dP$ implies a negative activation volume for the motion of dislocations in stage III.

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²⁵ K. H. Matucha and P. Haasen, Nachr. Akad. Wiss. Goettingen, II. Math. Physik. Kl. 17, 219 (1967).