TABLE II. Pressure dependence of work-hardening characteristics.

	Stage II				Stage III			
	N_{II}[a]	$(\delta\sigma/\sigma)_s$ $\times 10^2$	$\delta K_s/K_s$ $\times 10^2$	$\delta K_e/K_e$ $\times 10^2$	N_{III}[a]	$(\delta\sigma/\sigma)_s$ $\times 10^2$	$\Delta\epsilon$[b] % (shear)	$\delta\sigma_{\mathrm{III}}/\sigma_{\mathrm{III}}$ $\times 10^2$
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 $(\delta\sigma/\sigma)_s\sim0$ 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 $(\delta\sigma/\sigma)_s\simeq-1.5\%$, 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); $(\delta\sigma/\sigma)_s\simeq+6\%$ (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 $(o\sigma/\sigma)_s$ 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 ($\delta\sigma/\sigma\simeq\delta K/K$), which may be long range according to a Taylor mechanism[9] or short range according to the debris mechanism of Gilman and Johnston[10] and Gilman.[11]

Davidge and Pratt[5] found for stage I in NaCl that the shear stress, σ, and the dislocation density, N, are related by

$$\sigma=\alpha b\mu N^{1/2}, \tag{1}$$

where b is the Burgers vector, μ, the shear modulus and α is a constant. Equation (1), with $\alpha\simeq0.2$ (in reasonable agreement with $\alpha\simeq0.4$ from their etch-pit experiments) is a well-known consequence of the Taylor[12] elastic work-hardening mechanism and Davidge and Pratt conclude that this mechanism controls stage I in NaCl. However, Nabarro, Basinski, and Holt[13] 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]

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Stage II

In an earlier paper[2] the authors emphasize the close correspondence of $\delta\sigma/\sigma$ and $\delta K/K_{e,s}$ 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_s 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 Pratt[3] 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, Saada[16] 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 $\delta\sigma/\sigma \simeq \delta K/K$. 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. Hesse[6] has examined the temperature and strain rate dependence of σ_{III} in NaCl. His data fit the equation

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

where T is absolute temperature, $\dot{\epsilon}$ is the strain rate, k is Boltzmann's constant, and A and ϵ_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 climb[18] 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, Hesse[6] 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. Fontaine[23] also proposes a

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