# Stress threshold for precursor decay in LiF

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Single crystals of LiF have been mechanically shocked by projectile impact so as to produce shocks propagating in a ⟨100⟩ direction. Velocities of projectiles have been varied to produce shock pressures from 4.9 to 28.6 kbar in the LiF. Pressures were measured with thick quartz gauges after shock travel distances of approximately 3 mm. The 4.9-kbar wave was perfectly elastic. The precursor of an 8.3-kbar wave showed no attenuation, but stress relaxation occurred between precursor and plastic shock. A 10.4-kbar precursor was measurably attenuated from its impact value. These results are taken to indicate a threshold shear stress between 2.4 and 3.0 kbar for nucleation of dislocations in the shock front.

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## I. INTRODUCTION

It has often been noted that dislocation densities found in unshocked materials are as much as three orders of magnitude smaller than required to explain measured rates of precursor decay in plane-shock-wave experiments by conventional dislocation theory.[1–7] Three explanations of this discrepancy have been described[7]: dislocation velocities may be supersonic, multiplication of dislocations by cross glide or other processes may occur in the shock front, or dislocations may be nucleated around defects in the crystal lattice. It is implausible that dislocation velocities are sufficiently supersonic to explain the observed discrepancy, since drag forces increase at an enormous rate as the sonic limit is exceeded. The plausibility of regenerative multiplication in the shock front depends on rise time of the elastic precursor and value of the dislocation multiplication constant $M$.[8] The possibility that this process is important is hard to evaluate because measured rise times are often suspect, being affected by experimental procedures as well as by material properties.

Asay *et al.*[3] and Gupta *et al.*[7] have constructed a persuasive case for the thesis that nucleation is responsible for the observed decay in lithium fluoride. In the latter paper it is shown that the strong dependence of precursor decay rate on shear stress on slip systems for ⟨100⟩ shock propagation is compatible with the theory of dislocation nucleation around impurity precipitates. In a later paper, Gupta[9] has also shown that rate of decay varies with impact velocity in accord with the above model.

The dependence of inferred dislocation density on resolved shear stress shown in Fig. 3 of Ref. 7 suggests that for impact pressure less than approximately 10 kbar, no precursor attenuation at all should be measured in a laboratory shock experiment. This paper is a report of results obtained in experiments to test this suggestion. The necessary formalism is described in Sec. II of Ref. 7 and measuring techniques are described in Sec. III of the same paper.

## II. EXPERIMENTAL DETAILS

Gupta referred to the lithium fluoride he used in measuring stress dependence of precursor decay rate as $H$(Ann. III).[9] It was obtained from Harshaw Chemical Co. and contained 120 ± 25-ppm magnesium as the principal impurity (molar concentrations are used throughout). Samples were kept at 400 °C for 12 h, then air quenched to room temperature. Following this they were annealed at 150 °C for 70 h to encourage precipitation of magnesium fluoride. Finally, they were slowly cooled to room temperature.

The boule from which Gupta's samples were drawn was exhausted, so new samples with 120-ppm magnesium were ordered from Rosenberger at the University of Utah. These were all grown from the same starting material but were not from a single boule. Several measurements of magnesium concentration were obtained and the results are shown in Table I. Magnesium con-

TABLE I. Measurements of magnesium concentration (spectrographic analysis also detected less than 2 ppm of Si, Cu, Ca, and Al).

| Specimen No. | Reported magnesium concentration, mole ppm[a] | Source |
|---|---|---|
| 14 | 74[b] | f |
| | 158[c] | g |
| 15 | 145[c] | g |
| 7 | 76,[b] 67,[c] 106[d] | f |
| | 151[c] | g |
| 16 | 148[c] | g |
| 17 | 152,[d] 380[d] | e |
| | 163[c] | g |
| 3 | 27[d] | h |
| | 76[b] | f |
| | 201[c] | g |
| 4 | 54[d] | h |
| | 73[b] | f |
| | 189[c] | g |

[a] This is the molar ratio of Mg to LiF in ppm.
[b] Annealed.
[c] Air quenched.
[d] As-received.
[e] West Coast Technical Service, Inc., Cerritos, Calif. atomic absorption; 2—5% accuracy.
[f] F. Rosenberger, Department of Physics, University of Utah; atomic absorption; 2% accuracy.
[g] Yield stress measurement and Ref. 10.
[h] American Spectrographic Laboratories, Inc., San Francisco, Calif.; spectrographic measurements; no accuracy stated.

  

TABLE II. Experimental parameters for precursor measurements.

| Shot No. | Specimen No. | Specimen thickness (mm) | Dislocation[a] density, $N_0$ ($10^5$/cm$^2$) | Yield stress (kbar) air quenched | Yield stress (kbar) annealed | Projectile material | Projectile velocity (mm/μsec) | Calculated elastic impact pressure (kbar) | Measured precursor amplitude (kbar) |
|---|---|---|---|---|---|---|---|---|---|
| 75-050 | 14 | 2.55 | 1.6 | 0.105 | 0.395 | PMMA | 0.162 ± 0.011 | 4.9 | 4.9 |
| 75-054 | 15 | 3.10 | 0.9 | 0.095 | 0.40 | PMMA | 0.270 ± 0.029 | 8.25 | 8.3 |
| 75-060 | 7 | 2.90 | 2.7 | 0.10 | 0.43 | PMMA | 0.366 ± 0.004 | 11.2 | 10.4 |
| 75-062 | 16 | 3.10 | 2.9 | 0.097 | 0.41 | PMMA | 0.450 ± 0.004 | 13.8 | 12.6 |
| 75-063 | 17 | 3.16 | — | 0.109 | 0.43 | Al | 0.2305 | 19.1 | 14.6 |
| 75-036 | 3 | 2.76 | 1.9 | 0.14 | 0.39 ± 0.04 | Al | 0.344 ± 0.004 | 28.6 | 21.8 |
| 75-040 | 4 | 3.00 | 1.8 | 0.13 ± 0.01 | 0.40 ± 0.02 | Al | 0.343 ± 0.002 | 28.6 | 21.85 |

[a]Measured by counting etch pits.

centrations were also inferred from quasistatic yield stress measurements on air-quenched samples, given in Table II, according to Fig. 1(a) of Ref. 10. Specimens 3 and 4 were treated differently from the others in two respects. They were annealed at 146 °C instead of 163 °C, and yield measurements were made at a strain rate of $(8.2 \pm 1.3) \times 10^{-4}$/sec instead of $(1.6 \pm 0.5) \times 10^{-4}$/sec, which was used for the others. These two factors may account for the large values of yield stress for specimens 3 and 4. The range of concentration values is distressing. It is not certain whether it represents real variation of magnesium content within and among speciments or uncertainties in measuring methods. Except for specimens 3 and 4, concentrations inferred from yield stress are closely grouped around 150-ppm magnesium. The mean of all determinations in Table I is 132 ppm, which is within the range of Gupta's values. Whether or not there is indeed a difference is uncertain.

Another difference between our specimens and Gupta's was annealing time. His were annealed for 70 h at 150 °C; ours, by accident, were annealed for 57 h. According to Ref. 7, this should have reduced annealed yield stress and precursor amplitude slightly relative to Gupta's values. The difference was thought to be inconsequential.

Experiments were conducted as described in Ref. 3, 7, and 9. Projectiles for shots 75-050, 75-054, and 75-063 were 2 ft long and more massive (11 lb) than the standard projectile, which weighs about 2 lb and is 8 in. long. Tilts at impact and precursor rise times of current output from quartz gauges are listed in Table III.

Quartz gauges were used in the shorted mode.[11] Three calibration shots were made at low stresses.

TABLE III. Rise time and tilt.

| Shot No. | Rise time (nsec) 10–90% | Rise time (nsec) 0–100% | Tilt (mrad) |
|---|---|---|---|
| 75-050 | 25 | 80 | 0.12 |
| 75-054 | ~12 | 27 | 0.44 |
| 75-060 | <10 | 13 | 0.14 |
| 75-062 | <9 | 12 | 0.14 |
| 75-063 | 10 | 18 | 0.34 |
| 75-036 | 9 | 11 | 0.24 |
| 75-040 | 4 | 6 | 0.3 |

Current coefficients derived from initial pressure jumps are shown in Fig. 1 and compared with values reported by Hayes and Gupta.[12] The ramping correction determined in these experiments was $(26 \pm 1)\%$ instead of 40% as reported by Hayes and Gupta. No significant difference was apparent in the three experiments. Deficiencies of shorted quartz gauges are discussed elsewhere.[12,13] They respond quickly to changes in $p_x$ and are accurate and reliable for a short time after first response.

## III. EXPERIMENTAL RESULTS

Quartz current profiles, converted to interface pressure $p_x$, are shown in Fig. 2. The profile from shot 75-050 appears to be absolutely elastic with amplitude equal to the calculated elastic impact amplitude. The error assignable to the amplitude measurement can be inferred from Fig. 1. Resolved shear stress in this experiment is 1.4 kbar, which is well below threshold values indicated in Ref. 7. The anticipated rate of decay of precursor in this experiment, assuming that no multiplication is occurring, can be calculated from Eqs. (2), (4), (5), (9), and (10) of Ref. 7. For a dislocation density of $1.6 \times 10^5$/cm$^2$, they give a precursor decay rate of approximately $10^{-3}$ kbar/mm, which would be unobservable in this experiment.

Shot 75-054, with calculated impact pressure of 8.25 kbar, has a precursor amplitude of 8.3 kbar. The two values are indistinguishable within the error of the experiment. $p_x$ decreases with time immediately behind

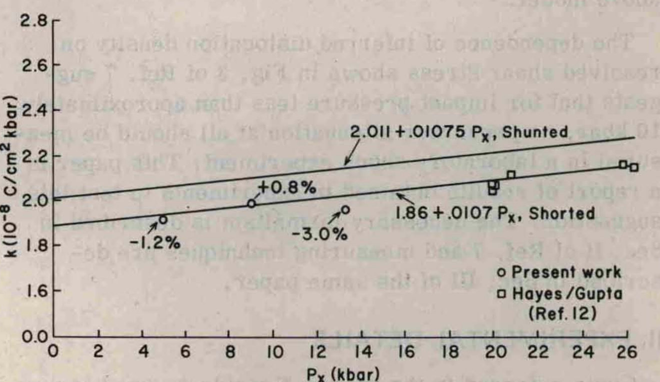


FIG. 1. Effects of pressure on the piezoelectric constants of quartz gauges.