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IN-SITU MAGNETIC GAUGE MEASUREMENTS IN KEL-F[†]

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In-situ gauge measurements have been made in Kel-F using multiple, embedded Lagrangian particle velocity and impulse gauges to measure shock attributes. Shock stresses attained were between 0.9 and 11 GPa. At the lower stresses, we were looking for the effects of a subtle phase transformation to be manifested in the form of a multiple wave structure. Clear evidence of this transformation was not observed but the shape of the transmitted waves indicated the viscoplastic nature of this material. This effect was nearly gone at 2.6 GPa. At the highest stress condition (11 GPa), the waveforms suggest that the single-crystal sapphire impactor was starting to yield, indicating that sapphire is not elastic all the way to 12 GPa, as had been previously thought. Rarefaction speed measurements at shock conditions were obtained from each experiment but it was not possible to obtain accurate estimates of the Grüneisen parameter.

1. INTRODUCTION

Kel-F is the trade name for poly(chlorotrifluoroethylene), a linear chain semicrystalline polymer. It has been studied under both static and dynamic high pressure conditions.¹⁻⁴ Kel-F is of importance to the weapons explosive community because it is used as a binder in the plastic bonded explosives PBX 9502 and LX-17. It is also being used as a substrate for PVDF gauges.

Johnson, Halleck, and Wackerle^{1,2} did low stress (0.3 to 2 GPa) quartz gauge front/back experiments on Kel-F in the early 1970's and postulated there may be a first order phase transition near 1 GPa (volume change on the order of 1%). Earlier experiments by Champion on polytetrafluoroethylene (Teflon) showed a transition at about 0.5 GPa³ and they thought, because the two materials were similar, Kel-F may have a similar transition. The Teflon transition was well studied in the static high temperature/high pressure community with measurements that agreed with Champion's dynamic data. Samara and Fritz did static high temperature/high pressure measurements on Kel-F to look for evidence of the phase transition but found no such evidence up to 2 GPa.⁴ This was quite surprising in view of the Teflon behavior.

Carter and Marsh did a large number of high explosive driven plane wave experiments on Kel-F (and a number of other polymers) in the pressure range from 4 to 75 GPa.⁴ Their data showed a high pressure transition at 43.7 GPa.

We have done a number of multiple magnetic gauging experiments in Kel-F to study its viscoplastic behavior, as well as to determine the repeatability of our multiple gauge measuring system.

2. EXPERIMENTAL SETUP

All the experiments were done using an 8 m long, 72-mm diameter bore single stage gas gun capable of projectile velocities up to 1.5 mm/ μ s. An electronagnet was installed in the gun target chamber to provide the magnetic field (≈ 775 gauss) for magnetic gauging.

The magnetic gauging system (MIV gauge for Magnetic Impulse and Velocity gauge) used in these experiments was developed by Vorthman and Wackerle in the early 1980's.⁶ The MIV gauge membrane consists of 25 μ m of FEP Teflon (fluorinated ethylene propylene copolymer), 5 μ m of aluminum (etched into a pattern of 5 particle velocity gauges and 5 impulse gauges), and a 25 μ m FEP Teflon cover. Epoxy is

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used to glue the layers together, producing an approximately 60 μm thick membrane. The Kel-F sample was a 50 mm dia. by 23 mm thick cylinder, consisting of a base and top machined so the gauge could be embedded at a 30° angle with the front of the piece. A gauge membrane was carefully positioned and epoxied so the particle velocity gauge ends were parallel to the sample front; this assembly was then carefully machined flat. Since the gauges are 2-mm apart on the membrane and it is mounted at a 30° angle in the sample, the Lagrangian gauge positions (from the sample front) are between $\approx$ 1 to 5 mm in the Kel-F and are each separated by 1 mm.

The Kel-F target was impacted by a Lexan projectile faced with either Vistal (multicrystalline pressed sapphire) or single crystal, z-cut sapphire, depending on the pressure developed at the impact condition. The impactor thicknesses (shown in Table I) were thin enough that a rarefaction (resulting from the projectile/impactor impedance mismatch) propagated through the experiment at late times providing sound speed at pressure information.

This gauging system makes it possible to measure particle velocity, impulse (pressure is obtained by numerical differentiation), and shock velocity (from the wave arrival times at each gauge) in a nonreactive material. This means the Hugoniot state in the Kel-F is overdetermined. A comparison of all the data from an experiment can be made to give an idea of the information consistency. We chose to use particle velocity and shock velocity as the primary data. When these

are used, it is not necessary to know anything about the impactor or the projectile velocity to completely determine the Hugoniot state in the Kel-F. Information regarding each experiment is given in Table I; the impedance match conditions were calculated using the Hugoniot fit to be discussed later.

3. RESULTS AND DISCUSSION

Particle velocity waveforms obtained in Shot 767 (input stress 1.4 GPa) are shown in Fig. 1. The viscoplastic nature of Kel-F is clearly shown by the wavefront dispersion. Also evident is the rarefaction wave that travels through the Kel-F at late times, spreading as it travels through the shocked sample. These waveforms demonstrate that a single MIV gauge experiment provides more consistent information than several experiments in which only one measurement is made, primarily because the input is not varying from experiment to experiment. This consistency was evident in each of the experiments. Hugoniot data obtained from this and the other experiments are listed in Table II. One can get an idea of the data consistency for each experiment by comparing the stresses from: (1) the impedance match, (2) the impulse gauge, and (3) the jump condition calculation. Differences among these are approximately 5% or less.

Our new Hugoniot data (using the maximum particle velocity and shock velocity) are very close to those of Refs. 1, 2, and 4 as seen in Fig. 2. After plotting all the Kel F data, it was obvious there was a definite rounding in the data as stress increases. Consequently,

TABLE I KEL F SHOT DATA

Shot No.	Impactor Mat'l	Impactor Thickness mm	Proj. Vel. mm/ μs	Kel F Initial Density Mg/m ³	Impedance Match Kel F Input Conditions		
					Part. Vel. mm/ μs	Stress GPa	Shock Vel mm/ μs
765	Vistal	11.07	0.211	2.14	0.189	0.93	2.32
769	Vistal	11.09	0.241	2.14	0.216	1.09	2.37
767	Vistal	11.09	0.300	2.14	0.268	1.40	2.46
766	Vistal	11.05	0.341	2.14	0.304	1.64	2.52
768	Vistal	11.02	0.501	2.15	0.442	2.61	2.77
689	Vistal	11.10	0.96	2.14	0.825	6.07	3.44
698	Vistal	11.09	1.16	2.14	0.986	7.85	3.73
703	Sapphire	12.67	1.45	2.14	1.21	10.7	4.13

Figure 1.
MIV gauge particle velocity waveforms obtained from Shot 767 with a shock input stress of 1.4 GPa.

Figure 2.
Plot of Kel-F Hugoniot data available up to 15 GPa.

the linear fit of Carter and Marsh is a little high at low stresses and that of Wackerle et al. too high at the higher stresses. Therefore, a new fit was made using all the data between 0 and 15 GPa $\cdot U_s = 1.989 + 1.763 u_p$ mm/ μ s. This fit was used to generate the impedance matching information given in Table I.

Johnson and Halleck² showed evidence of a slight cusp in the Kel-F Hugoniot at a stress of 1.1 GPa² but subsequent static high pressure experiments by Samara and Fritz³ did not show evidence of a transition. After carefully looking at our data in the 0.9 to 1.6 GPa regime, we see no direct evidence of a transition either. Morris et al. made sound speed measurements in Teflon at high dynamic stresses and observed evidence of a transition at ≈ 34 GPa.⁷ Their data were good enough to obtain values for the Gruneisen parameter at high stresses. We obtained Lagrangian sound speed information from our experiments by analyzing the wave speed of the rarefaction propagating through the experiment at late times. The sound speed values listed in Table II and plotted in Fig. 3 versus relative volume represent the slope of the line indicating the start of the rarefaction wave in the Lagrangian position/time plane at each gauge position. An attempt to obtain estimates for the Gruneisen parameter from our data failed because it was not accurate enough; Morris et al. indicated this could be a problem. As can be seen from the data plotted in Fig. 3, there is no evidence of a transition.

TABLE II KEL-F MEASURED AND CALCULATED DATA

Shot No.	Measured Kel F Parameters				Jump Cond Stress Cal. (Max. Vel.) GPa	Relative Volume V/V ₀
	Particle Velocity (Max.) mm/ μ s	Stress (from Impulse) GPa	Max. Shock Velocity mm/ μ s	Lagrangian Sound Velocity mm/ μ s		
765	0.185	0.89	2.31	3.02	0.92	0.9199
769	0.217	1.03	2.30	3.09	1.07	0.9057
767	0.266	1.37	2.46	3.57	1.40	0.8919
700	0.298	1.55	2.47	3.50	1.58	0.8794
768	0.429	2.53	2.80	4.47	2.55	0.8468
689	0.807	5.99	3.49	6.17	6.04	0.7688
698	0.971	7.84	3.75	6.89	7.82	0.7411
703	1.19	10.7	4.10	6.93*	10.7	0.7159

* Sapphire was apparently yielding. Data suspect.

Figure 3.
Lagrangian sound speed data obtained from analyzing the rarefaction wave traveling through the Kel-F experiments at late time.

Viscoplasticity was evident in all the lower stress experiments. The particle velocity waveforms obtained at 0.9, 1.1, and 1.4 GPa were disperse at the top (as seen in Fig. 1) and this dispersion increased with wave travel out to the position of the last gauge (≈ 5 mm). However, the amount of dispersion definitely decreased as the stress increased. Waveforms from Shot 766 (1.6 GPa) showed very little dispersion. Shock wave dispersion in polymethyl methacrylate (PMMA) has been carefully studied by Barker, Schuler, Nunziato, and others in the past⁸ and our data on Kel F seems to indicate that it behaves much like PMMA.

Shot 768 (2.6 GPa) showed little, if any, dispersion but there was evidence of subtle structure in the particle velocity waveforms. We do not know the cause of this and, since there was only one experiment in this regime, it is impossible to know whether the structure is real or an artifact of the particular experiment. On this experiment a separate particle velocity gauge was mounted on the Kel F front to measure the impact surface velocity. This waveform was virtually identical to that of the first embedded gauge, demonstrating that the embedded gauges are measuring the correct particle velocity. This was of interest because, in MIV gauge experiments in liquids, we have measured embedded particle velocities less (by up to 10%) than expected based on impedance match calculations. We

do not yet know the reason for this. There was no evidence of dispersion in the three higher stress shots at 6.0, 7.8, and 10.7 GPa.

In the highest pressure experiment (Shot 703), the impactor was z-cut sapphire, thought to be elastic up to 12 GPa. Our particle velocity waveforms show a decrease in particle velocity of about 6% with time and the impulse gauge data indicates a corresponding decrease in stress. The most reasonable interpretation for this is plastic relaxation in the sapphire which occurs approximately 1 μ s after impact. This suggests that single-crystal sapphire may only be good as an elastic impactor up to 10 GPa.

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