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Plate impact experiments on DC745U cooled to ∼-60°C

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Using gas-gun driven plate impact experiments, we have measured the $U_S - u_p$ Hugoniot of the silicone elastomer DC745U cooled to -60°C. In summary, the initial density changes from ρ_0(23°C) = 1.312± 0.010 g/cm^3 to ρ_0(-60°C) = 1.447± 0.011 g/cm^3. The linear $U_S - u_p$ Hugoniot changes from $U_S = 1.62 + 1.74u_p$ km/s at +23°C, to $U_S = 2.03 \pm 0.06 + (2.03 \pm 0.06)u_p$ km/s at -60°C. DC745U, therefore is much stiffer at -60°C than at +23°C, probably due to the crystallization that occurs at ∼ - 50°C. **Caveats/deficiencies:** 1)This report does not provide an adequate pedigree of the DC745U used. 2) References to unpublished room temperature shock compression data on the elastomer are inadequate. 3) The report has not been fact checked by a DC745 subject matter expert. RLG 08/11/2016

Keywords: Plate impact, Hugoniot, Magnetic Gauging, Silicone elastomers

I. INTRODUCTION

DC745U is a silicone elastomer originally manufactured by Dow Corning under the trade name of Silastic DC745U at their manufacturing facility in Kendaville, Indiana. Currently DC745U is available through Xiameter or Dow Corning's distributor R. D. Abbott Company. This silicone elastomer is used in numerous parts of weapon systems, including outer pressure pads, aft cap support in W80 and pressure pad in the B61.[1–7]

At ∼ -50°C, the polymer crystallizes with ∼ 40% crystallinity.[6,7] This transition affects many behaviors, including the shock compressibility.[7] The experiments we report here are intended to further determine the shock compressibility of DC745U that has been cooled below the crystalline transition temperature.

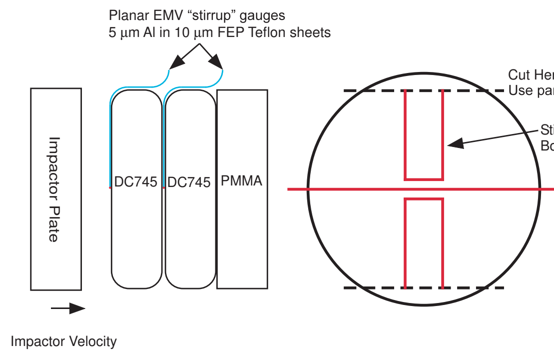

FIG. 1. Schematic of the plate impact shock compression experiment. DC745 slabs, ∼ 10 mm thick are cut into 50.8 mm diameter circles. The edges of the circles are cut off 21.6 mm from the center-line. Stirrup gauges are placed on the impact face and ∼ 10 mm deep.

II. EXPERIMENT

The configuration for the plate impact shock compression experiment is shown in Fig. 2. The planar electromagnetic velocity (EMV) 'stirrup' gauges measure the particle velocity, u_P in the DC745 sample. The shock velocity, U_S, is measured as the distance between the two gauge planes, Δx divided by the transit time, Δt. Impactor plates were made of Kel-F81, Z-cut single crystal sapphire and Z-cut alpha quartz. Shock stress in the sample is determined by the impactor material and the impact velocity.

A. DC745U Pedigree

DC745U used in these experiments was obtained from Dana Dattelbaum as cured rubber slabs about 10 mm thick. I was told the material was cured in the usual fashion. The slabs contained the odd bubble, but amples were cut from sections containing a minimum of bubbles and a special attempt was made to cut the sample disks so that any bubbles were at the edge of the disk and not in the center where the active elements of the stirrup gauge were located.

B. Sample density

Density of the DC745 parts was measured at room temperature by water immersion. Typically three separate measurements were made for each sample. At room temperature for all samples, densities was ρ_0(23°C) = 1.312 ± 0.010 g/cm^3. Densities used in samples for each shot are summarized in Table I.

Density at -60°Cwas calculated as follows. First, at -60°C, Phillip Rae and Dana Dattelbaum[8] have measured a thermal strain of

$$\epsilon(-60^\circ) = \frac{L(-60^\circ) - L(23^\circ)}{L(23^\circ)} = -0.032 \qquad (1)$$

Assuming that the material shrinks isotropically when cooled, the density at -60°Cis

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$$\rho_0(-60^\circ) = \frac{\rho_0(23^\circ)}{(1-\epsilon(-60^\circ))^3} \quad (2)$$

From all the samples, the calculated density at -60°Cis $\rho_0(-60°\text{C}) = 1.3417 \pm 0.011$ g/cm^3. Calculated sample densities at -60°Cfor each shot are also summarized in Table I.

C. DC745U sample thickness

The relevant sample thickness, Δx is the distance between the 'stirrup' gauges at -60°C. At room temperature, this was measured using a calibrated height gauge with sub μm precision. Standard deviation in the thickness measure of an individual sample was as much as 45 μm. DC745U comes in molded rubber slabs and can not be machined so large standard deviations in thickness are expected. At -60°Cthe thickness can be determined from the thickness at 23°Cand Eq. 1.

D. Cooling

The cooling methods closely follow that which we described in reference.[9,10] Chilled nitrogen gas from a liquid nitrogen Dewar flows through channels in the aluminum target mounting plate and the copper coil. Resistive heaters reheat the nitrogen gas to the desired temperature.

Temperature was monitored using 5 type E (*chromel-constantan*) thermocouples. One of these was embedded in the sample and two were attached to the sample surface. Final temperature was estimated from these three thermocouples. Two other thermocouples were attached respectively to the coil and the plate near the sample.

The sample was "soaked" at -60°C for more than an hour before the shot was fired.

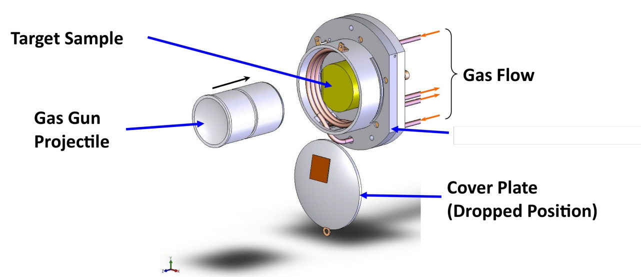

FIG. 2. Schematic of the experiment used for plate impact experiments on cooled DC745. The sample is cooled by flowing chilled nitrogen gas (obtained from a liquid nitrogen dewar) through channels in the target mounting plate and the surrounding copper coil. The cover minimizes radiative heating of the sample.

III. RESULTS

A. Wave Profiles

Table I summarizes the data for this series of shots on DC745U. Errors were forward propagated using Monte-Carlo Methods. Figure 3 shows wave profiles from the electromagnetic particle velocity gauges for shot 1s-1605. The impact surface particle velocity gauge indicates a particle velocity of $u_p = 0.135 \pm 0.005$ km/s. The shock transit time is $\Delta t = 3.944 \pm 0.110$ μs. The transit time uncertainty of 110 ns is derived from the 110 ns rise time (10% to 90%) of the gauges. Note that the transmitted shock is considerably more ramped out than the input shock. Ramping of the transmitted shock is probably due to the heterogeneous nature of the DC745 and the low stress. Ramping of the measured input wave profile is probably due to impact tilt from target mis-alignment. Target alignment is done before cooling begins and the target may move and tilt (relative to the projectile face) as it is cooled. Note also that the gauges typically only record for a short time before breaking.

Figures 4 - 7 show waveprofiles for the other experiments performed in this series. Annotations specific to each experiment are given with the captions. Experiments are listed in order of increasing pressure.

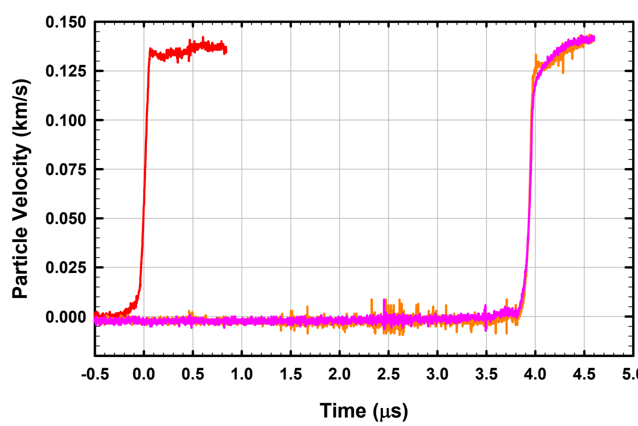

FIG. 3. Wave profiles from the four electromagnetic particle velocity 'stirrup' gauges for shot 1s-1605. Input pressure is 0.45 ± 0.02 GPa. The impact surface gauge gives the particle velocity: $u_p = 0.135 \pm 0.005$ km/s. The second set of stirrup gauges gives shock transit time;$\Delta t = 3.944 \pm 0.110$ μs. The shock velocity is $U_S = 2.32 \pm 0.06$ km/s.

B. Impedance Matching Calculations

Where possible, measured shock and particle velocities were cross checked using the impedance matching method.[11] In this method, the pressure, P, at the target/impactor interface must be equal in the target and impactor. Also, the particle velocity,u_p, at the target/

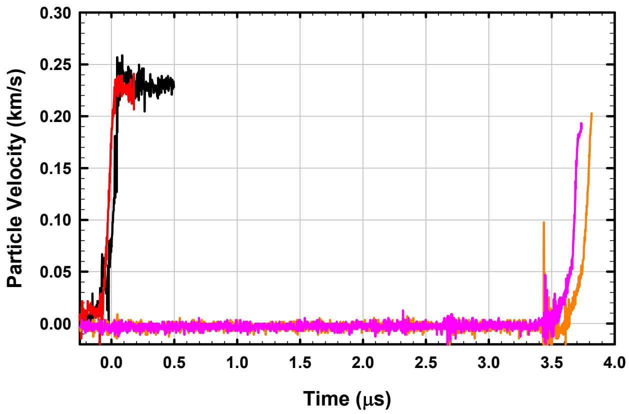

FIG. 4. Wave profiles from the four electromagnetic particle velocity 'stirrup' gauges for shot 1s-1604. Input pressure is 0.81 ± 0.04 GPa. Particle velocity is $u_p = 0.23 \pm 0.01$ km/s. Transit time is $\Delta t = 3.736 \pm 0.100$ μs. Shock velocity is $U_S = 2.46 \pm 0.07$ km/s.

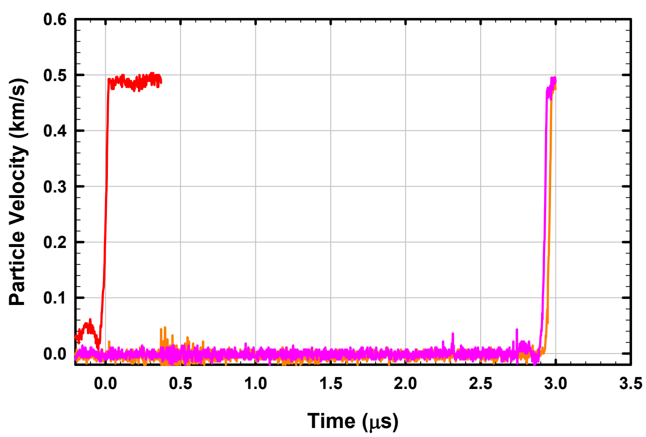

FIG. 5. Wave profiles from the four electromagnetic particle velocity 'stirrup' gauges for shot 1s-1603. Input pressure is 2.21 ± 0.07 GPa. Particle velocity is $u_p = 0.489 \pm 0.015$ km/s. Transit time is $\Delta t = 2.943 \pm 0.030$ μs. Shock velocity is $U_S = 3.11 \pm 0.03$ km/s.

impactor interface must be continuous. Using the subscript *1* to denote the target and *2* to denote the impactor we have,

$$P_1 = P_2 = P = \rho_{0,1} U_{S,1} u_p = \rho_{0,2} U_{S,2} (u_{imp} - u_p). \quad (3)$$

In Equation 3, ρ_0 is the density at zero pressure, u_{imp} is the impact velocity, and U_S is the shock velocity.

Using a linear $U_S - u_p$ equation of state for the impactor,

$$U_{S,2} = C_0 + S u_p. \quad (4)$$

Parameters used for Kel-F81, z-cut quartz, z-cut sapphire, and DC745 in Equations 3 and 4 are listed in Table II. Data for the Kel-F fit was taken from "LASL Shock Hugoniot Data"[12] and Sheffield et al.[13] Points originating from samples with $\rho_0 < 2.0$ g/cm^3 were excluded because the nominal density for Kel-F is 2.14 g/cm^3. Additionally, a few points with $u_p > 3.1$ km/s were excluded because it is believed the Kel-F may have reacted at these pressures. The fit for Z-cut sapphire is from Barker.[14]

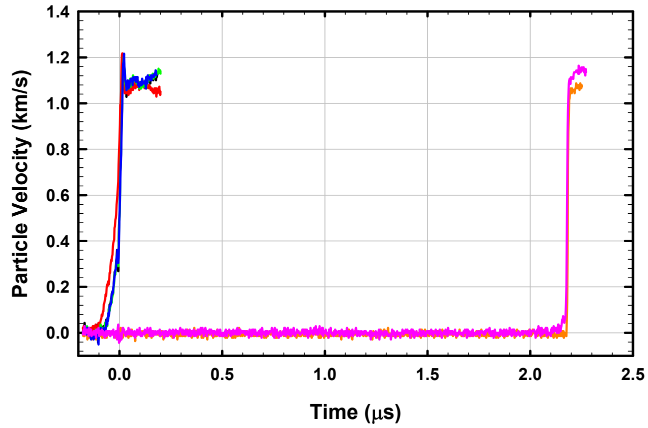

FIG. 6. Wave profiles from the four electromagnetic particle velocity 'stirrup' gauges for shot 2s-916. Input pressure is 6.7 ± 0.2 GPa. Particle velocity is $u_p = 1.12 \pm 0.03$ km/s. Transit time is $\Delta t = 2.182 \pm 0.040$ μs. Shock velocity is $U_S = 4.19 \pm 0.08$ km/s.

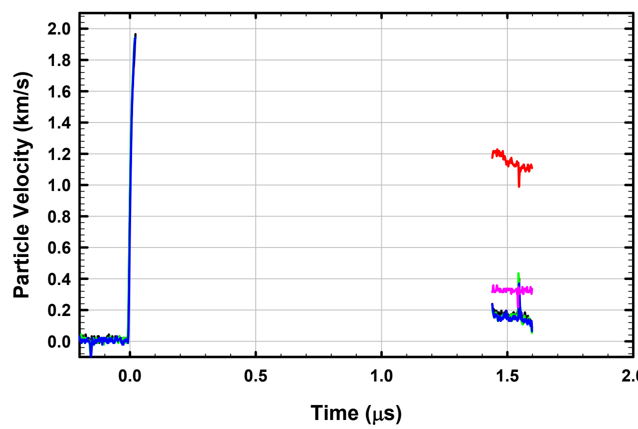

FIG. 7. Wave profiles from the four electromagnetic particle velocity 'stirrup' gauges for shot 2s-917. There were obviously severe problems with the gauges breaking early on. The impact surface particle velocity gauges stopped recording properly soon after wave arrival. They did, however give time of arrival and the indication that $u_p \sim 2$. The gauges embedded in the sample appear to put out an electromagnetic signal at $t = 1.544 \mu$s which is picked up and appears as a small "pip" on all of the gauges. We believe this signal was generated by the shock wave passing the second layer of gauges and inductively coupled onto all gauges. In summary, we take the shock transit time to be $\Delta t = 1.544 \pm$ 0.100 μs, where 100 ns is the order of the largest uncertainty in transit time of other experiments. Shock velocity is $U_S = 5.97 \pm 0.39$ km/s. Particle velocity by impedance matching is $u_p = 1.91 \pm 0.04$ km/s.

The fit for Z-cut quartz is from Knudson.[15] Parameter uncertainties for quartz and sapphire were assumed to be similar to those of Ta and Cu reported in Rigg et al.[16]

C. DC745U Hugoniot at -60°C

Figure 8 shows the $U_S - u_p$ Hugoniot for DC745 cooled to -60°C. Points from the current series that are listed in Table I are shown as blue points with error bars. Except for the point from 2s-917, we present the point from the direct measurement rather than the point from impedance matching. The solid black line is the Hugoniot for DC745 initially at room temperature: $U_S = 1.62 + 1.735u_p$.[4] The blue line is the Hugoniot at -60°Cfrom the present experiments $U_S = 2.03 \pm 0.06 + (2.03 \pm 0.06)u_p$ km/s. Note that DC745U is much stiffer at -60°Cthan at 23°C. This is undoubtedly due to the crystaline phase transition.

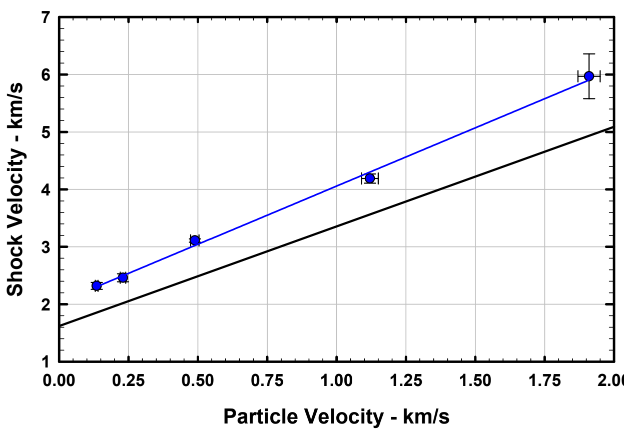

FIG. 8. Hugoniot for DC745U. The solid black line is the Hugoniot for DC745 initially at room temperature: $U_S = 1.62+1.735u_p$. Blue points and the blue line are the Hugoniot at -60°C.

IV. SUMMARY

We have completed a series of gas-gun driven plate impact experiments intended to measure the $U_S - u_p$ Hugoniot of the silicone elastomer DC745U cooled to -60°C. In summary, the initial density changes from ρ_0(23°C) = 1.312± 0.010 g/cm^3 to ρ_0(-60°C) = 1.447± 0.011 g/cm^3. The linear $U_S - u_p$ Hugoniot changes from $U_S = 1.62 + 1.74u_p$ km/s at +23°C, to $U_S = 2.03\pm0.06+(2.03\pm0.06)u_p$ km/s at -60°C. In conclusion, DC745U is much stiffer at -60°Cthan at +23°C, probably due to the crystallization that occurs at ∼ - 50°C.[6,7]

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TABLE I. Measured and calculated conditions in DC745U cooled to -60°C. Densities and thicknesses at -60°Cwere calculated as described in the text. U_S^* was calculated by impedance matching to the flyer using u_p from the stirrup gauges. u_p^* was calculated by impedance matching to the flyer using the measured U_S.

Shot no.	T °C	ρ_0(23°C) g/cm^3	ρ_0(-60°C) g/cm^3	Δx(23°C) mm	$\Delta x(-60°C)$ mm	impactor	u_{impact} mm/μs
1s-1605	-60±2	1.312±0.001	1.446±0.005	9.434±0.012	9.133±0.015	sapphire	0.150±0.001
1s-1604	-60±2	1.305±0.004	1.438±0.006	9.495±0.012	9.192±0.015	quartz	0.271±0.001
1s-1603	-60±2	1.319±0.013	1.455±0.015	9.445±0.021	9.142±0.023	quartz	0.614±0.001
2s-916	-60±2	1.299±0.001	1.433±0.005	9.449±0.029	9.147±0.030	kel-f	2.001±0.001
2s-917	-60±2	1.327±0.004	1.463±0.006	9.486±0.045	9.183±0.045	kel-f	3.548±0.001

Shot no.	Δt μs	U_S mm/μs	U_S^* mm/μs	u_p mm/μs	u_p^* mm/μs	P GPa	P^* GPa
1s-1605	3.944±0.110	2.32±0.06	3.5±1.3	0.135±0.005	0.139±0.001	0.45±0.02	
1s-1604	3.736±0.100	2.46±0.07	2.1±0.6	0.23±0.01	0.224±0.001	0.81±0.04	
1s-1603	2.943±0.030	3.11±0.03	3.0±0.5	0.489±0.015	0.486±0.002	2.21±0.07	
2s-916	2.182±0.040	4.19±0.08	4.1±0.3	1.12±0.03	1.113±0.008	6.7±0.2	
2s-917	1.544±0.100	5.97±0.39			1.913±0.044		16.7±1.2

TABLE II. Equation of State parameters used for Kel-F81, z-cut alpha quartz, z-cut sapphire and DC745U in Equations 1 and 2. Note also that r is the $C_0 : S$ cross correlation coefficient taken from the covariance matrix.

mat.	ρ_0 (g/cm^3)	C_0 (km/s)	S	r	ref.
kel-f81	2.137±0.004	2.032±0.016	1.676±0.011	-0.75	[12,13]
quartz	2.650±0.003	6.319±0.018	1.38±0.01		[15]
sapphire	3.985±0.003	11.19±0.018	1.0±0.01		[14]
DC745(+23°C)	1.312 ± 0.010	1.621	1.735		D. Dattelbaum in[4]
DC745(-60°C)	1.447 ± 0.011	2.03 ± 0.06	2.03 ± 0.06		This work