THE INFLUENCE OF TARGET TEMPERATURE ON CRATER MORPHOMETRY: EXPERIMENTS AND HYDROCODE MODELLING. M. C. Price[1], M. J. Burchell[1] and M. J. Cole[1]. [1]School of Physical Sciences, University of Kent, Canterbury, Kent, CT2 7NH, UK (corresponding author: mcp2@star.kent.ac.uk).

Introduction: We present data on an ongoing experimental and hydrocode modelling programme to investigate the effects of target temperature on the morphometry of hypervelocity impact craters. Experimental data on the effects of target temperature are sparse [1, 2], as most hypervelocity impact experiments are performed at room temperature. Here we have used a two stage light gas gun (LGG) [3] which can fire onto targets with a temperature range of 150 K – 550 K to increase the available data for both metal and rock targets [4] to help validate hydrocode modelling work.

Experimental methodology: In all cases the target was a 150 mm long x 60 mm diameter cylinder. The projectile was a 2 mm diameter sphere of the same material as the target. The target was heated in an in-situ heater in the LGG's target chamber. For cold target shots, the target was left overnight in a CO_2 freezer to reduce the temperature to 133 K then, immediately prior to the shot, it was further cooled in a LN_2 freezer to ~95 K. In both cases, the temperature of the target was monitored using a Pt-100 thermocouple so the temperature at impact was known to ±2 K.

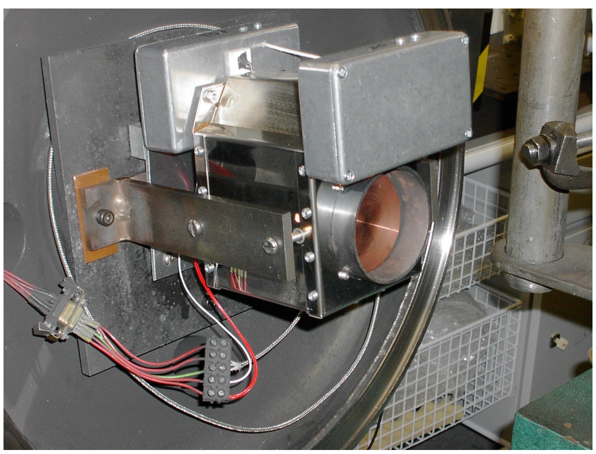

Fig. 1 Photograph of the in-situ LGG target heater showing a 60 mm diameter copper target prior to heating.

Hydrocode modelling: ANSYS' AUTODYN (v12.1) was used for all the modelling using the supplied, standard library material models for lead, copper and aluminium 6061. The thermal softening models incorporated were: Steinberg-Guinan [5] for lead and aluminium 6061; Johnson-Cook [6] for copper.

The model was a 2-D model (axial symmetry, see Fig. 2) with a resolution of 40 cells across the projectile diameter (1 cell = 50 μm). The target was modeled as a rectangle of 600 x 1000 cells with the mesh graduated along the long (impact) axis. All models were run for a simulated time of 50 milliseconds – sufficiently long to ensure that crater formation had completed.

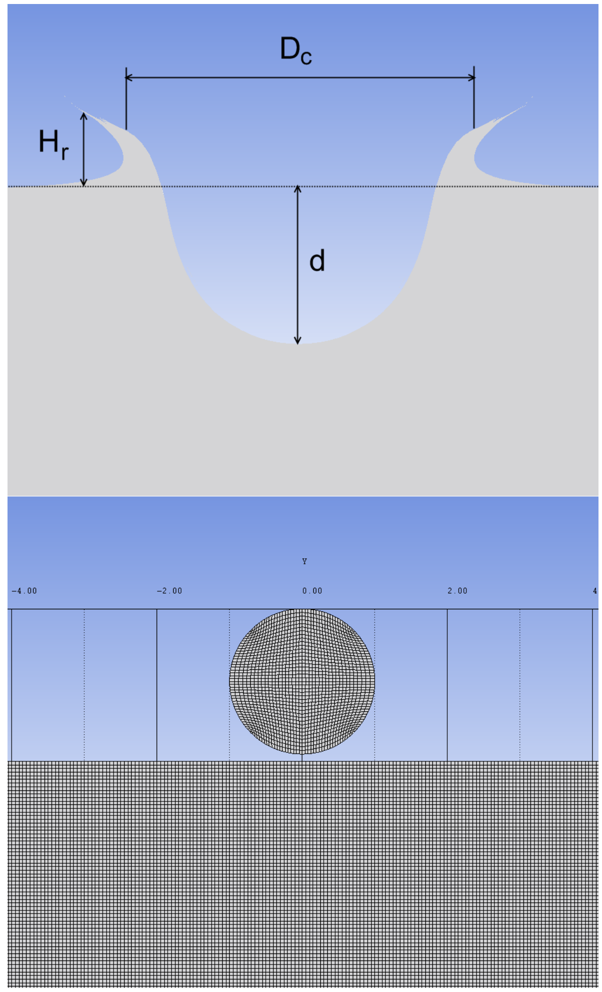

Fig. 2 Top: diagram showing AUTODYN output illustrating the nomenclature used to characterise crater dimensions. Bottom: diagram showing a close-up of the mesh used for the 2-D simulations.

Thermal softening models:

The Steinberg-Guinan model describes the yield strength, *Y*, of a material as:

$$Y \propto Y_o \left(\frac{G'_T}{G_o} (T - 300)(1 + \beta\varepsilon)^n \right)$$

where Y_o and G_o are the quasi-static yield strength and shear modulus (Pa), T is the temperature (K), ε is the strain, β and ε are material constants. G'_T is the rate of change of shear modulus with temperature (Pa K^{-1}).

The AUTODYN library values for aluminium 6061 are: β= 125, ε = 0.10 and G'_T= -1.70 x 10^4 kPa K^{-1} and, similarly, for lead: β= 110, ε = 0.52 and G'_T= -9.98 x 10^3 kPa K^{-1}.

For copper, thermal softening is modelled via the Johnson-Cook model where the temperature dependent component of the yield strength, Y, is described via:

$$Y \propto \left(1-\left(\frac{T-T_R}{T_m-T_R}\right)^m\right)$$

where T_R is the reference temperature (normally room temperature, K) at which the quasi-static yield strength is measured, T_m is the melting point temperature (K) and m is a material constant. AUTODYN library values for OFHC (oxygen free high conductivity copper) are: T_R= 300 K, T_m= 1356 K and m=1.09.

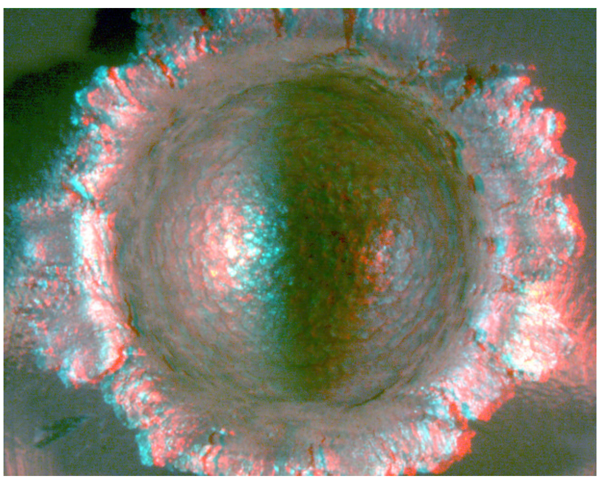

Fig. 3 Red-cyan anaglyph of a crater made in a copper target by a 2 mm copper projectile at 4.68 km s^{-1}. The target temperature at impact was 502 K.

Results: The results of the experimental and modelling programme are presented in Tables 1 – 3 for the lead, copper and aluminium targets respectively.

Symbols in the tables have the following meaning, ***T***: target temperature at impact (K). ***v***: impact velocity (km s^{-1}). $\boldsymbol{D_c}$: the rim-to-rim crater diameter (mm). $\boldsymbol{H_r}$: the crater rim height above the ambient target plane (mm). ***d***: the crater depth as measured from the target ambient plane (mm) (Fig. 2 – top panel). Superscript "**M**" refers to the corresponding AUTODYN modeled dimension. Figure 3 is a red-cyan anaglyph of a crater in a copper target formed by an impact from a 2 mm diameter copper sphere impacting at 4.68 km s^{-1}.

Table 1: Results for lead targets

T	v	D_c	D_c^M	H_r	H_r^M	d	d^M
507	4.34	25.1	17.8	3.2	*	12.5	9.50
402	3.86	19.5	17.3	2.5	*	7.84	8.82
350	3.93	17.5	17.3	1.8	*	7.79	8.76
293	3.81	16.6	13.2	1.8	*	8.96	7.63
293	2.07	11.7	11.0	1.4	*	5.19	5.93
170	3.90	15.6	13.3	2.5	*	6.73	7.66
173	4.05	14.3	17.4	2.0	*	5.26	8.58

*: No crater lip formation was observed in the impact simulation.

Table 2: Results for copper targets

T	v	D_c	D_c^M	H_r	H_r^M	d	d^M
502	4.68	12.3	11.7	2.1	2.1	4.73	5.80
293	4.66	11.2	11.8	1.8	2.3	4.34	5.69
293	5.55	12.6	12.6	2.1	2.5	4.64	6.44
293	5.15	11.1	12.2	1.9	2.3	4.24	6.11
137	3.59	9.50	10.4	1.5	1.8	3.40	4.67
118	5.50	12.0	12.3	1.8	2.4	4.48	6.23

Table 3: Results for aluminium targets

T	v	D_c	D_c^M	H_r	H_r^M	d	d^M
502	5.92	11.2	9.99	1.8	1.6	3.85	4.10
293	6.16	9.80	8.10	0.7	1.7	4.21	4.02
132	4.87	8.50	8.50	0.8	1.3	3.29	3.42

Conclusions: As expected, the crater size increases as the target metal approaches its melting point due to thermal softening and a loss of yield strength, with the greatest effect seen in the lead target. AUTODYN adequately reproduces crater dimensions for the copper and aluminium targets, but is far more inaccurate for the lead target, possibly as the melting point for the lead forming the targets differs from AUTODYN's library value. The target lead used is not pure lead, but structural lead containing impurities which may lower the melting point. Additionally, the thermal softening parameters quoted for lead may be inaccurate at temperatures close to its melting point.

Future work: We have recently acquired a 3-D reconstruction software package (Alicona's *MeX*) which will enable us to obtain much more precise measurements of the crater morphometry from stereo pair images. These data will be invaluable in determining the applicability of the thermal softening parameters used in AUTODYN for modelling hypervelocity impacts.

References: **[1]** K. Tanaka et al., (2008), *IJIE,* 35, 1821 – 1826. **[2]** D. Numata et al., (2008), *Shock Waves,* 18.3, 169 – 183. **[3]** M. J. Burchell et al., (1999) *Meas. Sci. & Tech.*, 10, 41 - 50. **[4]** A. Morris et al., (2010), these proceedings. **[5]** Steinberg, D. J. et al., (1980) *J. Appl. Phys.,* 51, 1498. **[6]** Johnson, G. R. and Cook, W. H., (1983) *Proc. 7th. Int. Symp. Ballistics*, 541 - 547.