Dynamical Behavior of Octahedrite from the Henbury Meteorite*

Michael D. Furnish¹, George T. Gray III² and John L. Remo³

¹Experimental Impact Physics Dept. 1433, Sandia National Laboratories, Albuquerque NM 87185

²MST-5, G730, Los Alamos National Laboratory, Los Alamos NM 87545

³Quantametrics, Inc., Brackenwood Path, Head of the Harbor, St. James, NY 11780

A suite of dynamic property measurements and characterization studies on an iron-nickel single crystal from the Henbury octahedrite containing Widmanstätten intergrowths of kamacite and taenite (initial density 7.810) has been performed. These measurements include six impact tests (wave profile compression/release) over the stress range 2 - 20 GPa, metallography, quasi-static and Hopkinson bar mechanical testing, and ultrasonic mapping and sound velocity measurements. A cryogenic impact test was included to evaluate effects of a brittle/ductile transition which has been reported at 200K. Temperature sensitivity of the dynamic behavior was measured at high and low strain rates. The impact test results show loading strength (HEL), Hugoniot and $\alpha \rightarrow \epsilon$ transition signatures to be similar to those for Armco iron, and do not show evidence for a ductile-brittle transition at these extremely high strain rates. Metallographic analyses, quasi-static and Hopkinson bar testing suggest that the material is in a work-hardened state and that kamacite properties dominate the bulk octahedrite properties.

INTRODUCTION

The dynamic response of materials representative of meteors, asteroids and comets is of interest for a variety of problems, most notably, those concerned with the origin of asteroids, with the deflection of large meteors or asteroids on Earth-intercepting paths, or with the modeling of terrestrial or extraterrestrial impact events.

Samples of the Henbury octahedrite were selected for testing as representative of the large class of iron-nickel meteorites. This central Australian fall, dated about 3,000 BC[1], has a composition roughly 7.5 wt% Ni, 0.4 wt% Co and 94% Fe (with traces of P, C, S, Cr, Cu, Ge, Ir, Ga and Zn.)

The microstructure of the Henbury consists of large lamellar kamacite (bcc-phase; nickel-poor) and mixed regions of taenite and plessite (fcc-phases; nickel-rich) as shown in Figure 1. Numerous deformation twins, labeled "A" in Figure 1, are seen within the kamacite lamellae. This microstructure is consistent with that previously documented as typical in octahedrite meteorites, such as the Henbury [1,2]. Previous studies have shown the

Henbury to consist of ~ 70-80 vol.% kamacite and 20-30% taenite and plessite[1], with minor schreibersite ((Fe,Ni)₃P) precipitates and occasional troilite nodules.

IMPACT EXPERIMENTS

Method and Matrix

A suite of six impact tests was designed to allow the observation of strength effects, the Hugoniot, the $\alpha \rightarrow \epsilon$ transition (in the bcc kamacite com-

Figure 1. Optical metallography of the Henbury showing deformation twins (labeled "A") in the kamacite.

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ponent), release properties and whether important effects of a brittle/ductile transition which has been reported at 200K are present. The configurations used are shown schematically in Fig. 2, with important dimensions given in Table 1.

Figure 2. Impact Configurations Used

Results

The three lower-velocity transmitted waveform tests gave the waveforms shown in Figure 3 (timed according to ultrasonic sound velocity measurements of samples).

The highest-velocity transmitted waveform is shown in Fig. 4 (note that this experiment utilized a LiF window). Of particular interest are the elastic precursors (amplitude 0.9 GPa) and the waveform morphology. The waveforms do not suggest an increased brittle component in the 163K test (OCT

Test →	OCT1	OCT2	OCT4	OCT3
<i>Projectile (thicknesses in mm)</i>				
Cu backer	3.199	3.205	3.189	12.649 (Al)
Space	0.095	0.254	0.301	4.973 (Foam)
Sapphire	3.193	3.193	3.189	1.647 (Cu)
<i>Target (thicknesses in mm)</i>				
Sample	4.999	5.006	4.996	4.999
Window	25.40	25.40	25.40	25.29 (LiF)
<i>Shot parameters (m/sec)</i>				
Impact Vel.	107	312	311	993
VPF	40.334	40.608	40.608	55.995
Test →	OCT5		OCT6	
<i>Projectile (thicknesses in mm)</i>				
Al Noseplate	3.199		3.205	
20# Foam	0.095		0.254	
Sample	3.193		3.193	
<i>Target (thicknesses in mm)</i>				
Sapphire Buffer	4.999		–	5.006
Sapphire Window	25.40		25.40	
<i>Shot parameters (m/sec)</i>				
Impact Vel.	107		312	
VPF	40.334		40.608	

Table 1. Parameters for Impact Tests

4) over the corresponding 300K test (OCT2).

Two reverse-ballistic (sample in projectile) experiments were conducted to provide a check on Hugoniot measurements as well as further information on release paths.

Hugoniot results are summarized in Table 3 for this material. In all cases, the starting density is

Figure 3. Forward-Ballistic Waveform (Sapphire window experiments)

Figure 5. Hugoniot of Henbury Octahedrite. Iron Hugoniot for comparison. Lagrangian analysis of Hugoniot state in OCT 3 is questionable because of large sample-window impedance mismatch.

□ ○ Present Data (Impedance match, Lagrange analysis, resp.)
+ × Armco and other Iron ($\bar{\rho} = 7.85$)

Figure 4. Forward-Ballistic Waveform (Lithium fluoride window experiment)

taken as 7.82 gm/cm³. For the reverse-ballistic tests (OCT 5 and 6), a precursor of amplitude 0.9 GPa and wavespeed 6 km/sec was assumed.

These Hugoniots are plotted against Armco iron data in Figure 5. Lagrangian analysis results and standard P/U_p impedance match results are included; only the latter are tabulated in Table 2.

Wavecode modeling of the two reverse-ballistic waveforms (Fig. 6), assuming a strength of 0.51 GPa and no phase transitions, produces good agreement with the observed velocity history. Agreement could be further improved by assuming a more dispersive lower release in OCT 6.

OTHER CHARACTERIZATIONS

The true stress-true strain response of the Henbury was measured at both quasi-static strain rates ($\sim 10^{-3} \text{ s}^{-1}$) and using a split-Hopkinson pressure bar (3000 s^{-1}) at 77 and 298K. The yield strength and work-hardening behavior of the Henbury meteorite are seen to depend on the strain rate and temperature of loading (Figure 7).

Figure 6. Reverse-ballistic waveforms with corresponding Mie-Grüneisen modeling

Test #	Particle Vel. km/s	Stress GPa	Density gm/cm ³	Shock Vel. km/s
OCT1	0.055	2.37	7.90	4.69
OCT2	0.174	6.24	8.13	4.44
OCT3	0.537	18.80	9.04	3.82
OCT4	0.166	6.57	8.09	4.97
OCT5	0.078	3.05	7.95	4.69
OCT6	0.218	8.85	8.17	5.13
<i>α → ε state</i>				
OCT3	0.335	13.34	8.41	5.05
<i>Elastic precursor states</i>				
OCT1	0.031	1.51	7.862	6.21
OCT2	0.020	0.93	7.849	5.92
OCT3	0.019	0.90	7.848	5.96
OCT4	0.020	0.93	7.849	6.01

Table 2. Hugoniot states for Henbury octahedrite.

Figure 7. Stress-strain response of Henbury as a function of temperature and strain rate.

Ultrasonic studies were also conducted with the samples prepared for impact testing. A coarse (2-8 mm) banded, granular structure is apparent in mappings of the longitudinal velocity and attenuation, with longitudinal velocity variations ranging up to 7% across the samples. Transducer shear velocity measurements made with the particle motion polarized along the bands gave sound velocities averaging 0.85 of the velocities measured for the perpendicular particle velocity motion. Transducer measurements of the longitudinal velocity were also made; these were increased by 15 m/sec to give the HEL velocities of Table 2.

DISCUSSION

Compared to its constituents the ~300 MPa yield strength at 0.001 s^{-1} and 298K suggests that the Henbury is in a work-hardened state. A rule-of-mixtures approximation to stress-strain data for pure Ni and Fe shows that ~15% true strain must be present in the meteorite to have a 300 MPa yield. This hardening is clearly related to the deformation twins and dislocation substructure in both phases. Definitive determination of the exact origin of this substructure however, including the twins, is difficult. While both earth cratering impact and very old events associated with parent break-up can both cause significant shock pulses in meteorites, previous studies suggest it is primarily preatmospheric[3]. Cosmic collisions remote in time and space are thought to generate the majority of the substructures and hardening seen in most meteor-

ites[3].

In addition, the yield strength of the Henbury is seen to increase from nominally 300 MPa to ~425 MPa with increasing strain rate at 298K or increase to ~550 MPa during low or high-rate testing at 77K. Increasing strain rate or decreasing temperature result in an increased level of work-hardening consistent with the suppression of dynamic recovery processes. The rate and temperature sensitivity of the yield stress is consistent with: a) the bulk mechanical response of the Henbury being controlled by the primary constituent, the bcc kamacite, and b) the work-hardened state of the Henbury overall leading to an increased rate and temperature sensitivity compared to annealed metals.

The strengths derived from the impact wave profiles ($Y = \sigma_{\text{HEL}} \cdot (1-2\nu)/(1-\nu)$; $\nu \equiv$ Poisson's ratio) of 450 MPa are consistent with the Hopkinson bar measurements, as well as with Armco iron data[4].

The α to ϵ transition was observed in the only impact test above 13 GPa. Its level (13.34 GPa) is similar to that reported for Armco iron (13 GPa [4]), with a slight elevation possibly due to nickel content. The density increase observed here (7%) is similar to that for Armco iron. There is, however, a puzzling post-Hugoniot decay in this waveform which may represent kinetics of the $\alpha \rightarrow \epsilon$ transition or micromechanical relaxation.

Finally, we do not find evidence in the wave profiles for the brittle - ductile transition inferred at ~200K[2]. This is not surprising considering that the present studies probed the high rate constitutive response of the Henbury rather than fracture processes. Fracture events depend critically on yield/failure surface interactions which can be stress state dependent and were not considered.

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