EOS DATA OF Ti-6Al-4V TO IMPACT VELOCITIES OF 10.4 KM/S ON A THREE-STAGE GUN

N. A. Winfree *, L. C. Chhabildas †, W. D. Reinhart †, D. E. Carroll † and G. I. Kerley**

*Dominca, Albuquerque, NM, 87111
†Sandia National Laboratories, Albuquerque, NM, 87185
**Kerley Technical Services, Appomattox, VA 24522

Abstract. Experiments were conducted to acquire Hugoniot data for Ti6-Al-4V at compressive stresses up to 250 GPa for use as a standard material on the three-stage gun at Sandia. Ti-6Al-4V was chosen over several other standards because in previous work on the three-stage gun it was most readily launched intact and flat. In each experiment, a graded-density launch plate travelling at 6.3 or 6.7 km/s launches a Ti-6Al-4V flier plate to 9.8 or 10.4 km/s. The flier impacts a stationary target disk of Ti-6Al-4V. Shorting pins and optical fibers imbedded in the target serve as time-of-arrival sensors to determine the shock velocity. These also permit quantification of the bow and tilt of the flier plate, which are found to be comparable to shots on two-stage guns. Corrections are made for the temperature of the flier in order to calculate the stress and particle velocity behind the shock.

INTRODUCTION

Existing data for the equation of state (EOS) behavior of Ti-6Al-4V extend to 202 GPa. This paper reports two new points at ~230 and 250 GPa, obtained on the Sandia hypervelocity launcher. This work was detailed in (1), but the data analysis has changed.

CONFIGURATION

The Sandia hypervelocity launcher has been described elsewhere (2, 3). In brief, a two-stage gun accelerates a graded density impactor to 6–7.5 km/s. This impactor enters a third stage and impacts a 17–19 mm diameter × 0.6–1 mm Ti-6Al-4V flier, Fig. 1. The graded density impactor is a 2–4 mm thick stack of plastic (TPX) and metal disks having densities that increase from 0.81 g/cm³ at the impact face to 16.96 g/cm³ farthest from this face. When this assembly impacts the flier, it induces a series of gradually increasing compressive shocks in the flier, approximating a “ramp wave.” This ramp wave launches the flier to 10–11.5 km/s with far less shock-induced heating than if it were launched to the same terminal velocity by a single-density impactor. A plastic disk on the flier’s impacted surface provides additional protection.

Ti-6Al-4V is used for the flier because, compared to other metals, greater success has been achieved launching it intact and flat from the third stage. A sacrificial guard ring bears the worst of the edge effects, leaving the center of the flier fairly flat.

The flier impacts a Ti-6Al-4V target (Fig. 2) instrumented with two types of sensors: mechanical pins short when the shock in the target encounters them, and optical fibers housed in...
hypodermic needles emit light when the shock encounters them. Six pins on diameter \(D_A\) are inserted from the non-impacted face into flat-bottomed holes that end on plane “A” near the impacted face. Six pins on diameter \(D_B\) end on plane “B,” approximately 2 mm behind plane A. Needles are inserted similarly. The pins and needles provide the transit time of the shock wave from plane A to plane B, from which the shock velocity \(U_S\) in the target is determined to within 2%. An extra pin on the centerline extends to plane A. Bow and tilt are calculated from the differences in the time of the shock’s arrival at each sensor on plane A.

The diameter of each plate is much greater than its thickness to ensure that waves emanating from the lateral surfaces do not reach the sensors during the duration of the experiment. Likewise, the radial distance between the diameters \(D_A\) and \(D_B\) is appreciably greater than the distance between planes A and B so that disturbances caused by the outer detectors would not reach the inner detectors.

The velocity \(V_1\) of the graded density impactor is determined to within 2% by detecting the times at which it breaks five beams of laser light spaced at \(~57\) mm increments.

With the target in place, the flier’s velocity \(V_0\) cannot be measured. Instead, it is predicted by CTH simulations: inputs include the velocity \(V_1\) of the graded-density impactor, and the thickness and material properties of each layer of the impactor and flier. This method is justified in (4): the flier’s velocity was determined by interferometry in four tests conducted with no target. The predicted and measured terminal velocities agreed within 1%.

Further details are given in (1).

RESULTS AND ANALYSIS

Two shots were conducted, Table 1. We assume that the \(x-t\) diagram of Fig. 3 represents the response of the target and the flier. Continuity and conservation of momentum require that particle velocity and stress must be continuous across the impact interface. Across the discontinuities that propagate into the flier and target, continuity and conservation of momentum impose the jump conditions

\[
u_p - V_0 = U_S' \gamma', \quad \rho_0' (u_p - V_0) U_S' = P, \quad (1)
\]
\[
u_p = -U_S \gamma, \quad \rho_0 u_p U_S = P, \quad (2)
\]

where \(\gamma = (\rho_0 - \rho)/\rho\) and \(\gamma' = (\rho_0' - \rho')/\rho'\).

As one bound, assume “symmetric impact,” i.e., that the target and flier have identical densities and temperatures at impact, and that their responses are identical. We impose \(U_S' = U_S, \rho_0' = \rho_0,\) and \(\rho' = \rho\) in (1) and (2), then solve for \(P,\)
TABLE 1. Impact parameters in second stage, calculated terminal velocity $V_Q$ of flier launched from second stage, measured shock velocities $U_S$ in third stage, and tilt and bow in third stage.

<table>
<thead>
<tr>
<th>Shot</th>
<th>TPX/Mg/Al/Ti/Cu/Ta</th>
<th>$V_1$ km/s</th>
<th>$V_0$ km/s</th>
<th>Sensors</th>
<th>$U_s$ km/s</th>
<th>Tilt</th>
<th>Bow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Needles</td>
<td>10.566</td>
<td>2.96</td>
<td>≈10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Needles</td>
<td>11.074</td>
<td>8.22</td>
<td>5.8</td>
</tr>
</tbody>
</table>

$u_p$, and $\rho$. The results are included in Table 2 and Figures 4 to 6.

The preceding analysis does not account for shock-induced heating of the flier during launch. To correct for this, we first need the temperature in the flier. Therefore we conducted experiments with no target, monitoring the flier's free surface with infrared pyrometry. These suggested that its temperature did not exceed 650 K when launched to 9.8 km/s, or 850 K when launched to 10.8 km/s. Linearly extrapolating $V_0$ for HVLTi7-P and interpolating for HVLTi8-P produces the upper temperature bounds given in Table 2.

We find the density of the flier at the elevated temperatures from $\rho'_0 = \rho_0 / (1 + \alpha \Delta T)^3$, where $\alpha$ is the coefficient of linear expansion measured between room temperature (assumed to be 298 K) and the elevated temperature. The results are given in Table 2.

Finally, we assume that the propagation velocities $U'_S$ and $U_S$ are related to the jump in particle velocity across them by the same linear relation:

$$U_S = c_0 + S u_p, \quad U'_S = c_0 + S(V_0 - u_p).$$  \(3\)

From (1)–(3) we can find

$$\rho_0 U_S u_p = \rho'_0 (U_S + S(V_0 - 2u_p))(V_0 - u_p).$$  \(4\)

All quantities except $u_p$ and $S$ in (4) are known. We found that varying $S$ from 0.9 to 1.4 produced less than 0.1% change in $u_p$, $P$, and $\rho$. Existing data for $u_p > 1.8$ km/s are well-described by $U_s = c_0 + S u_p$ with $S \approx 1.1$, so we chose $S = 1.1$. Substituting for $S$ in (4), we solve for $u_p$, then use (1) and (3) to find the other unknowns. The results are given in Table 2 and Figures 4 to 6.

CLOSING REMARKS

The Sandia hypervelocity launcher has been used to acquire two new data points for the equation of state (EOS) behavior of Ti-6Al-4V above 220 GPa. The data were first analyzed without accounting for thermal expansion in the flier caused by shock-induced heating during launch. Then, the maximum temperature of the flier was bounded by pyrometry, and the data analyzed using the density of Ti-6Al-4V at this temperature. The results of the two analyses are nearly identical, and suggest that Ti-6Al-4V stiffens considerably at these high pressures.

ACKNOWLEDGEMENT

The authors are grateful to T. K. Bergstresser for assistance in pyrometry.

REFERENCES

TABLE 2. Results of analyses.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Symmetric analysis</th>
<th>Analysis that accounts for density change of flier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$ (GPa) $u_p$ (km/s) $\rho$ (g/cm$^3$)</td>
<td>$T$ (K) $\alpha$ (5) $\rho_0^0$ (g/cm$^3$) $P$ (GPa) $u_p$ (km/s) $\rho$ (g/cm$^3$)</td>
</tr>
<tr>
<td>HVLT17-P Pins</td>
<td>229.1 4.885 8.181</td>
<td>644 9.8e-6 4.373 228.3 4.868 8.160</td>
</tr>
<tr>
<td>HVLT17-P Needles</td>
<td>228.0 4.885 8.212</td>
<td>644 9.8e-6 4.373 227.2 4.868 8.194</td>
</tr>
<tr>
<td>HVLT18-P Pins</td>
<td>252.3 5.200 8.383</td>
<td>770 10.1e-6 4.355 251.1 5.175 8.355</td>
</tr>
<tr>
<td>HVLT18-P Needles</td>
<td>264.4 5.200 8.336</td>
<td>770 10.1e-6 4.355 253.2 5.175 8.294</td>
</tr>
</tbody>
</table>

**FIGURE 4.** Shock velocity versus particle velocity in the target. “x” = previous data (6, 7, 8). “o” = present work assuming symmetric impact. “+” = present work compensated for thermal expansion of flier. Results using both pins and needles are plotted.

**FIGURE 5.** Shock velocity versus specific volume ratio $v/v_0 = \rho_0/\rho$. Symbols as in Fig. 4.