Ballistic Limit Equation for Single Wall Titanium

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Abstract: Hypervelocity impact tests and hydrocode simulations were used to determine the ballistic limit equation (BLE) for perforation of a titanium wall, as a function of wall thickness. Two titanium alloys were considered, and separate BLEs were derived for each. Tested wall thicknesses ranged from 0.5mm to 2.0mm. The single-wall damage equation of Cour-Palais [ref. 1] was used to analyze the Ti wall's shielding effectiveness. It was concluded that the Cour-Palais single-wall equation produced a non-conservative prediction of the ballistic limit for the Ti shield. The inaccurate prediction was not a particularly surprising result; the Cour-Palais single-wall BLE contains shield material properties as parameters, but it was formulated only from tests of different aluminum alloys.

Single-wall Ti shield tests were run (thicknesses of 2.0 mm, 1.5 mm, 1.0 mm, and 0.5 mm) on Ti 15-3-3-3 material custom cut from rod stock. Hypervelocity impact (HVI) tests were used to establish the failure threshold empirically, using the additional constraint that the damage scales with impact energy, as was indicated by hydrocode simulations. The criterion for shield failure was defined as no detached spall from the shield back surface during HVI. Based on the test results, which confirmed an approximately energy-dependent shield effectiveness, the Cour-Palais equation was modified. The resulting equation is

$$tw = 2.4 * 5.24 * BHN^{-0.25} * \rho t^{-0.5} * Ct^{-(2/3)} * [(12/\pi) * \rho p^{+0.5} * E]^{+(1/3)}$$

where

- tw is the Ti wall thickness [cm]
- BHN is the Ti Brinell Hardness Number
- ρt and ρp are material densities of Ti and impacting particle, respectively [g/cc]
- Ct is the speed of sount in the Ti
- E is the impact energy [J]

A single thickness of Ti 15-3-3-3 alloy from sheet stock material was also subjected to impact tests at three different impact energies. It had a lower Brinnell hardness number (BHN), due to heat treatment. Because of its lower BHN, the modified Cour-Palais equation would predict that it fails at lower impact energy. However, it performed as well as the other Ti material. The 1.6mm wall withstood a 7.2J impact, although the BLE predicted failure from a 4.3J impact. It seems unlikely that the experimental uncertainty or shot-to-shot variability of a single-wall test would explain the discrepancy. Some unidentified dependence on material properties seems to be the most plausible avenue for further study.

Reference

1. Christiansen, E.L., "Design and Performance Equations for Advanced Meteoroid and Debris Shields", Int. J. Impact Eng. Vol. 14, pp 145-156, 1993.