International Journal of Impact Engineering 116 (2018) 34–50

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

A scaling law for predicting the ballistic limit of aluminium alloy targets perforated in ductile hole formation

Shannon Ryan[a,*], Long H. Nguyen[a], Denver Gallardy[b], Stephen J. Cimpoeru[a]

[a] Defence Science and Technology Group, 506 Lorimer St., Fishermans Bend, VIC 3207, Australia
[b] U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066, USA

ARTICLE INFO

Keywords:
Terminal ballistics
Armour
Aluminium
Predictive modelling

ABSTRACT

The ballistic performance of monolithic targets perforated in ductile formation by rigid projectiles can be reasonably approximated by an energy balance based on the work done in expanding a hole from zero initial radius to that of the penetrating projectile. For a specific projectile, these energy balance laws can be expressed in terms of a simple scaling law which requires an empirical fit to ballistic data. However, once this fit has been performed for a specific projectile against a specific target material, predicting the performance of other materials against this projectile can be done from a simple quasi-static compression stress–strain curve, provided the target is perforated in ductile hole formation. Four variations of ductile hole formation analytical and semi-empirical models have been reformulated as scaling laws and evaluated for their ability to characterise the performance of monolithic aluminium plates impacted by 7.62 mm APM2 projectiles at normal incidence. The database used to fit and evaluate the performance of the scaling laws incorporates more than 1600 V_{50} measurements against 24 different alloys and tempering/strain-hardening combinations with thicknesses ranging from 16.2 to 63.5 mm. The highest performing scaling law formulation was found to characterize the measured V_{50} to within 5% of the experimental value for over 97% of the database entries. Further improvements in accuracy are likely impossible when representative stress–strain curves are used for performance characterization rather than tests of each individual plate used in the ballistic tests. The scaling law can be applied to predict the performance of targets perforated in ductile hole formation with a high level of confidence, an example of which is provided for the 12.7 mm APM2 projectile against a range of aluminium alloys.

1. Introduction

Predicting the outcome of ballistic interactions is a highly complex problem due to the wide range of materials, geometries, loading rates, and subsequent failure mechanisms of projectile and armour components. Woodward [1] provided an overview of metallic target failure modes, reproduced in Fig. 1, which serves to illustrate the complexity of the problem. Typically, the applicability of a penetration algorithm is limited to a single failure mode.

The perforation of a ductile target by a hard, sharp-nosed penetrator has been experimentally observed to occur through ductile hole formation, some examples of which are shown in Fig. 2. For this condition, the ballistic limit of the target armour can be estimated by the work required to expand a hole from zero initial radius to that of the penetrating projectile according to cylindrical cavity expansion theory (based on Taylor [2]),

$$W_{DHF} = \pi r^2 h_0\ C\ \sigma \tag{1}$$

where r is the final radius of the hole (i.e. half the projectile calibre), h_0 is the initial thickness of the target, σ is the stress at the edge of the hole in the target material, and C is a constant referred to as the shape factor which defines the thickening at the edge of the expanded hole, $C = h/h_0$.

The ballistic limit, V_{bl}, is determined by equating the work done in cavity expansion, W_{DHF}, to the kinetic energy of the projectile, i.e.

$$\frac{1}{2} m_p V_{bl}^2 = \pi r^2 h_0\ C\sigma \tag{2}$$

where m_p is the mass of the projectile. Rearranged, the ballistic limit is calculated as:

$$V_{bl} = \sqrt{\frac{2\pi r^2}{m_p} h_0 C\ \sigma} \tag{3}$$

The product of the shape factor, C, and radial stress at the edge of the hole, σ, defines the work per unit volume done in expanding the hole. There are a number of formulations of Eq. (3) that vary, for the

* Corresponding author.
E-mail address: shannon.ryan@dst.defence.gov.au (S. Ryan).

https://doi.org/10.1016/j.ijimpeng.2018.02.005
Received 11 December 2017; Received in revised form 12 February 2018; Accepted 13 February 2018
Available online 15 February 2018

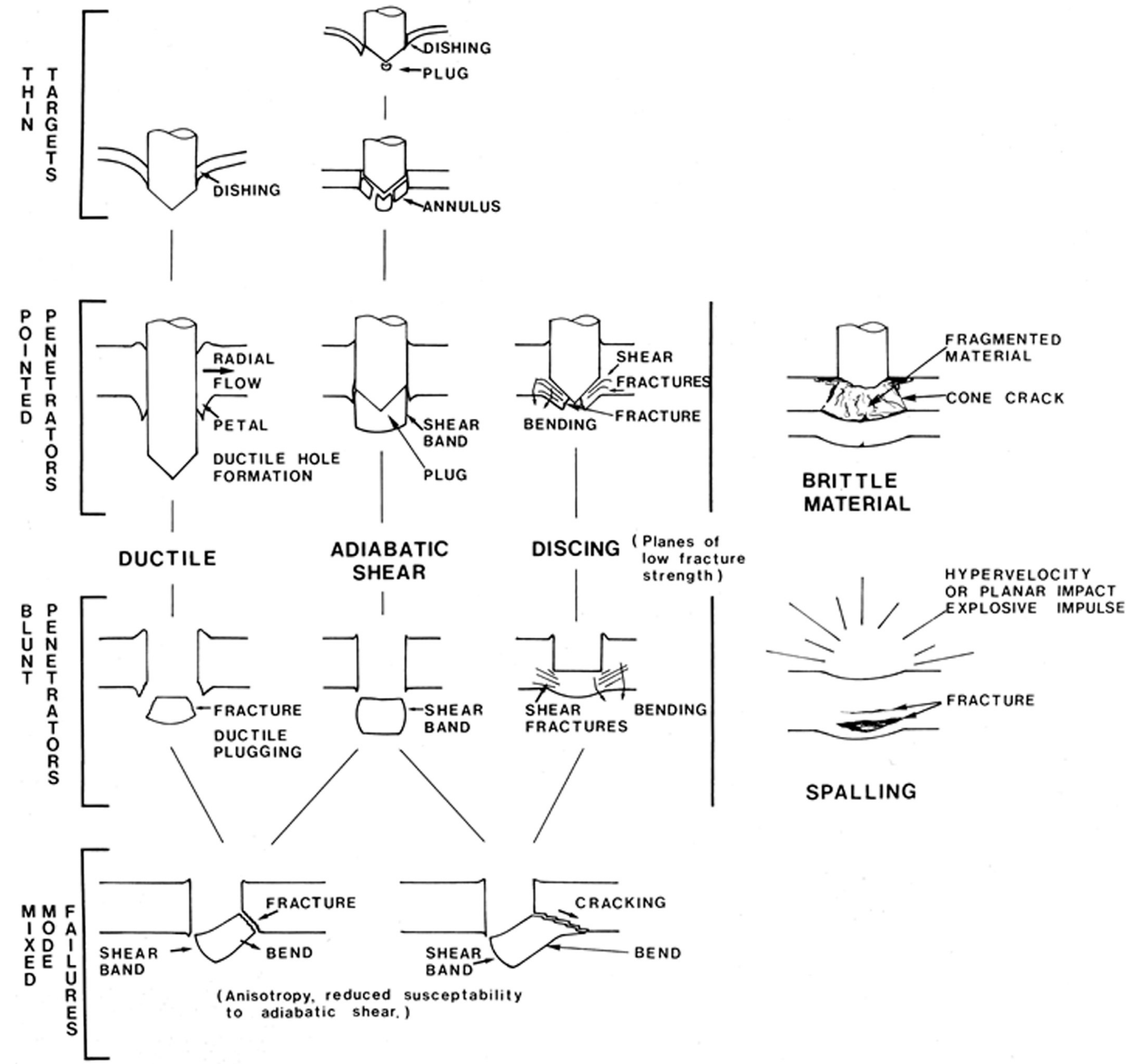

Fig. 1. Classification of failure modes to illustrate the influence of material properties, structure, projectile and plate geometry on the outcome of a dynamic impact event [1].

most part, in the formulation of this product. Taylor [2] found thickening at the boundary of a cylindrical cavity to be 2.66 times the original plate thickness, i.e. $C = 2.66$. Taylor defined the radial stress at the edge of the expanded hole, $\sigma = -Y/2$, where Y is the tensile yield strength of the material. Thus the work per unit volume in expanding the hole, $C\sigma$, is equal to 1.33Y. In [2] Taylor refers to previous work by Bethe [3] in which the shape factor, $C = 2.0$, however in this formulation the radial stress at the edge of the hole is simply $-Y$, thus the specific work per unit volume required to expand the hole is 2Y, i.e. greater than that formulated by Taylor. Hill [4] performed an improved integration of Taylor's work and found a shape factor $C = 3.84$, resulting in a specific work of 1.92Y closer to the value of Bethe's 2.0 (using the radial stress definition of $-\ Y/2$). Variations in the solutions by Bethe and Taylor are found to be a result of the material constitutive formulation – Bethe's solution uses a Tresca model for the material response while Taylor (and in turn, Hill) use a mixed Tresca-Mises material response [5].

Woodward [6] reviewed the accuracy of Eq. (3) with Taylor's values for shape factor and radial stress, and determined that for a range of conditions the work performed, and thus the ballistic limit, was under estimated for armour materials which exhibit ductile flow failure. Rather than relating the radial stress at the edge of the hole to yield strength, $\sigma = -Y/2$, Woodward proposed using a material flow stress, σ_0, defined either directly from quasi-static test data or via the Holloman power fit [37]:

$$\sigma_0 = K\varepsilon^n \quad (4)$$

where K and n are constants defining the strength and work hardening behaviour of the material, respectively. Woodward regularly defined the flow stress at a true strain of 1.0, however the definition of σ_0 can be made at any sufficiently high level of true strain, providing the strain hardening has plateaued [6].