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Predicting indenter nose shape sensitivity for quasi-static perforation of thin metallic plates

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ABSTRACT

Perforation resistance is an important design consideration for thin-walled metallic structures. However, the perforation energy of thin metallic plates is known to be sensitive to the nose shape of the indenter. This poses a challenge for predictive modelling, both analytical and numerical, as the material deformation and state of stress at the onset of failure can vary significantly from one indenter geometry to the next. Effective design requires an understanding of the key modelling parameters, and their influence on the predicted perforation response, across the widest range of possible indenter geometries. This paper aims to investigate systematically the indenter nose shape sensitivity of the quasi-static perforation of a 1 mm thick plate of aluminium alloy 6082-T4, and the modelling of the conditions at failure. The nose shape of the indenter is gradually changed from flat (i.e. blunt) to hemi-spherical either by (i) introducing a chamfer at the edge of the indenter or (ii) by changing the indenter frontal nose radius. This allows a wide range of states of deformation at the onset of failure to be spanned. The problem is investigated by both analytical and numerical methods. The results of both modelling techniques are compared with quasi-static perforation experiments, and the conditions necessary to achieve good agreement are obtained. Careful consideration of (i) material anisotropy, (ii) indenter-plate friction and (iii) boundary compliance is necessary for accurate prediction of the perforation energy. A Lode angle-dependent model for the onset of failure in the metal is found to be essential for predicting the perforation response for a range of indenter chamfer radii.

1. Introduction

The perforation resistance of thin-walled metallic structures, for both quasi-static and impact loading, is known to strongly depend on the nose shape of the indenter. The tip geometry controls the mode of deformation, and the type and distribution of fracture observed during the perforation. Four types of indenter nose shape have formed the focus of most previous investigations of perforation: flat (i.e. blunt), hemi-spherical, conical and ogival tips. These induce contrasting failure mechanisms in the target. For most studies of thin, ductile metallic plates reported in the literature, perforation resistance is highest for a hemi-spherical nose shape (Corran et al., 1983; Gupta et al., 2007; Kpenyigba et al., 2013). In this case, failure is by tensile tearing, which is observed to dissipate more energy than alternative failure mechanisms such as shear plugging or discing (Grytten et al., 2009; Langseth and Larsen, 1994; Liu and Stronge, 2000) for flat-nosed, or petal bending for conical- and ogival-tipped indenters (Iqbal et al., 2010; Landkof and Goldsmith, 1985; Leppin and Woodward, 1986).

The transition between different failure modes and its effect on the perforation resistance have been investigated in the literature by gradually changing the nose shape from one to another (e.g. flat to hemi-spherical). Corran et al. (1983) conducted a series of impact tests on 1.3 mm mild steel targets – their tests used a 12.5 mm diameter projectile. They progressively changed the ratio of the projectile radius to the tip radius (R_I/R_f) from 0 to 1, corresponding to the limits of a blunt and a hemi-spherical tip, respectively (Fig. 1a). It was observed that failure occurs by plugging when $R_I/R_f < 0.52$. On the other hand, for larger ratios (e.g. $R_I/R_f = 0.66–1$) failure occurs by tensile tearing. Their results show a maximum in the perforation energy at a tip geometry for which the transition between these two failure modes occurs.

A similar change in the failure mode was also observed by Teng and Wierzbicki (2005) by altering the size of the chamfer (R_{ch}) on a circular cylindrical projectile of radius R_I (Fig. 1b). Their numerical

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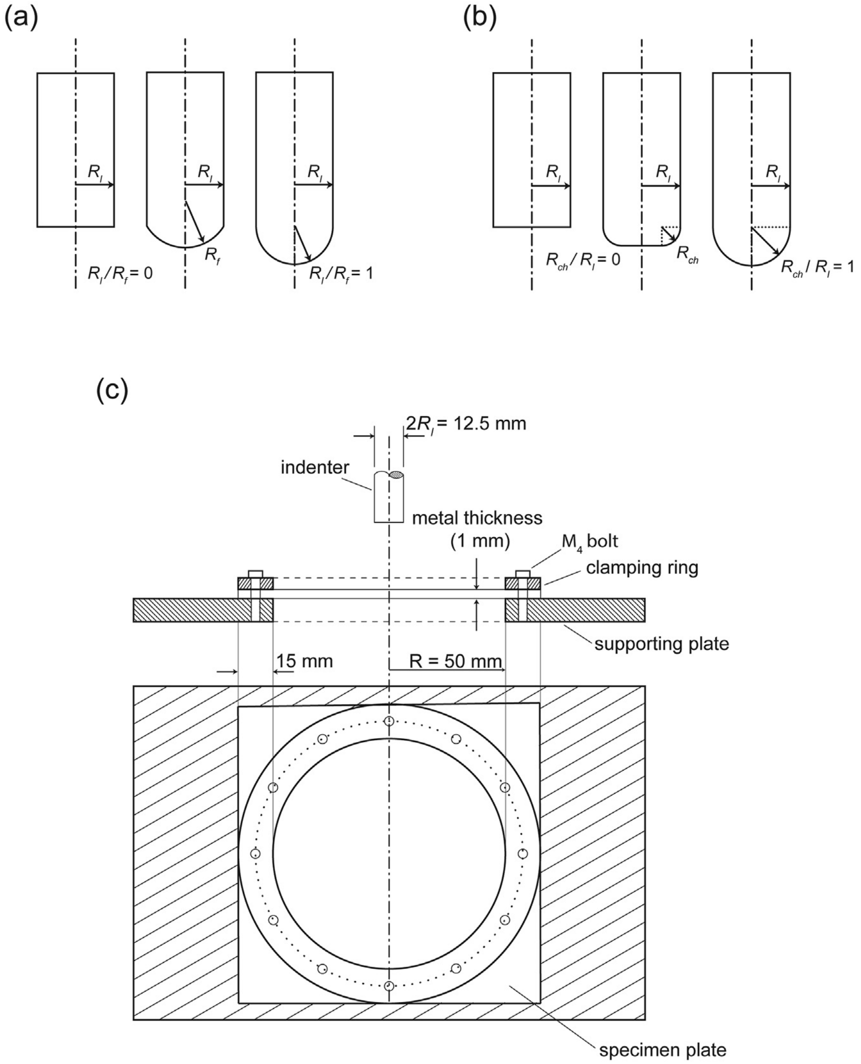

Fig. 1. Schematic of the two indenter nose shape types, permitting a transition from a flat to a hemi-spherical indenter by (a) changing the frontal nose radius (R_f) and (b) introducing different chamfer radii (R_{ch}). (c) The plate clamping arrangements for the punch indentation tests.

results suggest that while shear plugging occurs under a blunt projectile (i.e. $R_{ch}/R_I = 0$), the failure mode changes to tensile failure for $R_{ch}/R_I = 0.5$. Note that a hemi-spherical tip corresponds to $R_{ch}/R_I = 1$. Iqbal et al. (2010) numerically investigated the effect of changing the nose shape on the ballistic limit and failure modes of metallic targets. They changed the projectile nose shape from flat to hemi-spherical and ogival by changing R_{ch} in the range $0 \leq R_{ch}/R_I \leq 5$. Values of $R_{ch}/R_I > 1$ represent ogive nosed projectiles (Iqbal et al., 2010). Their results for 1 mm thickness aluminium targets suggest that the ballistic limit increases as the tip is changed from a blunt to a hemi-spherically tip projectile, and then significantly drops for ogive nosed projectiles. For $R_{ch}/R_I > 2$, the ballistic limit becomes less sensitive to further increases in the chamfer radius.

In all of the above studies, the failure mode transition was achieved by changing the shape of a non-deformable indenter (or projectile). However, for a single nose shape, a change in the failure mode can also be observed if a more deformable indenter is used. Liu and Stronge (2000) investigated the effect of projectile deformability on the failure modes and ballistic limit of metallic targets. The projectiles were all initially blunt and had the same mass, but were made from different materials, including pure aluminium, two types of aluminium alloy and PTFE. By decreasing the material strength, more deformation (normally called ‘mushrooming’) occurred in the projectile. As a result, both the diameter and tip radius of the projectile change. This has a direct effect on the failure mode in the metal target. For a projectile with higher strength, shear failure is most likely to occur. Conversely, for more deformable projectiles, tensile tearing is more favourable. The increase in the ballistic limit for softer projectiles is considered to be the result of more dishing in the plate (Liu and Stronge, 2000). The mushroomed nose observed for softer projectiles caused larger curvatures at the periphery of the contact region which reduced the shear strains (Liu and Stronge, 2000).

For a non-deformable indenter (or projectile), the effective nose shape can also be changed indirectly by placing a layer of a soft and deformable material in front of the target (e.g. in the case of polymer-metal bi-layers (Mohagheghian et al., 2016)). Deformation of this soft layer between the projectile and the metal backing changes the effective nose shape of the projectile, alters the failure mode and in turn increases the energy absorbed by the metal layer (Mohagheghian et al., 2016). This phenomenon is found to be very sensitive to the thickness of the soft layer and the initial indenter geometry (Mohagheghian et al., 2016). The biggest increase in the perforation energy is observed for a blunt indenter when the