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A numerical study on the deformation and fracture modes of steel projectiles during Taylor bar impact tests

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ABSTRACT

A heterogeneous material model based on macro-mechanical observations is proposed for simulation of fracture in steel projectiles during impact. A previous experimental study on the deformation and fracture of steel projectiles during Taylor bar impact tests resulted in a variety of failure modes. The accompanying material investigation showed that the materials used in the impact tests were heterogeneous on scales ranging from microstructure as investigated with SEM to variation in fracture strains from tensile tests. A normal distribution is employed to achieve a heterogeneous numerical model with respect to the fracture properties. The proposed material model is calibrated based on the tensile tests, and then used to independently simulate the Taylor bar impact tests. A preliminary investigation showed that the simulations are sensitive to assumptions regarding the anvil behaviour and friction properties. A flexible anvil and a yield-limited friction law are shown to be necessary to correctly reproduce the experimental behaviour. The proposed model is then shown to be capable of correctly reproducing all fracture modes but one, and also predict critical impact velocities for projectile fracture with reasonable accuracy. Fragmentation at velocities above the critical velocity is not well reproduced due to excessive element erosion. Measures to make the element erosion process more physical are proposed and discussed with their respective drawbacks. The use of a simple fracture criterion in combination with an element erosion technique accentuates the effect of distributing the fracture parameter.

1. Introduction

The Taylor bar impact test, proposed by Taylor (1948), Whiffin (1948) and Carrington and Gayler (1948) as an experimental method to measure the dynamic yield strength of metallic materials, has been a subject for numerical calculations since the early seventies (Wilkins and Guinan, 1973). This coincides with the evolution of hydrocodes and with the implementation of plasticity in both Eulerian and Lagrangian codes in the years prior to this (Johnson and Anderson, 1987). Lagrangian codes are in general better suited for Taylor bar impact test problems because the history dependent behaviour of a material point in plasticity is tracked exactly (Anderson, 1987), even though the possibly large distortion of the mesh may be detrimental for the critical time-step in the simulations.

Subsequent investigations have shown that the usefulness of the Taylor bar impact test as a material characterisation test is minimal, since Taylor's original analysis is too simplified to accurately describe the dynamic yield stress and the final displacements of the specimen (Johnson, 1972). However, previous investigations on the ballistic perforation resistance of armour plates have shown that the projectile may fracture upon impact (Børvik et al., 2003; Dey et al., 2004, 2007). In that sense, the Taylor bar impact test is ideal for investigating the projectile deformation and fracture modes isolated from the target plate behaviour. It has also been shown that computer-aided designs of protective structures with insufficient fracture criteria for the projectile may cause misleading conclusions (Dey et al., 2011). Based on this, a thorough experimental study of the deformation and fracture modes of steel projectiles at three different hardness values, combined with a material investigation including tensile tests and metallurgical studies, was conducted (Rakvåg et al., 2013). The final goal of the present work is to use this new knowledge to predict the critical velocity for projectile failure and the associated loss of penetrating capability, and thus to increase the reliability of computer-aided design of protective structures.

Failure modelling in numerical simulations of ballistic impact problems has been investigated for a long time (Bertholf et al., 1975), but this work has mainly concentrated on fracture in the target. The earliest efforts limited itself to a measured value of a critical stress or strain, whereas contemporary methods often

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employ a cumulative damage function, based on macro-mechanical tests (Johnson and Cook, 1985) or micromechanical analysis (Gurson, 1975). In consideration of dynamic fracture, time dependence is observed (Tuler and Butcher, 1968), which should be accounted for. The time dependence is due to inertia effects on void growth, favouring void nucleation (Antoun et al., 2003).

In the Taylor bar impact test, large strains combined with high strain rates result in adiabatic heating of the material (Johnson et al., 2006). Thus, it is often used as validation of thermoviscoplastic constitutive models such as the Johnson–Cook (1983) and the Zerilli–Armstrong (1987) models. An interesting observation is that Johnson and Cook (1983, 1985) found discrepancies both for the final shape and the damage evolution between their numerical results and experiments. We will show that these discrepancies may be attributed to the stiffness of the anvil and frictional effects which are two simplifications from Taylor's original analysis that are not justified in all cases.

Regarding simulation of fracture in the Taylor bar impact tests, the work of Johnson and Cook (1985) is already mentioned. They did not simulate crack propagation explicitly with element erosion, but observed that their damage model did not predict fracture at the critical impact velocity from experiments. Anderson et al. (2006) obtained the opposite result using a simplified version of the Johnson–Cook damage model. Their numerical simulations predicted failure at lower impact velocities than the experiments. These results highlight some of the difficulties in predicting failure in the projectile in numerical simulations of the Taylor bar impact test.

In Fig. 1 five distinct failure and fragmentation modes in the projectile during the Taylor bar impact test are shown. These are in order of increasing severity: (a) plastic mushrooming without any visible cracking, even though extensive void growth just behind the centre of impact due to hydrostatic tension in the projectile may still occur; (b) tensile splitting on the edge of the mushroomed end due to tensile hoop strains exceeding the material ductility; (c) adiabatic shear cracking either by (1) principal shear fracture where a circular wedge separates or (2) combined spiral shear fracture and tensile splitting where the mushroomed material separates from the impact end of the projectile; (d) petalling initiated by tensile splitting that may cause fragmentation of the petals at the highest impact velocities and (e) full fragmentation initiated by crack growth from one or several shear cracks. Note also that combinations of two or more of these generic modes are likely in real situations.

Teng et al. (2005) recreated numerically three of these fracture modes, namely interior void growth, spiral shear fracture and petalling. They also compared results obtained with the Johnson–Cook fracture criterion with a fracture locus proposed by Bao and Wierzbicki (2004). Based on this they proposed a modification of the Johnson–Cook fracture model in which the fracture strain approaches infinity when the stress triaxiality goes to $-1/3$. They further showed that this modification of the Johnson–Cook fracture model gives fewer eroded elements for simulations of ductile steel projectiles. The latter result was also shown by Xiao et al. (2011) for simulations of a high strength aluminium alloy. In addition, they performed experiments and showed that simulations with a cut-off on the failure strain in the Johnson–Cook model predicted more realistic critical velocities for the various fracture modes. It was also shown that fewer eroded elements gave a better representation of the physical damage modes. In an evaluation of several fracture models for Taylor bar impact tests, Zhang et al. (2011) concluded that a modified Johnson–Cook model with a cut-off criterion or the Cockcroft–Latham (1968) fracture criterion are the best options.

Although it is common to use homogeneous fracture properties in numerical simulations, the stochastic nature of fracture can be deduced already from Leonardo Da Vinci's tensile tests of wire (Lund and Byrne, 2001). This is the earliest scientific material investigation recorded (Timoshenko, 1953), and it has been used in analysis of fracture and fragmentation since around WWII (Mott, 1947). In numerical simulations of fracture, a Weibull distribution, as in the Beremin model (1983), is often used. In the Beremin model, the Weibull distribution of the fracture parameter is coupled with a term V/V_0, where V is the volume represented by the integration point and V_0 is a reference volume. The result of this is that with mesh refinement, the average integration point becomes stronger, but since there are more elements in the refined mesh the probability of failure initiation is the same in the domain regardless of mesh size. With this approach the size effect on failure will be reproduced automatically, since a larger domain increases the possibility for the onset of failure.

The method described above assumes that when the first point in the domain reach failure, it immediately follows that the rest of the structure fails catastrophically (Meyer and Brannon, 2012).

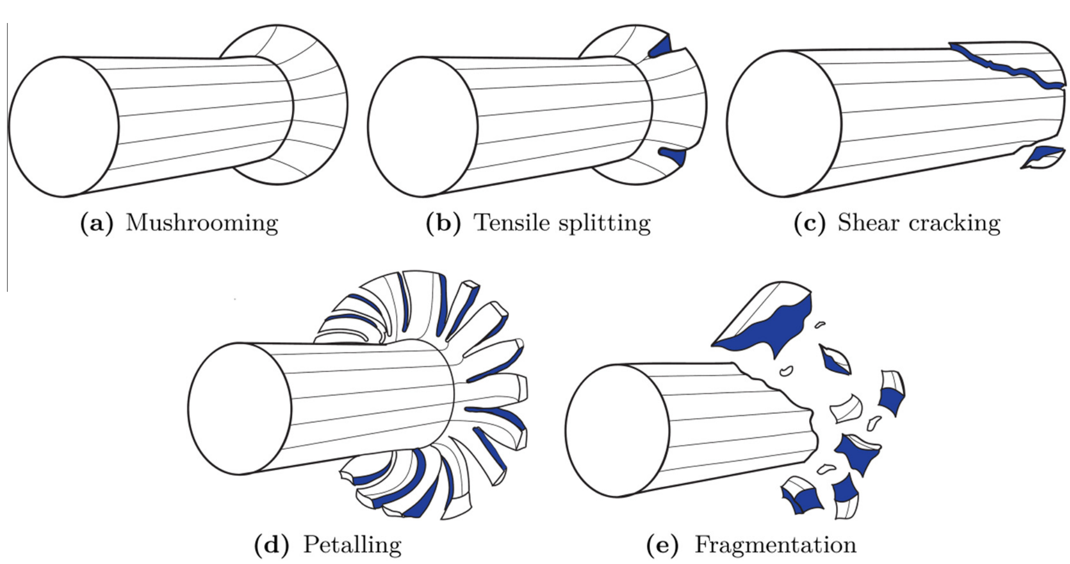

Fig. 1. Deformation and fracture modes in the Taylor bar impact test (Rakvåg et al., 2013).