NUMERICAL SIMULATION OF THE TAYLOR TEST WITH FRACTURE

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ABSTRACT

The paper presents a study of the phenomenon and fracture in a classical problem of the Taylor test. The problem is formulated as an impact of a flat-nosed cylinder projectile into a rigid target. The range of the impact velocity is between 240 m/s and 600 m/s. The lower impact velocity applies to 2024-T351 aluminum alloy projectile while 500 m/s and 600 m/s was introduced for Weldox E 460 steel. The numerical simulation was performed using ABAQUS/Explicit. A full 3-D model was developed with 120, 000 8-noded brick elements. The kinematical contact with friction coefficient 0.1 was chosen for our analysis.

Three types of simulations were performed. The standard simulation without fracture produces a familiar mushroom-like deformation mode. The fracture criterion (shear failure from ABAQUS/Explicit) was introduced into two different ways. First, it was assumed that fracture is controlled by the accumulated plastic strain. Then, the fracture criterion was modified by introducing the effect of the stress triaxiality. According to the recent work of one of the authors, any type of fracture is prevented if the stress triaxiality is less than -1/3. This new effect was incorporated into our simulation leading to very interesting results. Three types of fracture were observed. The so-called contained fracture is always present around the axis symmetry of the projectile for both materials regardless of the impact velocity. In the aluminum projectile, a spiral shear type of fracture was observed on the outer surface of the specimen. Finally, a number of radial cracks were developed due to circumferential tensile stress as the material was flowing and curling away from the impact area. It was found that the number of cracks and fragments are created was very much dependent on the type of fracture criterion. The fracture criterion without the cut-off value (such as Johnson-Cook's fracture criterion) produces too many cracks and fragments which is unrealistic. At the same time the fracture criterion with the cut-off value gave very realistic fracture pattern.

Tests are being planned at Ernest Mach Institute in Germany to validate our numerical findings experimentally. The above findings appear to be first published results on simulation of fracture process in the Taylor test.

1 INTRODUCTION

Shooting flat-nosed metal cylinders into rigid targets can provide information on dynamic yield stresses of materials. This type of tests was developed in late 40's and is known by the name of Taylor tests [1]. Because large plastic deformation, high strain rates, and thermal effects are involved, the Taylor test is often performed to verify material constitutive models by comparing mushrooming deformation profiles of the cylinder. If an impact velocity is sufficiently high in the Taylor test, cracks will be generated in the cylinder. Only a few papers in the literature investigated experimentally fracture phenomena and mechanisms in the Taylor test. Three basic types of fracture modes were identified from post-test specimens such as tensile splitting and shear cracking. Void nucleation, coalescence and growth inside the cylinder was also observed from sectioned post-test specimens.

Compared to a great number of experimental studies and numerical simulations on the process of mushrooming deformation, numerical prediction of fracture in the Taylor test appears to be scarce. Since the cylinder in the Taylor test is dominated by compression, ductile fracture is not easy to be predicted numerically. Most of existing ductile fracture criteria such as Johnson-Cook (JC) fracture locus [2] and constant fracture strains were developed from tensile tests on smooth and notched axisymmetric specimens. In application, such fracture loci were often extrapolated to the range in which compression and shear is dominant. This extrapolation is questionable and may give unrealistic predications.

In the present paper, a newly developed ductile fracture criterion by Bao and Wierzbicki [3] is used to predict crack formation and growth in the Taylor test. The initial impact velocity of the cylinder ranges from 240 m/s to 600 m/s. The lower velocities apply to 2024-T351 aluminum alloy, and the higher velocity is introduced for Weldox 460 E steel. Three distinct fracture modes are successfully captured: confined fracture inside the cylinder, petalling, and shear cracking.

2 DUCTILE FRACTURE CRITERION AND CALIBRATION

To numerically predict fracture, an adequate fracture criterion has to be developed. Recently, a ductile fracture criterion in the space of effective plastic strains and stress triaxialities has been formulated and calibrated by Bao and Wierzbicki (BW) [3] based on a series of tests and parallel numerical simulations, Figs. 1 & 2. Tensile tests on smooth and notched axisymmetric bars give the fracture strains in the range of the stress triaxiality from 0.4 up, where the specimens fail by void nucleation and growth. Upsetting tests on short cylinders provide the fracture strains in the range of the stress triaxiality from –1/3 to zero, where the specimens fail by shear cracking. In the intermediate range, the fracture strains were obtained from combined shear and compression tests on butterfly-like specimens. The unique feature of this ductile fracture criterion is the cut-off value for the negative stress triaxiality at –1/3. Its physical meaning is that a material is predominantly under compression, a crack will never be generated even plastic deformation is very large.

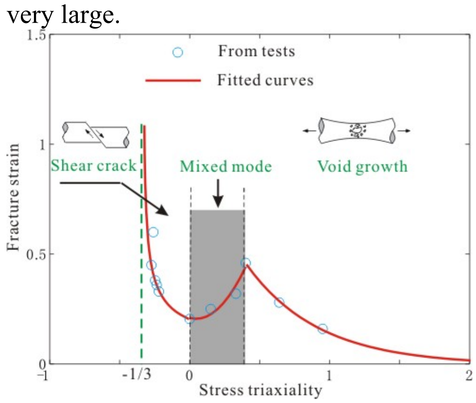


Figure 1: Bao-Wierzbicki fracture locus


Figure 2: Post-test specimens

3 FINITE ELEMENT MODELING

The geometry of the impact problem is defined in Fig. 3. The length and diameter of the cylinder are, respectively, l=30 mm and d=6 mm. The frictional effect on the interface is considered and the coefficient is taken to be μ=0.1. ABAQUS/Explicit was used to model the deformation and fracture process of the cylinder.

The cylinder was discretized by means of 8-noded linear solid elements (C3D8R), Fig. 4. There were totally 120,000 elements in the model. Very fine meshes were generated in the front part where fracture was expected to occur, while relatively coarse meshes were used for the rear part of the cylinder. The technique of element deletion embedded in ABAQUS/Explicit was used to model crack formation and growth. The element size has to be very small to minimize the effect of element removal on the impact response. The minimum length of the cubic elements was therefore taken to be 0.2 mm.

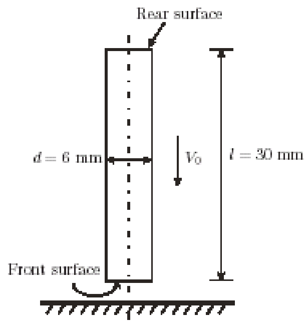


Figure 3: Schematic of computational model

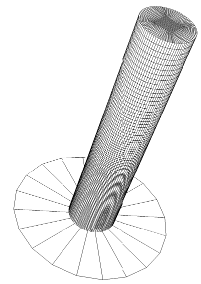


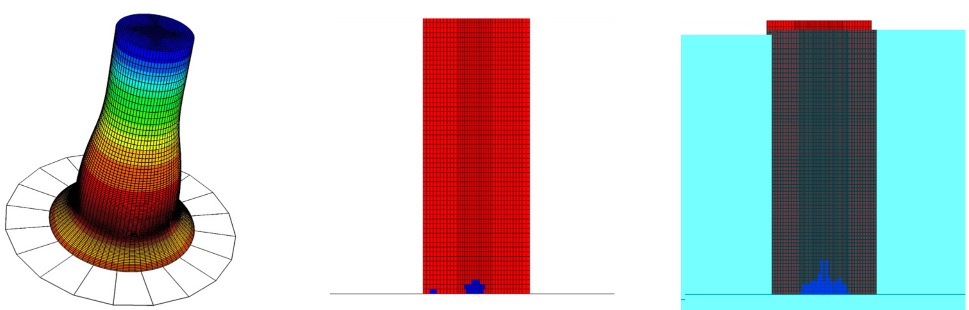
Figure 4: Finite element model of the cylinder

The Johnson-Cook material constitutive model was adopted to characterize the stress-strain relation under high strain rates and elevated temperature. Detailed discussion on the determination of material coefficients for 2024-T351 aluminum alloy was presented by the present authors in Ref. [4]. The material coefficients for Weldox 460 E steel were taken from Borvik et al. [5]. In the original paper, two sets of material constants are given; one for the material model uncoupled from the fracture model and the other for the coupled model. In the present paper, calculations are run for the coupled model. Similar results for the uncoupled model are summarized in Ref. [6].

4 FAILURE MODES

4.1 Mushrooming deformation

A typical deformation pattern of the Taylor test is known as mushrooming deformation. Due to compressive stress wave loading, the front part of the cylinder bulges out while the rear part remains almost undeformed. An example of mushrooming pattern for a Weldox 460 E steel projectile traveling at a relatively low velocity of V_0=400 m/s is shown in Fig. 5(a). The elements at the interface have not failed even though they are subjected to large compressive deformation. Failure of interface elements is prevented by the cut-off concept for the negative stress triaxiality which is incorporated in the Bao-Wierzbicki fracture criterion.



(a) (b) (c)

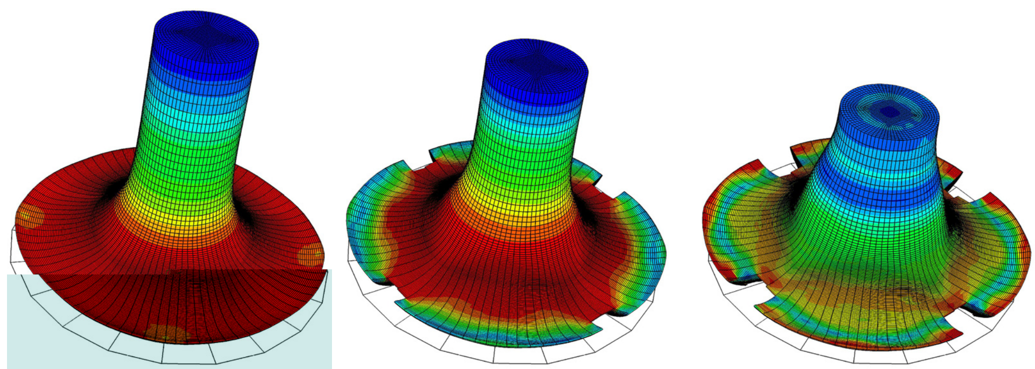
Figure 5: (a) Mushrooming deformation of the Weldox 460 E steel projectile at V_0=400 m/s. (b): Confined fracture in the Weldox 460 E steel cylinder at V_0=500 m/s. (c): Confined fracture in the Weldox 460 E steel cylinder at V_0=600 m/s. The dark elements represent failed elements, which were mapped back to the original, undeformed configuration.

4.2 Confined fracture

By increasing the impact velocity to 500 m/s, a different failure pattern was observed. In addition to the familiar mushrooming mode, several elements fail in the region near the front surface and the central axis, Fig. 5(b), (c). This failure mode is caused by void nucleation, coalescence, and growth, which were demonstrated experimentally by e.g. Worswick and Pick [7], and Addessio et al. [8]. Since the failed elements are embedded by the unfractured material, this type of failure mode is termed "confined fracture" in the present paper. The mechanism of the void growth (tensile failure) is caused by tensile wave reflected from the transient gap formed in the interface soon after the impact.

4.3 Petalling

As the impact velocity increases further to V_0=600 m/s, the petalling fracture mode was predicted, Fig. 6. Initially, many small cracks are formed on the interface and grow towards the outer periphery of the mushroom. However, later on only four cracks survive and propagate towards the projectile axis. Those cracks are finally arrested as the impact velocity decreases.



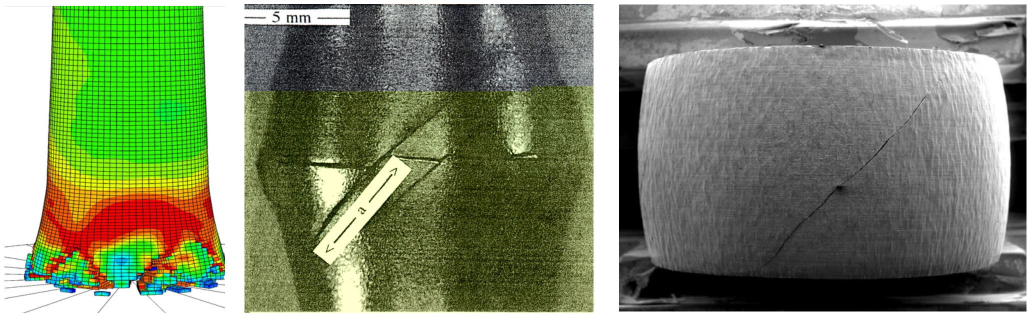
(a) t=25μs (b) t=30 μs (c) t=45μs

Figure 6: Petalling process of the Weldox 460 E steel cylinder at V_0=600 m/s.

4.4 Shear cracking

Shear cracking was observed for less ductile materials. An example of such a material is 2024-T351 aluminum alloy. The fracture locus for this material was determined by Bao and Wierzbicki [3]. Upon impact at V_0=240 m/s, shear cracking was identified from numerical solutions, Fig. 7. Several cracks are formed at the periphery of the front surface, and grow on the lateral surface of the cylinder in a spiral fashion. This failure mode is similar to shear cracking in upsetting tests where a crack is generated near the equator of a short cylinder due to barreling and resulting hoop stresses, see Fig. 7(c).

The present prediction is consistent with experimental observations by Couque [9], who performed a symmetric Taylor test on tungsten alloy of small ductility. It can be concluded that shear cracking would more likely take place in a less ductile cylinder while tensile petalling would be present in more ductile materials.



(a) (b) (c)

Figure 7: Shear cracking in the Taylor test (a): Numerical simulation, (b) Experimental results by Couque[9], (c) Fracture in upsetting tests (Courtesy of Bao and Wierzbicki [3]).

5 EFFECT OF A TYPE OF THE FRACTURE CRITERION

The projectile response in the Taylor impact tests is very sensitive to the type of the assumed fracture criterion. The authors have performed a limited comparison between the prediction of the Johnson-Cook and the present fracture criteria. The difference between the above the two fracture loci is illustrated in Fig. 8. While the JC fracture locus is an ever increasing function of the negative stress triaxiality, there is a cut-off value in the BW fracture locus at the stress triaxiality at -1/3. Comparison of the BW's and JC's fracture criteria for the Weldox 460 E steel is given in Fig. 8. It was found that the JC fracture criterion produces too many cracks and fragments which is physically not realistic, see Fig. 9.

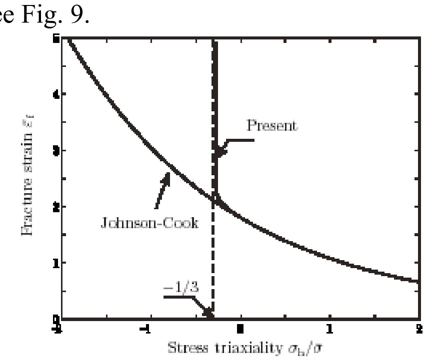


Figure 8: BW's and JC's fracture loci for the Weldox 460 E steel.

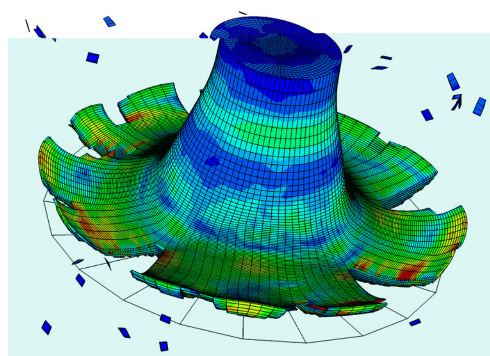


Figure 9: Failure pattern of the steel cylinder at V_0=600 m/s using the JC fracture locus.

6 CONCLUSIONS

The numerical simulation of fracture process in the Taylor test was performed using the newly developed Bao-Wierzbicki fracture locus and the classical Johnson-Cook fracture locus. Three fracture modes have been reproduced: confined fracture, petalling, and shear cracking, all of which are consistent with experimental results published in the literature. Tests are being planned at Ernest Mach Institute in Germany to validate our numerical findings experimentally.

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