Evaluation of ductile fracture models in high velocity impact problems

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Abstract: As resourceful stress states, high strain rates, and large plastic deformation were involved, the Taylor test can be used to identify the most suitable fracture criterions for high velocity impact problems. A systematic evaluation is carried out for the maximum principal stress, the maximum principal strain, equivalent plastic strain and Johnson–Cook fracture models by numerical simulations. The applicability of the ductile fracture models are discussed, finally.

Keywords: Taylor impact, Ductile fracture, Johnson–Cook fracture model

1. Introduction

Considering high temperature and high strain rates, strength models and fracture criterions are needed in impact response calculation of metal material. There are J-C, ZA, MTS strength models and the maximum principal stress, the maximum principal strain, equivalent plastic strain and Johnson–Cook fracture models to chose from. It is necessary to evaluate these fracture models.

The Taylor test can get high strain rate (10^4~10^6), in which a deformable flat-nosed cylinder is fired against a fixed, rigid wall and was originally proposed to determine dynamic yield stresses of materials [1]. Taylor test results are used to validate or to estimate coefficients for phenomenological strength models needed for simulating dynamic loading processes using inverse identification procedures[2-4].

When Taylor bar runs fast, cracks and fragmentation phenomenon are very common. Couque (1998)[5] observed several spiral cracks which formed on the lateral surface of the cylinder in symmetric Taylor tests on swaged tungsten alloys.

Material mechanics performance test of Q235 was taken to calculate parameters of fracture criterions. The display dynamic analysis software AUTODYN was used to forecast failure modes of Taylor tests. The differences and limitations of the ductile fracture models are discussed, finally.

2. Mechanical property testing of Q235

To get parameters of the fracture criterions, cold quasi static single axis tensile test was done on MTS. Specimens were processed according to <GB/T228-2002>, whose diameter was 10mm, length of test part was 100mm (see Fig.1). Loading rate of this test was 0.6mm/min (strain rate was 2×10^{-4}/s).

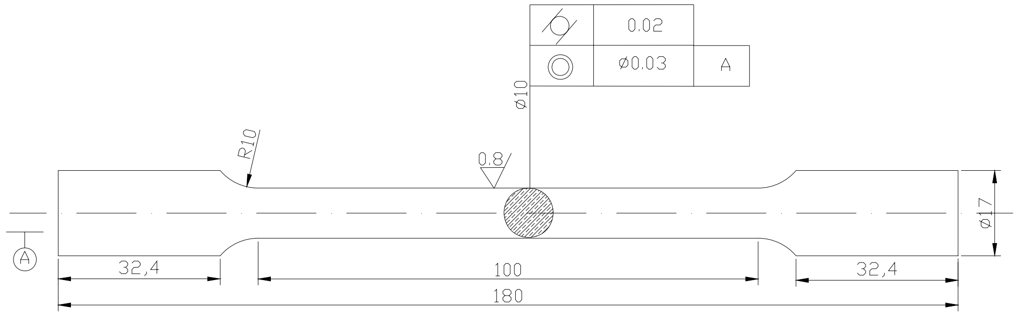


Fig.1 Schematic of specimen for quasi static single axis tensile tests

Engineering stress strain curve was got by the load-displacement curve. Parameters of the maximum principal stress, the maximum principal strain, equivalent plastic strain and Johnson–Cook fracture models were got by Stress triaxial degree test and tensile test at high temperature.

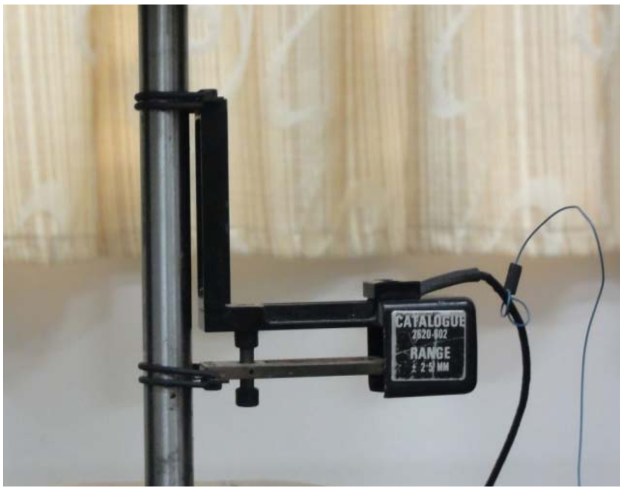


Fig.1 quasi static single axis tensile test

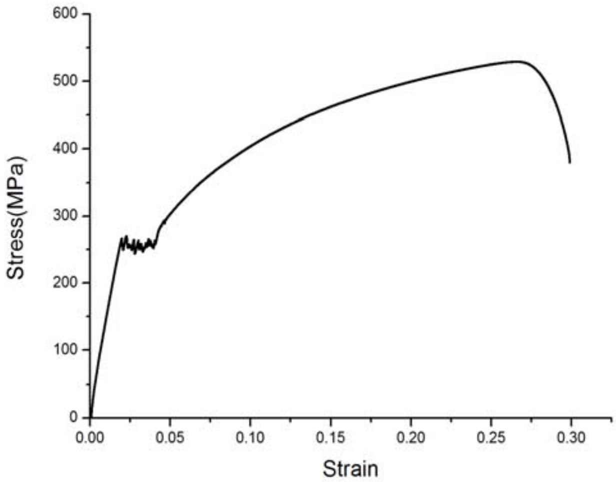


Fig.2 stress-strain curve of Q235

3. The numerical simulation model and the strength model

3.1 The numerical simulation model

Generally, in the Taylor test a deformable flat-nosed cylinder is fired against a fixed rigid wall (see Fig. 3). The cylindrical projectile is of the diameter d= 6mm and the length l= 30mm. The friction coefficient between the front surface of the projectile and the rigid wall is assumed to be $\mu = 0.1$.

Smoothed Particle Hydrodynamics method (SPH) was used to simulate the failure phenomena of cylinder. A 3-D solid finite element model was built rather than an axisymmetric model (see Fig. 4).

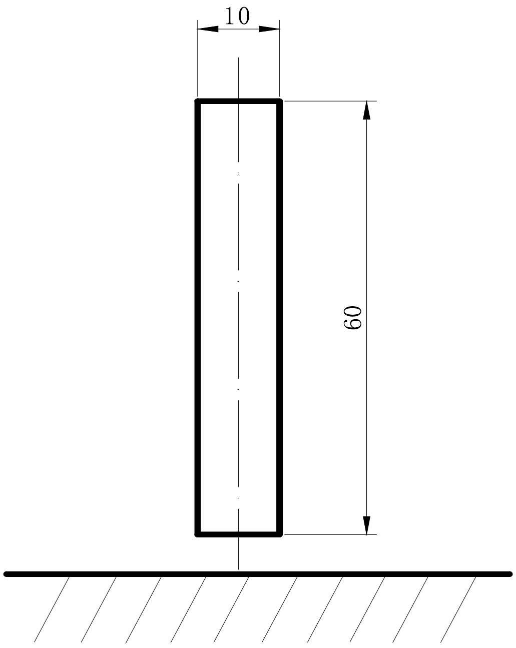


Fig. 3 Schematic of a cylindrical projectile impacting a rigid wall

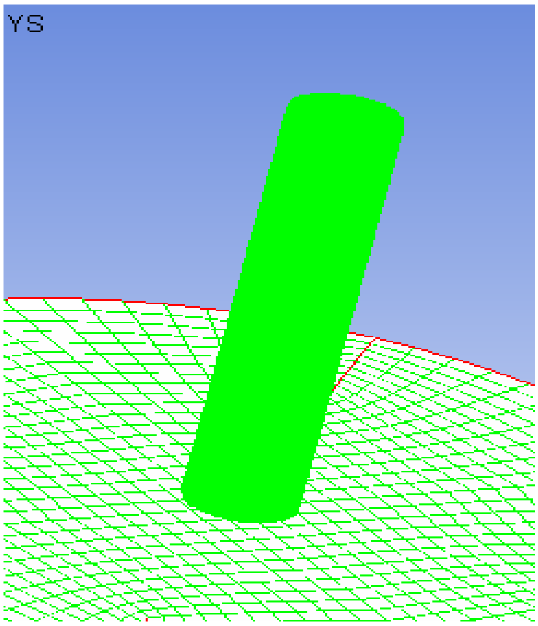


Fig.4 Finite element model of the projectile-target system

3.2 The strength model

Due to simplicity and availability of material coefficients, the Johnson–Cook (JC) material model implemented in AUTODYN was used in the present calculation. The material model should not be confused with the fracture model which will be discussed later. In the JC model the equivalent stress σ is an explicit function of the equivalent plastic strain ε_{eff}, the temperature T, and the plastic strain rate $\dot{\varepsilon}$.

$$\sigma = (A + B\varepsilon^{n})(1 + C\ln\dot{\varepsilon}^{*})(1 - T^{*m}) \tag{1}$$

Where the reference plastic strain rate $\dot{\varepsilon}^{*} = \dot{\varepsilon}/\dot{\varepsilon}_0$, $T^{*} = (T - T_r)/(T_m - T_r)$, T_r and T_m are the room temperature and the material melting temperature respectively, and A, B, n, C, and m are five material constants. The JC model accounts for isotropic strain hardening, strain rate sensitivity, and thermal softening in the uncoupled form. The first term of the right hand side of Eq. (1) represents the quasi-static stress–strain relation at room temperature; the second term signifies the strain-rate hardening; the third term means the temperature dependence of the stress–strain relation. It should be pointed out that in the computation, the material behaves elastically up to the point of initial yield and then follows Eq.(1).

The material parameters in the JC model for Q235 were listed in Table 1.

Table 1 Material parameters for Q235

Material	A（MPa）	B（MPa）	n	C	m
Q235	249.2	45.6	0.875	0.32	0.76

4. Results and analysis

4.1 The maximum principal stress failure criterion

Refering to quasi static tensile tests, the maximum principal stress of Q235 was 560MPa , The maximum shear stress of Q235 was 448MPa. With the simulation computation, failure mode of the maximum principal stress for different velocity is showing in Fig.5 and 6.

After impacting on the rigid wall, the Taylor bar was smashed. The fragments were very small and almost in the same volume (v=400m/s).

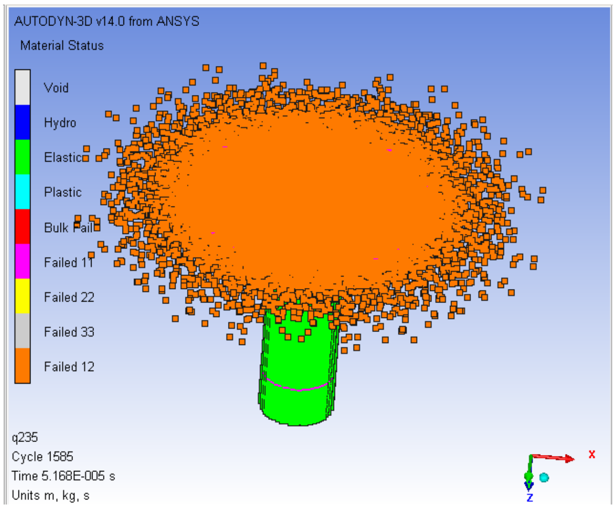


Fig.5 Failure mode of the maximum principal stress (v=300m/s)

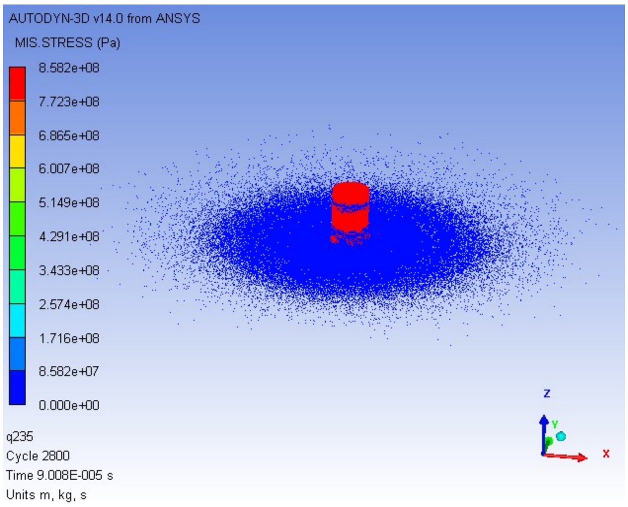
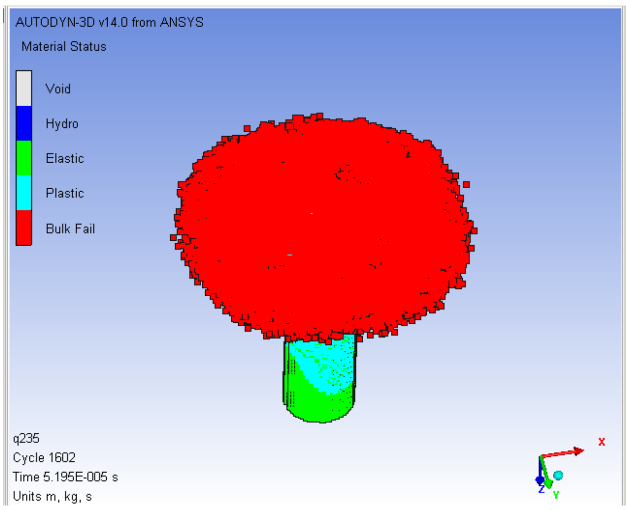


Fig.6 Failure mode of the maximum principal stress (v=400m/s)

4.2 The equivalent plastic strain failure criterion

Refering to quasi static tensile tests, the equivalent plastic strain, $\varepsilon_f = 2\ln\left(\frac{d}{d_0}\right)$, for Q235 $\varepsilon_f = 1$.

Through the simulation, failure mode of equivalent plastic strain for different velocities (v=300m/s, 400m/s) are showing in Fig.7and 8.



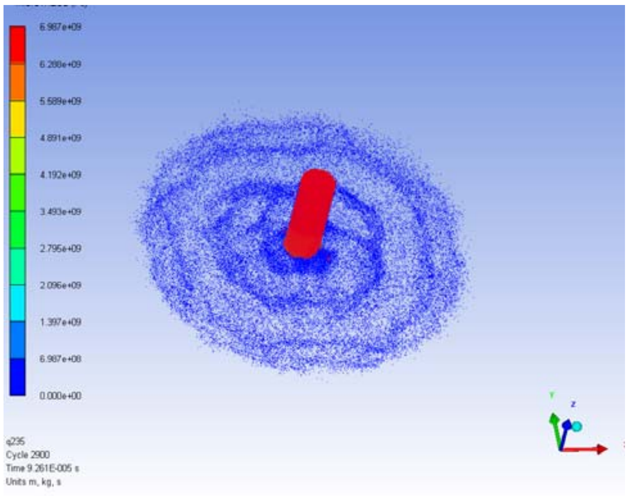


Fig.7 Failure mode of equivalent plastic strain (v=300m/s)

Fig.8 Failure mode of equivalent plastic strain (v=400m/s)

4.3 The maximum principal strain fracture criterion

Refering to quasi static tensile tests, The maximum principal strain was 0.33. Through the simulation, failure mode of the maximum principal strain in different velocities (v=300m/s, 400m/s) are showing in Fig.9 and 10.

About thirty fragments produced in this process, and the fragment volume was larger than that of above two fracture criterions.

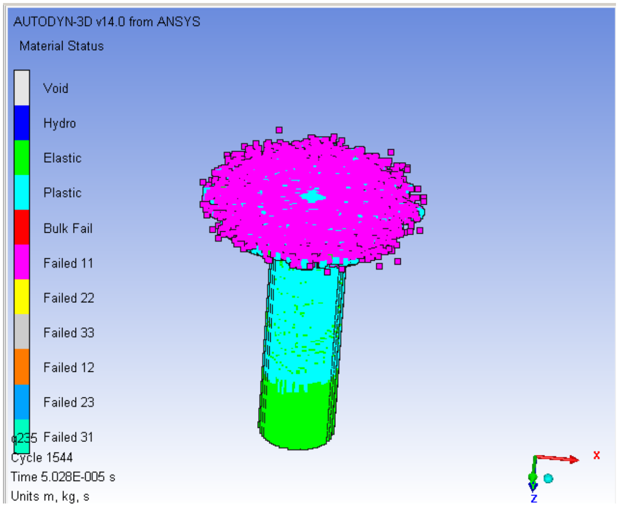


Fig.9 Failure mode of the maximum principal strain (v=300m/s)

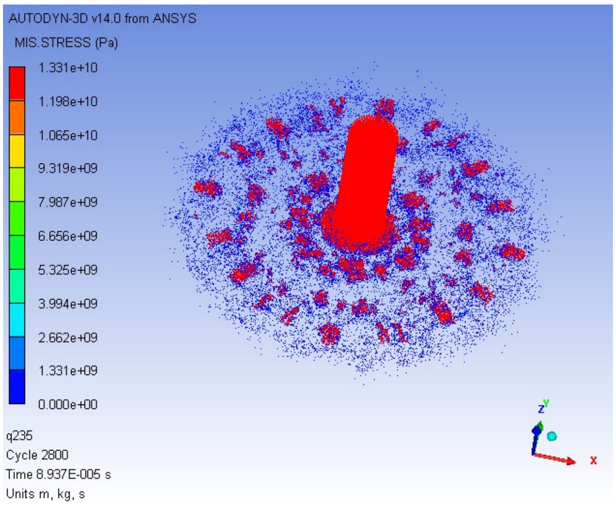


Fig.10 Failure mode of the maximum principal strain (v=400m/s)

4.4 J-C fracture criterion

The influence of the stress triaxiality in these models is based on the void growth equation proposed[6, 7].The expression of J-C fracture strain ε_f is[3]

$$\varepsilon_f = \left(D_1 + D_2 e^{(D_3 \sigma^*)} \right) \left(1 + D_4 \ln \dot{\varepsilon}^* \right) \left(1 + D_5 T^* \right) \tag{2}$$

D_1, D_2, D_3, D_4 and D_5 are material parameters; $\sigma^* = p/\sigma_{eff} = -\sigma_{kk}/\sigma_{eff} = -R_\sigma$, p is pressure, σ_{eff} is equivalent stress, R_σ is stress triaxiality; $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is dimensionless plastic strain rate, $\dot{\varepsilon}_0$ is Referenced plastic strain rate; $T^* = (T - T_r)/(T_m - T_r)$, T_r and T_m are the room temperature and the material melting temperature. For Q235, D_1=0.38, D_2=1.47, D_3=2.58, D_4=-0.0015, D5=8.07.

Through the simulation, failure modes of J-C in different velocities (v=300m/s, 400m/s) are showing in Fig.11 and 12.

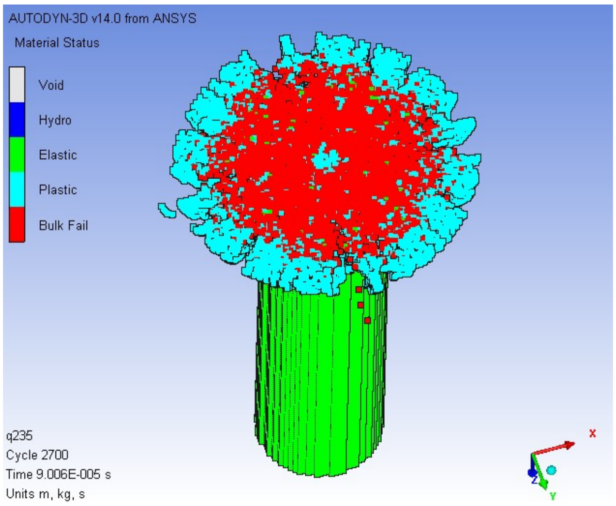


Fig.11 Failure mode of J-C(v=300m/s)

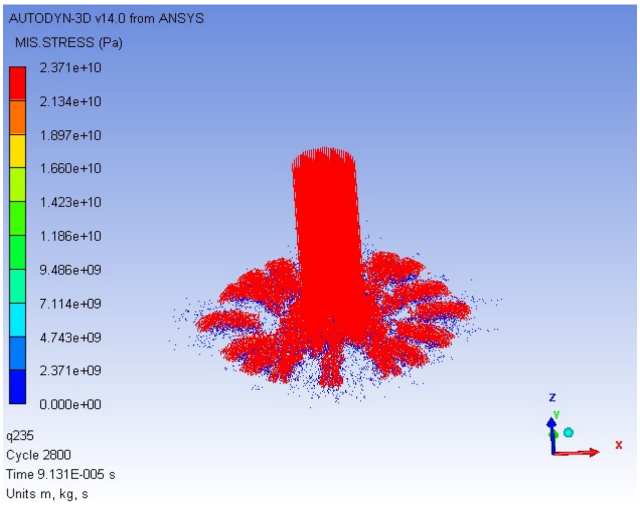


Fig.12 Failure mode of J-C(v=400m/s)

4. Conclusion

Through the above analysis and Taylor test, in which the Taylor bar was broken like petals, Finally, conclusions are summarized:
(1) Failure modes in high velocity impact problems are quite different because of choosing different fracture criterions.

(2) J-C fracture criterion is the most accurate fracture criterion in four fracture criterions for ductile metal in high velocity impact problems.

(3) The maximum principal stress and the equivalent plastic strain failure criterions lead to many fragments for ductile metal in high velocity impact problems.

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