The Ductile Fracture of Armor Steel Targets Subjected to Ballistic Impact & Perforation : Calibration of Four Damage Criteria.

I. A. MBAREK[1], A. RUSINEK[2], E. PETIT[3], G. SUTTER[4], G. LIST[5]

1. LaBPS, National Engineering School of Metz, Lorraine University, France imen-asma.mbarek@univ-lorraine.fr
2. LaBPS, National Engineering School of Metz, Lorraine University, France alexis.rusinek@univ-lorraine.fr
3. LEM3, Lorraine University, France etienne.petit@univ-lorraine.fr
4. LEM3, Lorraine University , France guy.sutter@univ-lorraine.fr
5. LEM3, Lorraine University, France gautier.list@univ-lorraine.fr

Abstract

Over the past two decades, the automotive, aerospace and army industries have been paying an increasing attention to Finite Elements FE numerical simulation of the fracture process of their structures. Several researches have been conducted via experimental investigations coupled to numerical simulations in order to find a fracture model which is suitable for various applications. The present paper addresses ballistic impact and perforation of thin armor steel targets. The target fracture usually depends on: the projectile nose shape, the target thickness and its mechanical properties as well as impact conditions (friction, oblique/normal impact...). The investigations presently reported address the normal impact of a conical head-shaped projectile on thin armor steel targets. The main aim of the present paper is to establish a comparative study of four fracture criteria that are commonly used in the fracture process simulations of structures subjected to extreme loading such as ballistic impact and perforation. The four failure criteria are: the critical strain to failure model, the Johnson-Cook fracture model, the Wierzbicki model and finally, the Modified Hosford-Coulomb model MHC. The aforementioned fracture criteria are implemented into the FE code ABAQUS via VUMAT subroutine and they were coupled to suitable constitutive relations allow having reliable results of ballistic impact problems simulation. The calibration of these damage criteria as well as a concise evaluation of the applicability of each criterion are detailed in the present paper.

Key Words : *Armor steels, ballistic impact, damage criteria, ductile fracture, Scanning Electron Microscopy SEM.*

1. Introduction

The FE numerical simulation of structures subjected to ballistic impact and perforation requires a good FE model, a suitable constitutive relation describing the material behavior and a reliable fracture criterion describing the fracture process and the damage evolution in the structure subjected to extreme loading. The FE model includes the structure, its geometric properties and the boundary conditions. The projectile properties as well as the impact conditions must be taken into account in the FE simulation. The parameters of the constitutive relation describing the material behavior of the structure is identified thanks to characterization experiments conducted in a wide range of strain rates, temperatures and loading paths.

Eventually, the fracture criterion describing the damage evolution and the crack propagation during perforation process is calibrated using fracture characterization experiments coupled to fractography investigations.

The present paper addresses ballistic impact experiments conducted on thin armor steel targets coupled to fracture characterization experiments and fractography investigations allowing to calibrate the fracture criteria and to assess the failure pattern of the impacted targets (plug ejection due to high shearing, petalling due to radial necking, debris ejection, crack propagation ...)

2. Ballistic Impact Results

The ballistic performance of three different armor steels was assessed for a wide range of initial impact velocity from 40 to 200 m/s in the presently reported work. For thin armor steel targets impacted by a conical projectile a failure mode by petaling occurs inducing radial necking due to a process of piercing and the plastic strain is localized at the ends of the petals.

3. Fracture Characterization

3.1 Fracture Characterization Experiments

The fracture characterization experiments reported in this section allow drawing the effect of the strain rate, the stress striaxiality, the temperature and the loading path on the critical strain to failure. We have performed both tensile and double shear tests on specimens of three different armor steels at room temperature and under quasi-static strain rates ranging from 10^{-4} to 10^{-1} 1/s, as shown in **Fig.1.** The aforementioned quasi-static tensile experiments were also conducted at three different temperatures ranging from 297K to 500K, allowing in order to explore the influence of temperature on the fracture process.

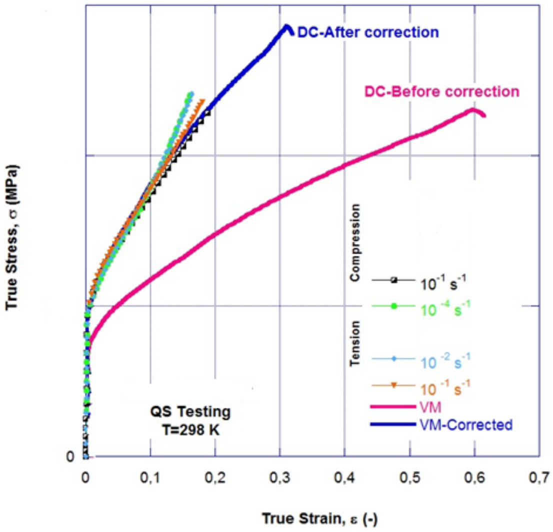

Fig.1 Strain to failure evolution for different quasi-static loading paths

Intermediate tension tests was coupled to dynamic double shear experiments conducted on the Hopkinson tube device, allowing to analyze the effect of strain rate on the crack opening and propagation. Those different loading paths allow to cover various values of stress triaxiality **η** and of the Lode angle parameter **ϴ**.

3.2 Fractography

The fractography results reported in this section allow a concise choice of the fracture criteria: ductile, brittle or mixed-mode fracture criterion. The Scanning Electron Microscopy SEM observations of the tensiled specimens and of armor steel targets impacted between 50 to 200m/s reveal ductile fractures evidenced by microcavities an dimples on the surface as demonstrated in **Fig.2.** Ductility and striction behavior determine the length of the leaves and the shape of the cracks.

Macroscopic and microscopic observations lead to choose only fracture criteria able to reliably model ductile fracture in FE simulations of impact and perforation.

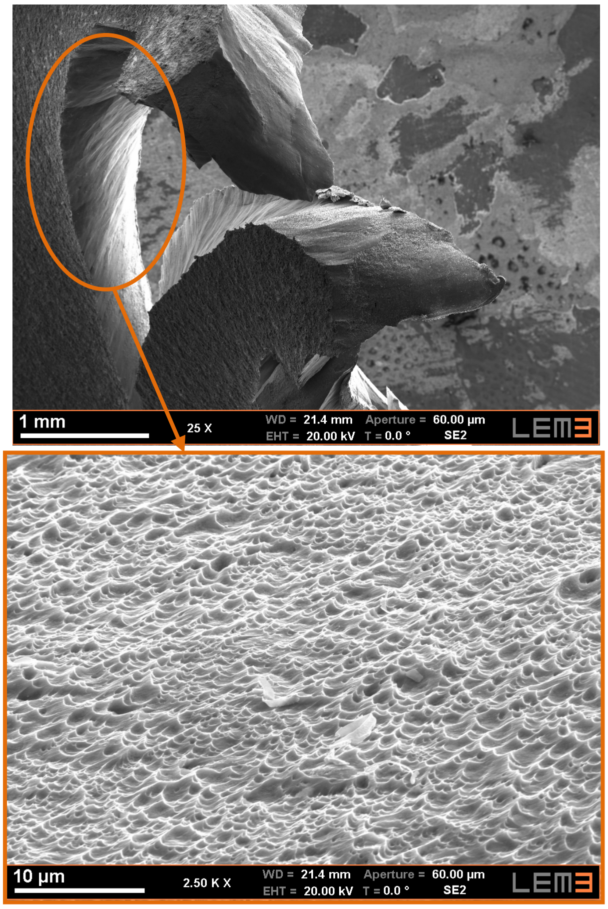

Fig.2 Microcavities and dimples on the fracture surface of an armor steel target impacted at 160 m/s.

4. Calibration and Assessment of Fracture Models

The aforementioned four fracture criteria detailed in the following section are implemented into the FE code ABAQUS via VUMAT subroutine. These fracture criteria coupled to suitable constitutive relations allow having reliable results of ballistic impact and perforation problems simulation. In the present work, the parameters of each fracture model have been identified for three armor steels and the applicability of each criterion was evaluated using experimental investigations coupled to numerical simulations.

4.1 Critical Strain to Failure Model

$$\bar{\varepsilon} = \sqrt{\frac{2}{3}}\sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2}$$

Using this criterion [1], the fracture is assumed to occur in a material element when the equivalent plastic strain **ε** reaches a critical value $\boldsymbol{\varepsilon_f}$.
For this criterion, only one tension test is required to identify the critical strain to failure value for each material.

4.2 Johnson-Cook Model

Johnson and Cook [2], postulated that the critical equivalent fracture strain is a function of the stress triaxiality **σ***, the strain rate $\dot{\varepsilon}$ and temperature **T**, as follows

$$\varepsilon_f = (D_1 + D_2 \exp D_3(\sigma^*)) \left(1 + \frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\bar{\varepsilon}}_0}\right)^{D_4} \left(1 - D_5 \frac{T - T_{room}}{T_{melt} - T_{room}}\right)$$

where the stress triaxiality parameter **σ*** is a ratio of the mean stress σ_m to the equivalent stress and D_1-D_5 are the model parameters which are material dependent.

At least, three fracture tests are required to calibrate the JC fracture criterion.

4.3 Wierzbicki Model

Wierzbicki [3] proposed the following model in which the strain to failure is stress triaxiality dependent, **Fig.3**.

$$\begin{cases} \varepsilon_f = \dfrac{C_1}{1+3\eta} & -\dfrac{1}{3} \le \eta \le 0 \\ \varepsilon_f = \varepsilon_{f,t} + (\varepsilon_{f,t} - \varepsilon_{f,s})(3\eta - 1) & 0 \le \eta \le \dfrac{1}{3} \\ \varepsilon_f = C_2 \exp(C_3\eta + C_4) & \dfrac{1}{3} \ge \eta \end{cases}$$

Where C_1-C_4 are the model parameters which are material dependent.

The material parameters $\varepsilon_{f,t}$ and $\varepsilon_{f,s}$ are the tension strain to failure and the shear strain to failure values, respectively.

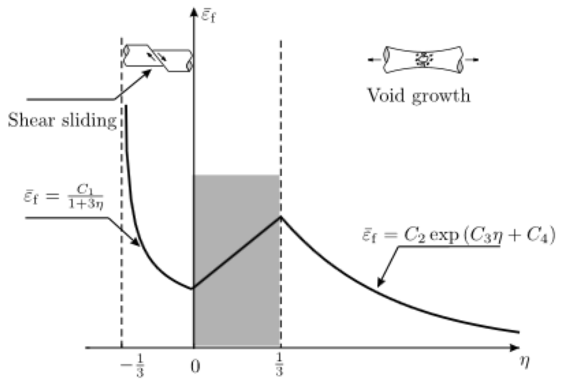

Fig.3 Schematic representation of the three-branch fracture locus [3]

Four fracture tests are at least required to calibrate this fracture criterion.

4.4 Modified Hosford-Coulomb Model

An empirical extension of the Hosford-Coulomb fracture model [4] is proposed to take into account the effect of strain rate on ductile fracture, along with the effect of stress triaxiality **η** and the Lode angle **Θ**, **Fig.4.**

$$\bar{\varepsilon}_f^{pr}[\eta, \bar{\theta}] = b(1+c)^{\frac{1}{n}} \left(\left\{ \frac{1}{2}\left((f_1 - f_2)^a + (f_2 - f_3)^a + (f_1 - f_3)^a\right) \right\}^{\frac{1}{a}} + c(2\eta + f_1 + f_3) \right)^{-\frac{1}{n}}$$

where **a** controls the effect of Lode angle and **c** is the friction coefficient that controls the stress triaxiality effect on the strain to failure value.

with the Lode angle parameter dependent trigonometric functions f_1, f_2 and f_3 :

$$f_1[\bar{\theta}] = \frac{2}{3}\cos\left[\frac{\pi}{6}(1 - \bar{\theta})\right], \quad f_2[\bar{\theta}] = \frac{2}{3}\cos\left[\frac{\pi}{6}(3 + \bar{\theta})\right] \quad \text{and} \quad f_3[\bar{\theta}] = -\frac{2}{3}\cos\left[\frac{\pi}{6}(1 + \bar{\theta})\right].$$

The strain rate dependent parameter is incorporated into the model through the coefficient b :

$$b = \begin{cases} b_0 & \text{for } \dot{\bar{\varepsilon}}_p < \dot{\varepsilon}_0 \\ b_0\left(1 + \gamma \ln\left[\frac{\dot{\bar{\varepsilon}}_p}{\dot{\varepsilon}_0}\right]\right) & \text{for } \dot{\bar{\varepsilon}}_p \geqslant \dot{\varepsilon}_0 \end{cases}$$

a, b and **c** are the model parameters and at least, three fracture tests are required to calibrate the MHC fracture criterion.

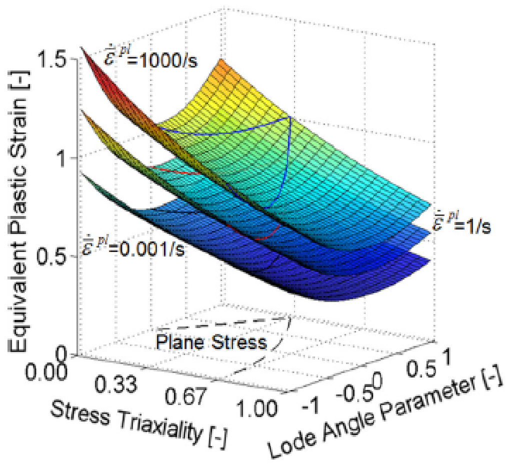

Fig.4 Illustration of the fracture surfaces for different strain rates in the space of stress triaxiality, Lode angle and equivalent plastic strain.

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