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Fracture of high-strength armor steel under impact loading

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ABSTRACT

Mars® 300 is an ultrahigh hard armor (UHHA) martensitic steel designed for ballistic protection. It is available in sheets of different thicknesses and also as perforated plates with a periodic pattern of cylindrical holes. Installed as an add-on layer in front of a main armor, its aim is to cause deflection or fragmentation of small-caliber projectiles. In the present study, the impact process is investigated with a hybrid experimental-numerical approach. Ductile fracture experiments are carried out at different stress states, strain rates and temperatures on a range of flat Mars® 300 steel specimens to identify the plasticity and fracture response. The plasticity model is composed of von Mises yield surface, a non-associated anisotropic flow rule, a combined Swift–Voce strain hardening law and a Johnson–Cook type of rate and temperature-dependency. To predict the onset of fracture, a stress state and strain rate-dependent Hosford–Coulomb fracture initiation model is used. Impact experiments are performed on targets of homogenous and perforated Mars® 300 plates by accelerating cylindrical Mars® 300 projectiles in a single-stage gas gun. Depending on the impact location, three different failure mechanisms are identified for the perforated plate. Subsequently, finite element simulations using the calibrated material model are carried out to thoroughly analyze the impact experiments. A very good prediction of the different impact cases and their fracture patterns is obtained, validating the applicability of the plasticity and the fracture model for impact loadings.

1. Introduction

Armor steels are a family of steel grades specially designed for ballistic protection. They are characterized by exceptionally high strength, hardness and moderate ductility which are often required to mitigate ballistic and explosive threats [1]. In the present study, an armor steel known under the trade name Mars® 300 that features a minimum yield strength of 1300 MPa and a minimum hardness of 580 HB [2] is chosen as a representative from this group. Example applications for this material are protective shields against kinetic energy projectiles or shape charges, as a part of light armors for ground vehicles and helicopters or heavy armors for MBT protection [2]. Mars® 300 steel is available as rolled homogenous plates of different thicknesses and also as plates with a regular circular hole pattern, so-called perforated plates.

When perforated plates are mounted onto light-weight and medium armored vehicles, they improve protective properties against the impact of small-caliber projectiles by decreasing their perforation capability. The hole pattern in such plates increases the probability of asymmetrical contact between the projectile and the plate [3], due to which small-caliber projectiles may be destabilized or fragmented before reaching the main-armor. It is experimentally observed that depending on the hit-point with respect to neighboring holes, different mechanisms can cause projectile failure. The core of the armor-piercing projectiles could be shattered, partially eroded or rotated [4]. The contact asymmetry is strongest when a projectile impacts on a hole edge, leading to bending loading of the projectile core and its subsequent failure. Most research on perforated plates (e.g. [3–6]) discuss in detail defeat mechanisms against small-caliber threats, but it focuses less on the effects of impact on perforated plates. The extent of plate fracture is strongly dependent on the impact position. A very complex behavior during a high-rate ballistic impact depends on the impact location, the contact conditions and the plasticity and fracture properties of each material involved. A bullet can hit directly the center of a hole, the edge of a hole, the web between two holes or at the geometric center of three holes, every time affecting a different number of holes.

In order to understand the failure mechanisms under high-velocity loading, as well as to be able to perform numerical studies, for example for virtual prototyping, a thorough understanding of a material's plasticity and fracture properties is required. A wide variety of models for the plastic response under dynamic loading can be found in the literature. They can be divided into physics-based models [7–11], usually inspired by thermodynamics and dislocation dynamics, and phenomenological/empirical models.

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Most established phenomenological models for impact problems are based on the work by Johnson and Cook [12]. Herein the flow stress is composed multiplicatively of a strain, strain rate, and temperature term. It has been shown that it provides reasonable predictions of temperature-dependent visco-plastic response up to large strains (e.g. [13–17]). Recently, Roth and Mohr [18] coupled the Johnson–Cook plasticity model with a combined Swift–Voce strain hardening function and a non-associated anisotropic flow rule, obtaining good results for different advanced high strength steels as well as for Ti-6Al-4 V [19].

Various approaches have been taken to model ductile fracture in metal materials. After the proposition of a first porous plasticity model by Gurson [20] which incorporates the effect of a void volume fraction on the plastic flow accounting for void growth, several modifications have been added to also account for the effects of void shearing [20–22]. As an alternative, a continuum damage mechanics approach was presented by Lemaitre [23]. The most widely used group of fracture models in impact engineering is based on a damage indicator approach. The plastic material response remains unaltered in these uncoupled models, while fracture occurs once a scalar damage indicator reaches a critical value. Stress-state dependent weighting functions may be derived from the theoretical analyses of McClintock [24] and Rice and Tracey [25] are directly taken from phenomenological fracture models (e.g. Johnson and Cook [26] or Bai and Wierzbicki [27]). Roth and Mohr [18] introduced a strain rate dependent Hosford–Coulomb model, incorporating the effects of the stress state and the strain rate on ductile fracture.

The accurate numerical modeling of interactions between the components of an armor-piercing projectile (brass jacket, lead cup and steel core) and a target is a very complex task in which at least four materials with distinct plastic and fracture properties have to be characterized. Here, a comprehensive experimental and numerical program is carried out, to thoroughly understand the mechanical response of an armor steel under impact loading. The paper is divided into three main parts: Firstly, the mechanical behavior of Mars$^{\circledR}$ 300 steel is characterized experimentally under a wide range of stress states, strain rates and temperatures. Employing a hybrid experimental-numerical approach, the parameters for a plasticity and fracture model are identified. Subsequently, impact tests are performed on homogenous and perforated plates of Mars$^{\circledR}$ 300 which are impacted by cylindrical Mars$^{\circledR}$ 300 projectiles. Close attention is paid to the relationship between plate fracture patterns and the impact position of the projectiles. In the last part, the dependence between the impact positions and the mechanisms of deformation leading to different fracture patterns are evaluated with finite element analysis.

2. Material characterization experiments

The producer of Mars$^{\circledR}$ 300 steel provided information about the material properties, which are presented in Table 1 [2]. Based on the given values, a general notion of the material performance may be taken, but to understand its behavior under impact loading, a thorough analysis of its properties over a wide range of stress states, strain rates and temperatures should be conducted.

2.1. Material and specimens

The homogenous Mars$^{\circledR}$ 300 material has a thickness of 6 mm in its as delivered state, which is the smallest available thickness. To facilitate the testing of the material with the given infrastructure, its thickness is reduced to 1 mm by cutting and grinding under permanent cooling to prevent any changes of the microstructure. The plates are ground from one side to the final thickness, whereas the second side is left in the as-rolled conditions. Ten hardness measurements are performed on both the as-delivered and the ground material. On each material an average hardness value of 650HB is obtained, which validates the applicability of the machining technique.

Table 1
Chemical composition of Mars$^{\circledR}$ 300 as stated in [2].

C	S	P	Si	Mn	Ni	Cr	Mo
45–0.55	< 0.002	< 0.01	< 1.0	< 0.7	1.4 –2.4	< 0.4	< 0.5

Five different types of specimens (Fig. 1) are extracted from the ground sheets by wire electric discharge machining with an accuracy of 5 μm:

- Uniaxial tension (UT) specimens with a 5 mm wide and 20 mm long gage section area (Fig. 1a).
- Notched tensile specimens (NT10) with a 10 mm wide gage section and circular cut-outs with a notch radius of R = 10 mm (NT10), reducing the width of the gage section to 5 mm in the center (Fig. 1b,c).
- Mini-Punch (PU) specimens with a diameter of 60 mm, to characterize the material response under equi-biaxial loading (Fig. 1d).
- Shear (SH) specimens featuring a single gage section as recently developed by Roth and Mohr [28] (Fig. 1e).
- Strip specimens for plane strain tension bending (VB) experiments. (Fig. 1f).

2.2. Experimental techniques for low strain rates and elevated temperatures

All experiments at low strain rates are performed under displacement control on a 100 kN hydraulic universal testing machine

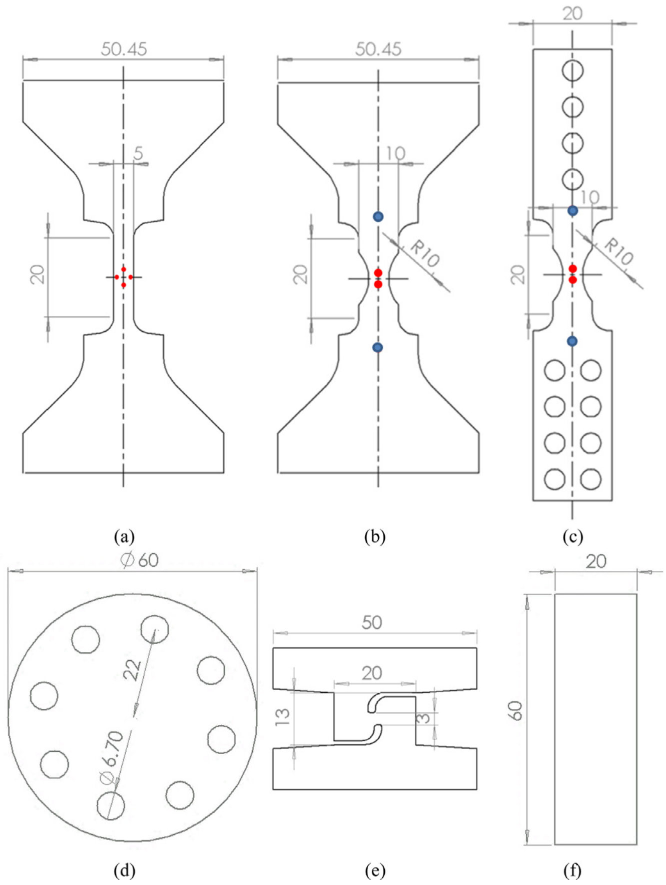

Fig. 1. Specimen geometries: (a) UT specimen, (b) NT10 specimen, (c) NT10 specimen for use on SHPB system, (d) Mini Punch specimen, (e) SH specimen and (f) (VB) bending specimen.