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# Influence of yield-surface shape in simulation of ballistic impact

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ABSTRACT

A high-exponent yield criterion is applied in 3D nonlinear finite element simulations of ballistic impact. The computational models are based on a comprehensive experimental study including material tests of 12 mm thick high-strength Weldox 700 E steel plates and ballistic tests where the plates were struck by blunt-nosed and ogive-nosed projectiles with a diameter of 20 mm and a mass of approximately 200 g. We thoroughly describe the constitutive model and the numerical modeling procedure. The simulation results are discussed in light of the perforation mechanisms as well as the experimental results. Changing the shape of the yield surface in the deviatoric plane increases the residual velocity of the projectile and the effect was largest in simulations with the blunt-nosed projectile. Although the difference in residual velocity can be significant close to the ballistic limit velocity, the variation in predicted ballistic limit velocity itself was not more than 7%. To put this into context, the effect of the yield-surface shape was compared to the effects of changing the parameters controlling friction, rate sensitivity, adiabatic heating, and temperature softening. These results suggest that a high-exponent yield criterion is not essential for ordinary steels and aluminum alloys where moderate yield-surface exponents are expected.



## 1. Introduction

The von Mises yield criterion is by far the most wide-spread yield criterion in ballistic simulations and it is used, by default, but in general with success, for most types of metals and alloys. It assumes that yielding occurs when the second principal invariant of the deviatoric stress tensor, $J_2$, reaches a critical value. Hence the name $J_2$ flow theory which is frequently used for plasticity theories based on the von Mises yield criterion. Further assumptions include isotropy and pressure insensitivity of the material, meaning that the yield locus is a right cylinder aligned along the hydrostatic axis in stress space. This yield locus can be changed by making it dependent on the hydrostatic stress or by altering its shape in the deviatoric plane. Dependency on the hydrostatic stress is important in frictional materials such as concrete, rock and soils, but also for foams and some polymers where the behavior in compression is different from the behavior in tension. This is most aptly introduced in models by changing the shape of the locus from a right cylinder into a cone [1]. Changing the shape in the deviatoric plane can be done by retaining isotropy [2,3], or by introducing anisotropy [4,5]. The latter can be vital in for instance rolled aluminum plates where the behavior in the rolling direction is different from the behaviors in the transverse and thickness directions of the plate.

There are many examples of impact-related studies that use $J_2$ plasticity and Johnson–Cook (JC) [6] type constitutive relations to simulate isotropic, and not so isotropic, materials [7–10]. Arias et al. [11] simulated the impact behavior of thin steel plates struck by projectiles with various nose shapes using the JC model. Iqbal et al. [12,13] studied Weldox 460 E steel plates and AA1100-H12 aluminum alloy plates, and Manes et al. [14] looked at the perforation and penetration behavior of AA6061-T6 aluminum alloy. A slightly different area of application was explored by Aune et al. [15] who recently used $J_2$ plasticity to study blast effects on rather anisotropic aluminum sheets.

Given the dissemination of $J_2$ plasticity, there are surprisingly few studies where the effects of the shape of the yield surface have been examined in a systematic manner for ballistic impact problems. Models where the third deviatoric stress invariant $J_3$, or the Lode parameter $L$, is accounted for have been presented by for instance Bai and Wierzbicki [16] and Chocron et al. [17] where the latter model was applied in ballistic impact simulations. They also considered Lode dependent failure loci.

A proper description of material anisotropy is imperative when modeling, for example, composites, but for metals this is often disregarded. Grytten et al. [18] reported limited effects when they included an anisotropic yield function (YLD2004-18p [5]) in numerical simulations of low-velocity impact. Conversely, Seidt et al. [19] looked at the effect of using an anisotropic yield surface in blunt-nosed projectile impact of aluminum sheets and plates.

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They conclude that the shape of the yield surface affects the results of ballistic impact simulations when using a six-component anisotropic yield function [20], suggesting that the shape of the yield surface does, in fact, influence the ballistic behavior.

The response of plates struck by projectiles of different shapes, particularly blunt-nosed and ogive-nosed projectiles, is vastly different. Chiefly, we can say that blunt-nosed projectiles induce plugging failure in intermediate thick plates. Here, bands of intense shear, often helped by adiabatic heating, cut through the plate which promotes the formation of a plug with the same diameter as the circumference of the projectile. Such shear bands have been found to be thinner than 10 μm for Weldox 700 E steel plate [21] and they complicate the simulation procedure for perforation by projectiles with flat noses. In the case of ogive-nosed projectiles the main perforation mechanism is ductile hole growth where the pointed projectile tip pushes material perpendicularly to the flight direction meaning that plastic dissipation takes place in a much larger portion of the plate than for blunt-nosed projectiles.

In this work, we study systematically how the shape of the yield surface affects the results of ballistic impact simulations. Previously obtained experimental data is revisited and will provide context to the numerical simulations. The isotropic and pressure independent high-exponent yield function is then presented along with the constitutive relation and the failure criterion. Ballistic impact simulations with varying yield surfaces, initial velocities and projectile nose shapes are presented before the results are discussed in the closing section.

## 2. Material and experimental tests

### 2.1. Weldox 700 E steel plates

Comprehensive experimental works on Weldox 700 E steel plates by Dey et al. [21] serve as the backdrop for the study of the yield-surface shape in this paper. Weldox 700 E is a quenched and tempered martensitic steel with high strength and high ductility. To calibrate the constitutive relation, Dey et al. [21] conducted uniaxial and notched quasi-static tension tests, tension tests at elevated strain rates and tension tests at elevated temperatures. Fig. 1 shows (a) the equivalent stress-strain curve, (b) the influence of stress triaxiality on the fracture strain, (c) the strain rate sensitivity, and (d) the temperature dependence of Weldox 700 E. The fracture strain is about 1.2 for smooth quasi-static tension tests and it decreases significantly with increased stress triaxiality ratio. The flow stress is sensitive to the strain rate and increasing the strain rate increases the stress (Fig. 1c). For increasing temperature, the yield stress drops as seen in Fig. 1d. Dey et al. [21] also reported that the fracture strain increased with temperature, but that the strain rate hardly affected the ductility of the material.

### 2.2. Ballistic testing

Sabot-mounted blunt-nosed and ogive-nosed hardened steel projectiles were launched toward 12 mm thick Weldox 700 E steel plates at impact velocities between 150 m/s and 370 m/s.

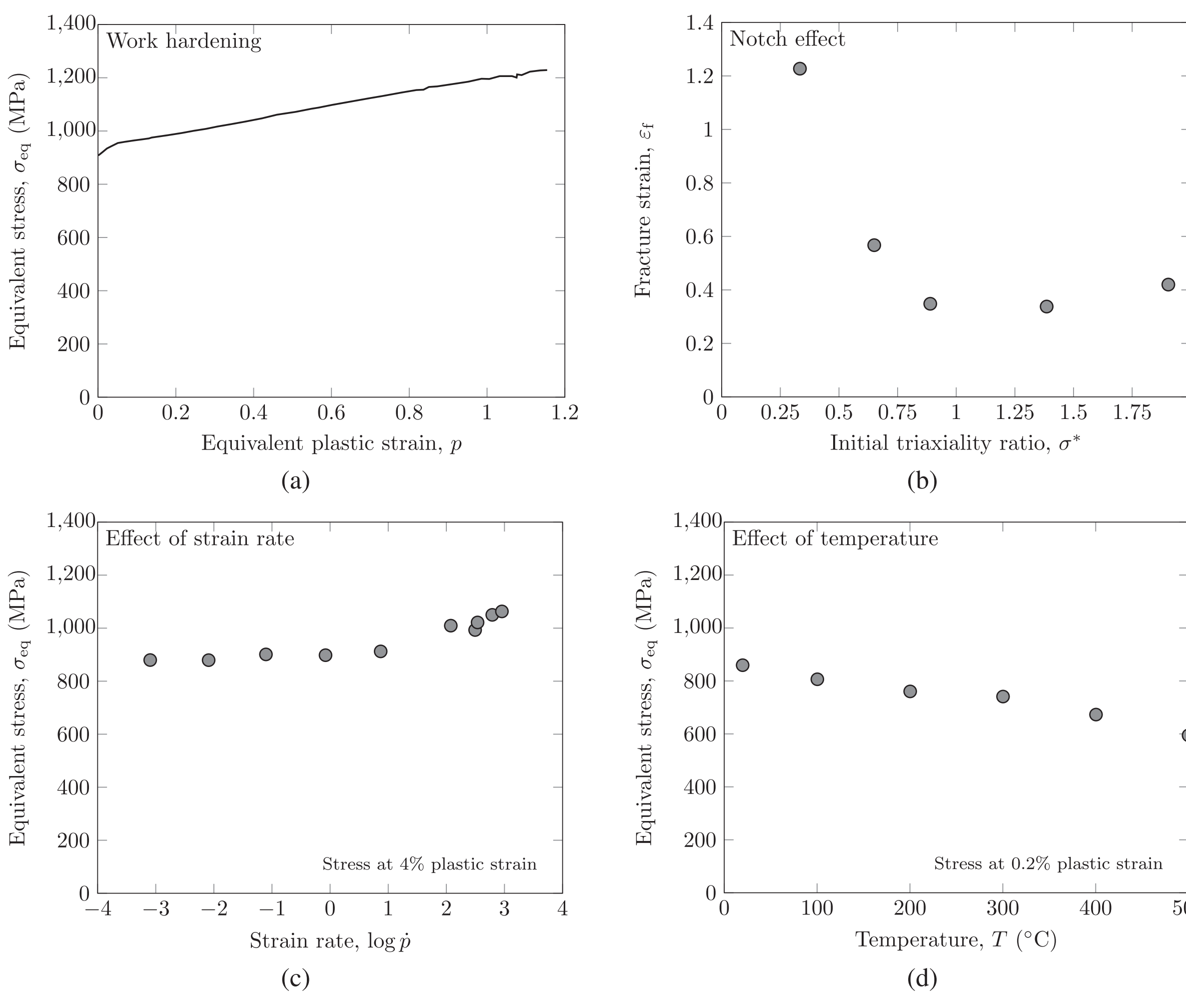


**Fig. 1.** Experimental data from the material tests of Dey et al. [21].