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The characterization and ballistic evaluation of mild steel

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ABSTRACT

The manuscript presents a systematic study for the characterization of mild steel under varying stress-triaxiality, strain rate and temperature. The effect of stress triaxiality was studied by performing tension tests on notched cylindrical specimens. The radius of the notch has been varied as 0.2, 0.4, 0.6, 0.8, 1, 2, 3, 4, 5 and 10 mm. The smooth cylindrical specimens were tested under tension at varying strain rate and temperature. The strain rate in the range, 0.0006 s^{-1}–1500 s^{-1}, was obtained on a universal testing machine and the Hopkinson pressure bar apparatus. The tests at elevated temperature were carried out using a portable furnace which enabled the variation of temperature from 100 °C to 750 °C. All the material parameters for the Johnson–Cook elasto-viscoplastic material model have been calibrated. The parameters thus obtained were validated by numerically simulating the material characterization under high strain rate using ABAQUS/Explicit finite element code. The numerical simulations were also carried out for the ballistic evaluation of 12 and 16 mm thick mild steel plates impacted by 7.62 AP projectiles at varying incidence velocities in order to obtain the ballistic limit. The angle of incidence has also been varied until the occurrence of critical ricochet. The numerical results have been validated by the experiments reported in earlier studies, Gupta and Madhu [1,2].

1. Introduction

The perforation mechanics is significantly influenced by the material behavior of projectile and target. The simultaneous occurrence of large strains, high strain rate and high temperature associated with the phenomenon, however, makes the description of the material behavior as well as its characterization quite complex.

Teng and Wierzbicki [3] employed six distinct fracture models to predict the damage in Weldox 460 E steel and 2024-T351 aluminum plates against blunt and conical projectiles. The predicted failure mechanism and residual projectile velocities were compared with their actual values and the limitations of each model were discussed. The Wilkins failure model predicted unrealistic spallation of material due to vanishing ductility effects. The maximum shear stress criterion could not predict the shear plugging under a range of incidence velocities. The resultant critical shear stress caused either premature or incomplete failure of the target. The modified Cockcroft-Latham model employed only one parameter to characterize the material, however, the single parameter could not represent the damage due to varying stress triaxiality. Similarly, the conventional critical strain and the simplified Bao-Wierzbicki (BW) fracture models failed to give satisfactory results for a wide range of problems. On the other hand, the Johnson–Cook (JC) failure model predicted the realistic fracture behavior and residual velocities. It was concluded, however, that the capability of the JC model to predict the shear dominant failure has not been established yet.

Banerjee [4] studied the limitations of the available constitutive models by simulating the behavior of OFHC copper under varying strain rate and temperature. The one dimensional tension and compression tests as well as the Taylor impact tests were simulated using JC, Steinberg–Cocharan–Guinan–Lund (SCGL), Zerilli–Armstrong (ZA), Mechanical Threshold (MTS) and Preston–Tonks–Wallace (PTW) models. The JC model overestimated the initial yield for the quasi-static test performed at room temperature. The rate of hardening was underestimated for the test performed at room temperature and 8000 s^{-1} strain rate while the strain rate dependence of the yield stress was under estimated at high temperature, 1173 K. The SCGL model underestimated the softening associated with increasing temperature, however, the yielding at 8000 s^{-1} strain rate was predicted reasonably

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accurately. At 4000 s^{-1} strain rate the performance of the model was worse at high temperature. The ZA model accurately predicted the quasi-static yield stress at room temperature however underestimated the same at 8000 s^{-1} strain rate. The yield stress at 4000 s^{-1} strain rate was reasonably predicted however the decrease in yield stress with increasing temperature was overestimated. The MTS model predicted higher yield stress under quasi-static test performed at high temperature (1173 K), whereas, the higher strain rate tests performed at high temperature were in agreement with the experimental results. The PTW model explicitly accounted for the rapid increase in yield stress at strain rate above 1000 s^{-1} and performed better under the tests carried out in compression than in tension. For Taylor impact tests however, the JC model predicted the mushroomed diameter and the final length most accurately. All the other models though correctly predicted the final length however under predicted the mushroomed diameter.

The Taylor impact tests were also carried out by Konokman et al. [5] on stainless steel 304 L and the results obtained were reproduced using ZA and JC models. Both the flow stress models predicted the peripheral bulging accurately however, the ZA model underestimated the final deformed length.

Sjoberg et al. [6] calibrated the JC and ZA constitutive models for alloy 718 and simulated the impact tests performed on a specially designed setup. The simulations with JC model had closer agreement with the experiments compared to the ZA model for the tests conducted at room temperature.

A number of constitutive models are available for predicting the plastic deformation and fracture behavior of metals under high rate of loading. A constitutive model should be capable of incorporating various phenomena occurring simultaneously during the flow and fracture process under varying strain rate. The practical issues such as number of material parameters, their availability, calibration procedure and compatibility of the model with available commercial finite element codes are fairly important considerations. A complex model with large number of material parameters may be quite accurate in predicting the in-depth local material behavior however its calibration would be highly complicated and time consuming and therefore a simpler model capable of capturing the overall structural response and employing fewer material parameters is considered more practical. The Johnson–Cook model, despite its empirical and uncoupled approach, accurately captures the global structural behavior in predicting the perforation behavior of metals [7–14] and possesses simplistic formulation and relatively easier calibration procedure.

Borvik et al. [7,8] slightly modified the equivalent flow stress and fracture strain expressions of the JC model and calibrated the material parameters for Weldox 460 E steel through uniaxial tension tests performed at varying strain rate and temperature. The model was then employed to simulate the perforation of 6 and 12 mm thick Weldox 460 E steel plates by blunt, conical and hemispherical projectiles in a series of studies [7–10,12] and results thus obtained were validated through experiments. The numerical model qualitatively captured the overall physical behavior of the target and accurately predicted the failure modes, energy absorption, maximum target deformation and residual projectiles velocities. The ballistic limit velocity for each projectile was predicted within 8% accuracy. In the case of conical projectile, however, there was a problem of distortion of the elements and error termination. To avoid this, erosion of the elements was carried out at an early stage by reducing the fracture strain parameters. The adaptive meshing technique was also employed in order to reduce the critical element distortion against conical projectile. The simulations employing adaptive meshing with original fracture parameters were successfully completed and these reproduced good correlation with experiments. The ballistic limit velocity and the residual velocities of the blunt and hemispherical projectiles were also reproduced with and without adaptive meshing and these were found to be identical.

Clausen et al. [11] studied the flow and fracture characteristics of AA5083-H116 aluminum alloy as a function of stress-triaxiality, strain rate and temperature. The material exhibited negative strain rate sensitivity at strain rate, 10^{-4}–1 s^{-1}, and significant reduction in flow stress at temperatures, 400–500 °C. The material characterization enabled the calibration of the parameters for modified JC model [8]. The model was then employed for predicting the perforation of 15–30 mm thick AA5083-H116 aluminum plates by 20 mm diameter conical projectiles using 2D axisymmetric elements and adaptive rezoning [15]. The simulations predicted the ballistic limit with a maximum deviation of 5% from the experimental results.

A number of materials have been characterized and calibrated for obtaining the JC model parameters [7,8,11,12,16,17]. Availability of the material parameters is an important reason for the popularity of the JC model. However, there are very few materials which have been characterized for obtaining all the required parameters of JC flow and fracture model. For example, Johnson and Cook [17] calibrated their complete model for OFHC Copper, Armco Iron and 4340 steel. The Weldox 460 E steel [7,8] and AA5083-H116 aluminum alloy [11] have also been characterized to obtain the complete set of material parameters for the modified JC model. Except these however, the authors could not find any material for which the complete model has been calibrated.

The present study addresses a detailed experimental investigation wherein the characterization of mild steel has been carried out under varying stress triaxiality, strain rate and temperature. The calibration of the original JC model has also been carried out for obtaining all the required parameters. The calibrated JC parameters were employed to simulate the material testing at high strain rate both under tension and compression. The stress–strain relationship thus obtained through the numerical results has been compared with those obtained from the experiments. The JC material parameters have also been employed to predict the ballistic performance of 12 and 16 mm thick mild steel plates impacted by 7.62 AP projectiles both at normal and oblique angles of incidence until the occurrence of projectile ricochet. The numerical results thus obtained were validated by the experiments performed by Gupta and Madhu [1,2].

2. Material characterization

The mild steel of hardness and chemical composition similar to that of the material employed for ballistic evaluation by Gupta and Madhu [1,2], see Tables 1 and 2, was procured in the form of plates of 12 mm thickness. The possible anisotropy of the material was studied by extracting the flat specimens from three different directions i.e., 0°, 45° and 90° and performing the uniaxial tension tests under quasi-static loading. The thickness of the flat specimen was 10 mm, width 12 mm and gauge length 50 mm, see Fig. 1(a). The engineering stress–strain relationship of the specimens did not indicate any significant anisotropy, see Fig. 2. Thus the material in principle was considered isotropic and the material coupons for the complete characterization were extracted from the middle of the thickness of the 12 mm thick plate along the 0° direction. Each test was repeated three times to ensure the accuracy and the repeatability and therefore the results reported in this study are the average of three tests. The measured and Bridgeman corrected trues stress–strain relationship along with the engineering stress–strain relationship is shown in Fig. 3 for comparison. The true-stress–strain relationship has been obtained by performing