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Prediction of fragmentation and experimentally inaccessible material properties of steel using finite element analysis

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ABSTRACT

High strain-rate properties of materials are needed for predicting material behavior in extreme environments. The demand for high strain-rate properties continues to increase for commercial and military applications as the operating environments become more extreme, such as fragmentation, impact and explosions. To reduce time and expense, Finite Element Analysis (FEA) is being used to simulate these behaviors and reduce the number of experiments needed to characterize how a material performs at high-strain-rates. A finite element model for predicting fragmentation behavior of a high strength steel ring was developed using Abaqus Computer Aided Engineering (Abaqus) software. AISI 4340 steel, a low alloy Cr–Ni–Mo steel, was used in the analysis. The results of the finite element model were compared to the results from CTH, a two-dimensional Eulerian shock physics hydro-code. CTH was also used to develop a transient loading curve for the Abaqus model. The fracture strain in the model was adjusted to induce failure in the ring. Element deletion was used to model failure. A fracture strain less than 1×10^{-5} was needed to initiate fragmentation. The effects of mesh type and model defects were also investigated.

1. Introduction

Material fragmentation at high strain-rates is difficult to characterize experimentally. Typically, a test article or projectile is subjected to a high-strain-rate that results in fragmentation. The fragments are collected and sorted into bins. Several fragments are examined under a microscope to determine failure characteristics, making this process very time consuming and expensive. In the past 60 years, many empirical material models have been developed to predict failure at high strain-rates to correlate with experimental results [1–4]. Most of these models rely on high strain-rate data obtained using the Split Hopkinson Pressure Bar (SHPB) or other high strain-rate testing. The SHPB method measures stress pulse propagation through a metal bar to predict the stress–strain relationships of a material [5,6]. There are shortcomings to this method as it requires many assumptions to be made, and loses accuracy when materials undergo tension testing at strain-rates above $10^3\ s^{-1}$ [7,8]. Components can be designed to improve fragmentation behavior and identify failure initiation sites. The models help identify failure modes, and reduce the number of samples that need to be tested. For this effort, a model was developed that incorporates high strain-rate data from previous SHPB experiments in a constitutive material model to predict failure.

2. Experimental procedure and approach

2.1. Ring development

A three dimensional solid model of a ring was developed using SolidWorks computer aided drafting (CAD) software [9]. The ring has a diameter of 81 mm, a wall thickness of 7 mm, and a notch depth of 3.5 mm. The notch is 5.7 mm tall with a 60 degree taper at the top. The ring was imported into Abaqus for analysis. The ring was partitioned into smaller sections to allow for the use of the automatic meshing function in Abaqus which is needed to utilize all mesh types when modeling high-strain-rate behavior. Partitioning in Abaqus was done by the three point method to develop a partitioning plane. The SolidWorks model of the ring is shown in Fig. 1.

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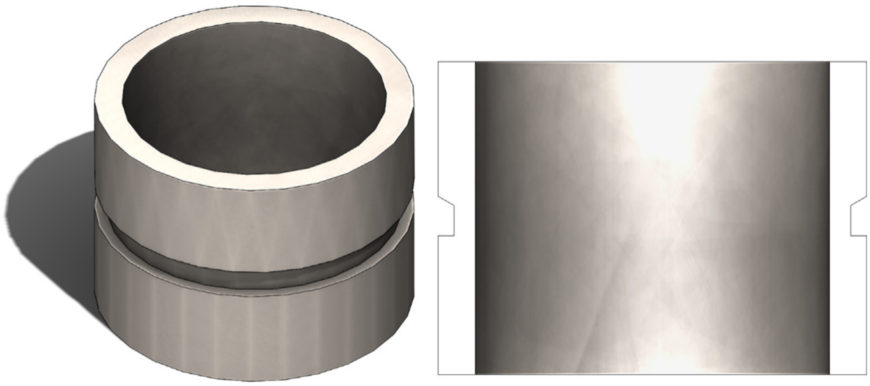

Fig. 1. Three Dimensional SolidWorks model of the ring. The cross section view is shown on the right. The diameter of the ring is 81 mm. Wall thickness is 7 mm.

2.2. Material properties

The material properties used in the model of the ring were those of austenitized, quenched, and tempered AISI 4340 steel determined by Johnson and Cook [1,2]. The hardness of this steel was reported to be Rockwell C30, which would correlate to a mainly pearlitic microstructure. The standard, strain-rate independent material properties for this alloy are found in Table 1 [1,2,10].

High strain-rate properties were added to the model using the Johnson–Cook (J–C) plasticity model [1,2] This empirical model contains five experimentally determined constants and is commonly used to predict behavior of ductile materials under high strain-rate conditions such as explosive loading. This model is available in the Abaqus software by default [1,2,11]. It defines the von Mises flow stress of a material as a function of the power law relationship of plastic strain and strain hardening, strain-rate, and thermal softening. The J–C model is shown in Eq. (1) [1,2].

$$\sigma = \left[A + B\varepsilon_p^n\right]\left[1 + Cln\varepsilon_p^*\right][1 - T_H^m] \quad (1)$$

$\varepsilon_p =$ equivalent plastic strain

$\varepsilon_p^* =$ normalized effective plastic strain rate

$T_H =$ homologous temperature $= \dfrac{(T - T_{\text{room}})}{(T_{\text{melt}} - T_{\text{room}})}$

The values of *A*, *B*, *C*, *n*, and m are experimental constants that are determined using uniaxial tension tests and the SHPB tests. T_{melt} and T_{room} are the melting temperature of the alloy and the ambient air temperature, respectively. The material constants used in the J–C model and are found in Table 2 [1,2].

The J–C equation was used to predict the room temperature von Mises flow stress at six different strain-rates shown in Fig. 2. The results indicate that the von Mises flow stress increases as the strain-rate increases. Strain is only plotted to 0.4 strain due to the fact that the Johnson–Cook model only predicts a linear increase in strength at large amounts of strain. This linear increase at large strains is due to the effect of the exponential power law factor in the equation.

The J–C strength model was not the only constitutive material model needed in this analysis. The J–C fracture model was used to initiate the failure of the elements through the use of a fracture strain value. Fracture strain can be measured easily under uniaxial tension at quasi-static strain rates using an extensometer, but at high-strain-rates this may not be possible. Modeling a complex structure at various fracture strain values maybe the only way to identify the proper fracture strain. In modeling, once an element reaches the fracture strain value, it is deleted from the equation. The J–C fracture model does not follow a typical nucleation and growth model. It is dependent on strain, strain-rate, temperature, and pressure [1,2]. The benefits are that it is less complicated to use, and most of the parameters can be found using adjusted quasi-steady state data. The J–C fracture model is also built directly into Abaqus, and is fully compatible with the J–C strength model. The J–C fracture model is defined in Eq. (2) [2],

$$\varepsilon^f = \left[D_1 + D_2 \exp^{D_3 * \sigma^*}\right][1 + D_4 \ln \dot{\varepsilon}^*][1 + D_5 T^*] \quad (2)$$

where ε^f is the equivalent strain to fracture, $D_1 - -D_5$ are material constants, $\dot{\varepsilon}^*$ is the dimensionless strain-rate, and *T* is temperature. Material constants for AISI 4340 from Johnson-and Cook are shown in Table 3 [2].

Table 1
Strain-rate independent material properties of AISI 4340 steel [1,2,10].

Elastic modulus (GPa)	Density (kg/m^3)	Poisson's ratio	% Elongation	Ultimate tensile strength (MPa)	Yield strength (MPa)
200	7830	0.29	22	745	470

Table 2
Johnson–Cook material constants for AISI 4340 steel [1,2].

A (MPa)	B (MPa)	C	*n*	*m*	T_{melt} (K)
800	510	0.014	0.26	1.03	1793

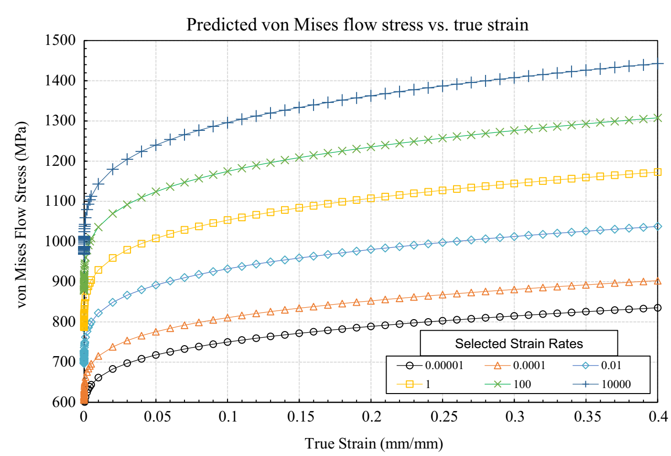

Fig. 2. von Mises Flow Stress vs. True Strain of AISI 4340 Steel at Room Temperature. Data is plotted at Room Temperature (300 K).