DYMAT

23rd Technical Meeting

DYNAMIC FRACTURE OF DUCTILE MATERIALS

ABSTRACTS

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DYMAT 23rd Technical Meeting

Dynamic Fracture of Ductile Materials

Material Testing in Support of the Development and Calibration of Constitutive Equations for Dynamic Plasticity and Fracture

Amos Gilat[a]*, Jeremy Seidt[a]

[a]Department of Mechanical and Aerospace Engineering
The Ohio State University, Columbus, OH, 43210, USA

Abstract

Extensive material testing is required for setting up, calibration and validation newly-developed material models for dynamic plastic deformation and fracture. One example is the material models MAT224 and MAT264 in the LS-DYNA code which are extension of the Johnson-Cook viscoplastic damage model. The tabulated form of these models extends their validity to a wide range of loading conditions, strain rates, temperatures, and fracture modes, but requires data from many experiments to setup. This paper describes the experiments that were used and new experiments that have been developed during the development of these material models. It includes compression, tension, and shear tests over a wide range of strain rates, including high strain rates using the Split Hopkinson bar (SHB) technique. Quasi-static and dynamic continuous and interrupted punch tests that include 3D DIC strain measurement of the deformation at the back surface of the specimen during the test. Tensile tests over wide range of strain rates (including SHB experiments) in which full-field deformation (using DIC) and full-filed temperature (using very high speed IR camera) are measured simultaneously during the experiment.

Data from testing at various strain rates, various temperatures, and different specimen geometries is used for setting up the plasticity material model, and a failure surface that gives the equivalent plastic fracture strain as a function of triaxiality and the Lode parameter. Punch tests with different punch geometries that produce different failure modes are used for validating the plasticity-failure model. The set-up of the dynamic punch test is shown in Figure 1. The specimen is mounted on the transmission bar of a compression SHB apparatus with a holder that provide optical path to two high-speed cameras to the back surface of the specimen. The punch is attached to the input bar. A specimen following a test and a sample of data is shown in Figure 2. DIC images that show the history of the maximum strain measured on the back surface of the specimen during the test are shown in Figure 3.

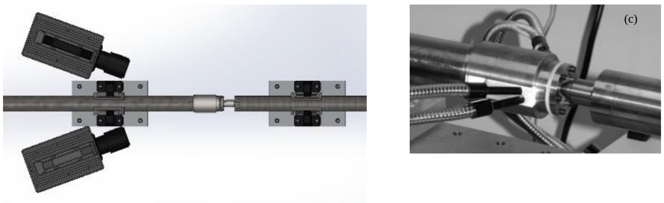

Figure 1: Setup of the dynamic punch test.

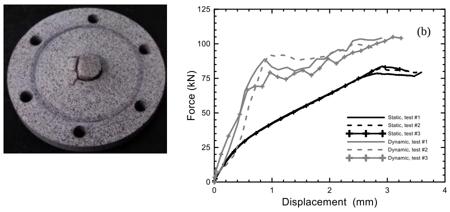

Figure 2: Punched specimen and data from a dynamic punch test.

* Corresponding author. Tel.: 1-614-292-1269; fax: 1-614-292-3163.
E-mail address: gilat.1@osu.edu

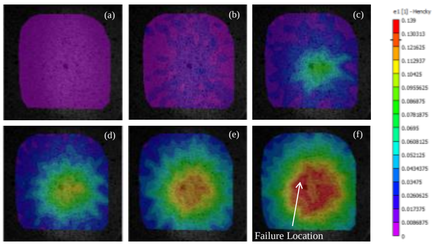

Figure 3: Contours of maximum principal strain from a hemispherical dynamic punch test: (a) 0 µs, (b) 40 µs, (c) 90 µs, (d) 120 µs, (e) 180 µs, (f) 230 µs.

Tension tests with simultaneous full-field strain and temperature measurement provide the data that is needed to uncouple the effect of strain hardening and temperature softening in the plasticity model. Figure 4 shows the experimental setup of such a high strain rate test with the tensile SHB technique. The history of the deformation and temperature in the gage section during the test is shown in Figure 5. Moderate and uniform temperature increase is observed during the initial homogeneous deformation and localized deformation and significant temperature rise is measured during necking. Data from such experiments over a wide range of strain rates show that even relatively low strain rate tests are not isothermal, and that the temperature rise in the neck region can exceed 300°C.

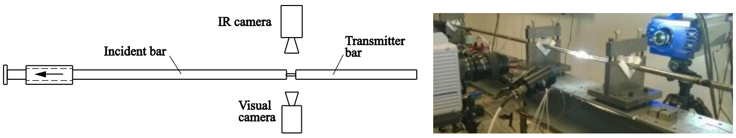

Figure 4: Setup of a tensile SHB test with full-field DIC and IR measurements.

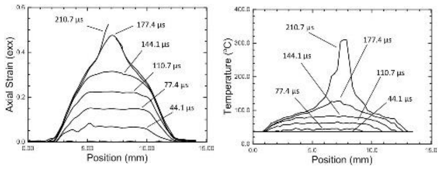

Figure 5: Strain and temperature measurements during a tensile SHB experiment.

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Dynamic Fracture of Ductile Materials

Structure / Property (Constitutive and Dynamic Strength / Ductile Damage) Characterization of Additively Manufactured (AM) 316L SS, 304L SS, and Tantalum

G.T. (Rusty) Gray III*, V. Livescu, C.P. Trujillo, C. Knapp, J. Carpenter, D. Jones

Materials Science and Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

For additive manufacturing (AM) of metallic materials, the certification and qualification paradigm needs to evolve as there currently exists no broadly accepted "ASTM- or DIN-type" additive manufacturing certified process or AM-material produced specifications. Accordingly, design, manufacture, and thereafter implementation and insertion of AM materials to meet engineering applications requires detailed quantification of the constitutive (strength and ductile damage) properties of these evolving materials, across the spectrum of metallic AM methods, in comparison/contrast to conventionally-manufactured metals and alloys. This talk summarizes strength and damage results on AM-316L and 304L SS and presents initial results of a new program quantifying the dynamic ductile damage response of AM-Tantalum.

For the AM-316L and 304L SS investigations, samples of 316L and 304L SS were produced using a LENS MR-7 laser additive manufacturing system from Optomec (Albuquerque, NM) equipped with a 1kW Yb-fiber laser as well as using an EOS Laser-powder bed machine. The microstructures of the AM-316L and 304L SS materials were characterized in both the "as-built" AM states and following a heat-treatment designed to obtain full recrystallization to facilitate comparison with annealed wrought SS. The dynamic shock-loading-induced damage evolution and failure response of the 316L and 304L SS materials were quantified using flyer-plate impact driven spallation experiments at peak stresses of 4.5 and 6.35 GPa. The ductile damage evolution as a function of AM fabrication method was characterized for the AM-316L and 304L SS using both optical metallography and electron-back-scatter diffraction (EBSD).

The constitutive behavior of both stainless steels as a function of strain rate and temperature was characterized and is compared to that of annealed wrought 316L and 304L SS plate materials. The spall strength of AM-produced 316L SS and the recrystallized-AM-316L SS were found to decrease with increasing peak shock stress while the annealed wrought 316L SS spall strength remained essentially constant. The ductile damage evolution was found to vary significantly across the 316L SS microstructures studied. The AM-as-built 316L SS displayed a 60% higher yield strength, pronounced macroscopic solidification boundary structure, and chemical segregation evident in the as-built microstructure compared to the equiaxed annealed wrought 316L SS; this increased strength believed to be due to the fine-scaled dendritic microstructure formed during solidification in the AM process. The AM-as-built material showed an ~10% higher spall strength when shocked to 4.5 GPa peak shock stress and ~10% lower spall strength when loaded to 6.35 GPa compared to annealed wrought 316L SS whose spall strength remained invariant for both peak shock stresses. Preferential ductile damage evolution in the AM-as-built 316L SS along solidification boundaries when shock-loaded orthogonal to the AM-build direction suggests future dynamic fracture and damage evolution studies should probe the dynamic spall behavior of AM materials as a function of loading orientation to the AM-build direction.

Plates of AM-304L SS were fabricated using both a laser directed-energy Optomec LENS MR-7 and a laser powder-bed Electro-Optical Systems (EOS) M280. The microstructure, mechanical properties, and spallation response of the AM-304L SS is compared to both annealed and forged 304L SS wrought products. The AM-304L SS characterization revealed significantly finer microstructural scale in the EOS build compared to the LENS build and this correlates with differences in both compressive and tensile yield strengths. Both the EOS and LENS builds produced reproducible mechanical behaviors with the EOS material 40% stronger in compression and 20% stronger in tension. The spall response

* Corresponding author. Tel.: 1-505-667-5452
E-mail address: rusty@lanl.gov

of the initial AM-304L SS, LENS-build displayed nominally similar spall strengths for all three orthotropic loading directions. The spall strength of the AM-304L SS was additionally seen to be similar to the forged wrought 304L SS studied for comparison.

Following on from the AM-stainless steel completed work, initial results on a study of AM Tantalum are in progress. Preliminary results on the structure/dynamic spallation property behavior of AM-Tantalum fabricated using both the directed-energy LENS and an EOS powder-bed AM techniques in comparison to wrought annealed Tantalum will be presented.

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* Corresponding author. Tel.: 1-505-667-5452
E-mail address: rusty@lanl.gov

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Dynamic Fracture of Ductile Materials

Low pressure shock response and dynamic failure of high density- and ultra-high molecular weight polyethylene

Dana M. Dattelbaum[a], Benjamin F. Schilling[a], John M. Lang,[a] Cynthia F. Welch[b], Jamie A. Stull[b], Bradford E. Clements[c]

[a]*Explosive Science and Shock Physics Division, MS P952, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[b]*Materials Science and Technology Division, MS E549, Los Alamos National Laboratory, Los Alamos, NM 87545 USA*
[c]*Theoretical Division, MS B221, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

Abstract

Polyethylene is a widely-encountered polymer that exhibits mechanical responses tailorable to a given application based on its network and chain structures (crystallinity) and molecular weight. Several earlier reports have provided shock Hugoniot data for polyethylene over a broad range of conditions to very high shock stresses (Marsh et al., Bourne et al.), while other reports have focused on the unusual and discontinuous low pressure shock adiabats of crystalline forms of polyethylene (Moro et al.). Surprisingly little is known about the influence of polyethylene's crystalline structure, and associated crystalline phase transitions including melt, on its dynamic compression response. Two different polyethylene materials – high density polyethylene and ultrahigh molecular weight polyethylene - were chosen for investigation of the influence of a high percentage of crystallinity (>40%) on the shock response and dynamic tensile failure (spall). We have applied *in situ* electromagnetic gauging techniques to measure the evolution of particle velocity wave profiles with wave propagation distance to elucidate the nature of the previously reported discontinuous Hugoniot at low pressures. The first evidence of a three-wave structure in highly crystalline polyethylene was measured above a shock stress of 0.5 GPa. Above this region of discontinuity in the principal Hugoniot, the transition is overdriven, and a single shock wave is observed to shock stresses exceeding 10 GPa. Details about the nature of the transition, including wave velocities and changes in density, will be presented. Further, a series of dynamic tensile experiments were performed on polyethylene to assess the dynamic tensile (spall) strength as a function of shock stress. Experiments were performed over a range of shock input stresses, and with two different types of impactors to vary the dynamic tensile condition, and the results for polyethylene were compared with earlier results for polymers such as polytetrafluoroethylene and polychlorotrifluoroethylene. The dynamic failure experiments were modeled using a failure criterion in the glassy amorphous polymer (GAP) model, which captures the volumetric and deviatoric responses of polymers at low shock stresses. The combined Hugoniot and dynamic failure data for polyethylene will be used to inform phase aware equation of state and failure models for this widely used polymer.

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Dynamic Fracture of Ductile Materials

Simulation of strain localization and dynamic crack growth in ductile materials using micromechanical damage models

Nicolas Jacques[a,1] , Sébastien Mercier[b], Alain Molinari[b]

[a] *ENSTA Bretagne, FRE CNRS 3744, IRDL, 2 rue François Verny, F-29806 Brest cedex 9, France*
[b] *Université de Lorraine, UMR CNRS 7239, LEM3, Ile du Saulcy, F-57045 Metz cedex 01, France*

Abstract

The understanding and modelling of the failure of ductile materials under dynamic loading conditions is an important issue for several applications, like the safety of pressurized structures (aircraft and gas pipelines), and the resistance of protective structures and shieldings to ballistic impacts and explosions. Damage in ductile solids is induced by the diffuse nucleation and growth of microscopic voids. The softening effect due to damage may lead to strain localization, promoting the damage development and leading to the formation of a crack, which can propagate through the specimen.

The proposed talk deals with the simulation of the initiation and propagation of cracks under dynamic loading using micromechanical damage models. Since the pioneering work of Gurson (1977, http://dx.doi.org/10.1115/1.3443401), the development of micromechanical models for ductile fracture was the subject of numerous studies, see e.g. the recent review of Benzerga and Leblond (2010, http://dx.doi.org/10.1016/S0065-2156(10)44003-X). An advantage of micromechanical damage models is that they allow one to analyse the influence of microstructural variables (void shape and orientation, volume fraction of inclusions in the material…) and therefore to relate the fracture behaviour of a material with its microstructure. There are also several shortcomings associated with the use of damage models. One of the most serious is the problem of spurious mesh dependency. Indeed, within the framework of standard continuum mechanics, the problem becomes ill-posed when a rate-independent strain-softening constitutive model is employed. In this case, damage tends to localize in a band of zero thickness (Bazant and Belytschko, 1985, http://dx.doi.org/10.1061/(ASCE)0733-9399(1985)111:3(381)). Because of this problem, the results of numerical simulations of ductile fracture are strongly dependent of the mesh size and orientation, and it is not possible to obtain a converged solution. Under static loading, it is necessary to resort to "non-local" models to alleviate the problem of spurious localisation, see e.g. Enakoutsa et al. (2007, http://dx.doi.org/10.1016/j.cma.2006.10.003). For dynamic problems, the introduction of rate effects in the constitutive model induces a regularizing effect and prevents damage to concentrate in a zone of zero thickness (Needleman, 1988, http://dx.doi.org/10.1016/0045-7825(88)90069-2). In the case of a damaged (porous) material, strain-rate dependence can be related to the viscoplastic behaviour of the matrix material (dense material surrounding the voids). There is also another mechanism that leads to rate effects in the behaviour of a porous solid: micro-inertia. This phenomenon is related to the void growth process. More precisely, micro-inertia effects are due to the accelerations sustained by the matrix material in the vicinity of the expending voids. A damage model incorporating the contribution of micro-inertia was developed recently (Jacques et al., 2015, http://dx.doi.org/10.1016/j.mechmat.2014.01.008).

In the proposed talk, simulations of dynamic ductile fracture will be presented for different configurations (notched bars, double edge cracked specimens and more complex specimens) and the influence of micro-inertia will be discussed. It will be shown that the regularizing effect of micro-inertia is more pronounced than the one related to viscoplasticity (with material parameters corresponding to a medium strength steel). Moreover, it will appear that with the proposed modelling, the fracture behaviour of a material under dynamic loading (crack speed and fracture toughness) is related to microstructural length scales (size and spacing between the inclusions present in the material). Finally, an analytical model will be proposed

* Corresponding author. Tel.: +33 2 98 34 89 36; fax: +33 2 98 34 87 30.
E-mail address: nicolas.jacques@ensta-bretagne.fr

to evaluate the size of the damaged zone. It will be seen that, with the micro-inertia based model, the size of the damaged zone increases with the magnitude of the applied load. This mechanism, referred to as “damage delocalisation”, was already observed in experiments.

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Dynamic Fracture of Ductile Materials

Fracture modeling of perforated Mars® 300 plates

Teresa Fras [a], Christian C. Roth[b], Norbert Faderl[a], Dirk Mohr[b,c*]

[a)] French-German Research Institute of Saint-Louis (ISL), 5 rue du Général Cassagnou, 68301 Saint-Louis, France
[b)] ETH Zurich, Department of Mechanical and Process Engineering, Technoparkstrasse 1, CH-8005 Zurich, Switzerland
[c)] Impact and Crashworthiness Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139, Cambridge MA, USA

Abstract

Mars® 300 belongs to a group of steels dedicated to ballistic protection as its properties, especially high hardness and strength, provide high level of ballistic performances. The steel may be used as a perforated passive add-on armor – a relatively thin steel plate with an array of punched holes, which is fixed in front of the main armor. A regular holes pattern in steel sheets increases the probability of asymmetrical contact between the plate and small-caliber projectiles, due to which projectiles may be destabilized or fragmented before they reach the main-armor. It is observed that depending on the hit-position, the projectile core may break into pieces or it may be partially eroded and rotated, [1-2].

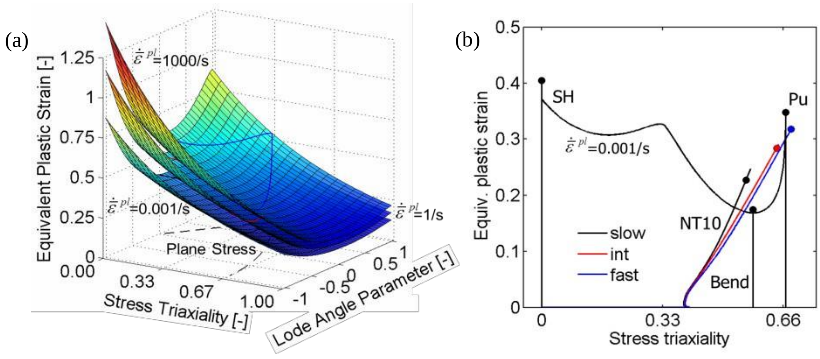

Fig. 1. Fracture response of the Mars®300 steel: (a) illustration of the fracture surfaces for different strain rates in the space of stress triaxiality, Lode angle parameter and equivalent plastic strain, (b) loading paths (solid lines) and predicted onset of fracture (dots) together with the fracture envelope corresponding for a strain rate of 0.001 s^{-1}.

In order to understand the mechanisms occurring in Mars® 300 due to impacts of small-caliber threats leading to different failure modes of bullets and causing different fracture patterns in the plate, the effect of stress state and strain rate on material behaviour must be analyzed. Low, intermediate and high strain rate tensile experiments are carried out on flat smooth and notched tensile specimens extracted from non-perforated plates. Additional fracture experiments are performed on shear, bending and punch specimens.

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* Corresponding author. Tel.: +33 (0) 0389 69 5088; fax: +33 (0)3 89 69 50 02.
E-mail address: teresa.fras@isl.eu

To determine the strain to fracture and to obtain an accurate description of the local strain fields at very large deformations, a hybrid experimental–numerical approach is applied. The results are used to calibrate a plasticity model with a Johnson–Cook type of rate and temperature-dependency and a combined Swift–Voce strain hardening law used in conjunction with a non-associated anisotropic flow rule, [3-4]. Fig. 1(a) illustrates the effect of the strain rate on the resulting fracture surface for Mars® 300 in the space of equivalent plastic strain, stress triaxiality and Lode angle parameter. The loading path to fracture describing the evolution of the equivalent plastic strain at the strain rate 0.001 s^{-1} in terms of the stress triaxiality is shown in Fig. 1(b).

To validate the applied material and fracture model, the impact of high-strength bainitic cylinders of length 35 mm and diameter 8mm into 4 mm thick Mars® 300 plates perforated by holes of diameter 4 mm were performed. As compared to an impact by a projectile consisting of a steel core, brass jacket and lead cup and the corresponding interactions, this simplified experimental configuration has the advantage of involving only two materials, the impactor and the target. Similar to effects of small-calibre projectiles, a dependence between the hit position and the damage zone in the target plate is observed for the cylinder impact, Fig. 2.

Fig. 2. (a) Side view on the cylinder passing through the perforated Mars®300 plate. Damage zone of target plates resulted from the cylinders impacts in the area between holes (b – c) and (d) in a hole.

The numerical simulations were performed in the explicit solver of the finite-element code Ls-Dyna, in which the plasticity and fracture models were implemented by an UMAT. The boundary conditions of the impact tests were repeated by the simulations, Fig, 3(a); the elements size 0.1 mm was suitable to model cracks formations and propagations.

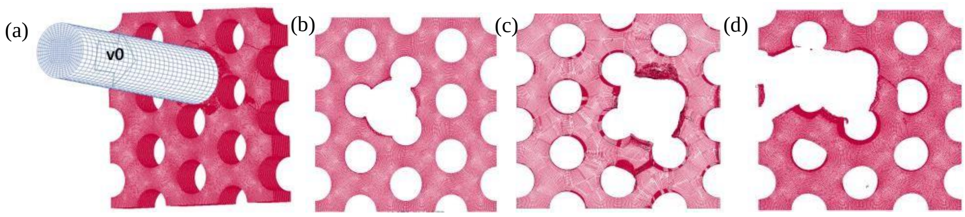

Fig. 3. (a) Numerical configuration. Results of numerical modelling of plates failed due to impacts of cylinders hit in the area between holes (b – c) and (d) in a hole.

Due to the cylinders impacts in the area between holes, a plug was sheared away from the plate. Fig. 2(b) illustrates the case when the cylinder was deviated from the position initally perpendicular to the plate but its end passed through the neighebour hole, whereas in Fig. 2(c), the larger damage zone was caused by the cylinder end which contact with the plate material was more intensive. The impact in a hole caused a larger damage of the target plate, the irregular shape of the damage zone was repeated by the numierical simulation. As the influence of contact point on the plate failure was properly described by the applied models, it may be concluded that the Swift-Voce modified Johnson-Cook plasticity model and strain-rate dependent Hosford-Coulomb fracture model are able to describe the behavior of Mars® 300.

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[3] Roth CC, Mohr D. Effect of strain rate on ductile fracture initiation in advanced high strength steel sheets: experiments and modeling. Int J Plasticity 2014;56:19-44.
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Dynamic Fracture of Ductile Materials

Implementation of a laser-based thermoreflectance diagnostic for full-field temperature measurements in SHPB experiments.

Lukasz Farbaniec, Jack Patten, David Chapman, Daniel Eakins

[a]*Institute of Shock Physics, Imperial College London, London SW7 2AZ, UK*

Abstract

The split-Hopkinson pressure bar (SHPB) technique is commonly used to study the dynamic behavior of engineering materials. In SHPB experiment, the specimen is typically subjected to high strains over microsecond time scales. Such conditions can often lead to significant, inhomogeneous temperature changes in the specimen, which are challenging to capture with conventional temperature measurement techniques. In this study, we propose a new concept for an active temperature diagnostic that is based on visible light thermoreflectance measurements, and which can be easily integrated with the SHPB system. The validation is performed on a thin-film gold sensor investigated in the visible reflectance spectrum at temperatures varying between 25 to 350ºC. A high-speed video camera is used to capture images of the specimen illuminated by superluminescent narrow-band diode lasers with microsecond exposures. The results showed measurable differences in optical signals for the investigated temperature range in close agreement with the literature. Finally, the thin-film gold sensor is applied to the surface of a forced-shear Ti alloy specimen to study its thermo-mechanical behavior using the SHPB technique under dynamic shear loading.

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Dynamic Fracture of Ductile Materials

Dynamic Fracture Characterization of Boron Steels with Tailored Properties

Michael J. Nemcko[a]*, Clifford Butcher[a] and Michael J. Worswick[a]

[a]*University of Waterloo, 200 University Avenue West, Waterloo N2L 3G1, Canada*

Abstract

This paper examines the dynamic fracture of a hot stamped ultra-high strength steel (UHSS) used in automotive applications (USIBOR® 1500-AS). Different material conditions are considered in which the constitutive properties are varied using in-die heating (IDH) to control the quench rate and resulting microstructure. High strain rate shear, hole tensile and notched tensile experiments are performed to vary stress triaxiality. *In situ* digital image correlation techniques are applied with high speed optical imaging to measure failure strain while high speed thermal measurements are used to characterize temperature rise during elevated rate testing. Measured failure strains are extracted as a function of the stress triaxiality for each quenching condition at quasi static and dynamic rates. Elevated strain rate tends to increase failure strain under tensile dominated triaxiality conditions, whereas significant temperature rise and adiabatic shear localization occur under high strain rate shear loading, leading to earlier onset of failure, at least in terms of displacement to failure. The effect of varying material strength, through IDH tailoring, on adiabatic temperature rise and the resulting high strain rate failure is examined.

* Corresponding author: Michael Nemcko. Tel.: +1-905-321-1867; fax: +1-519-885-5862.
E-mail address: mnemcko@uwaterloo.ca

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Dynamic Fracture of Ductile Materials

The deterministic nature of the fracture location in the dynamic tensile testing of steel sheets

Vaz-Romero, A.[a],*; Rodríguez-Martínez, J.A.[a]

[a]*University Carlos III of Madrid, Avda Universidad, 30, Leganés (28911),Madrid, Spain*

Abstract

In this research we investigate the key mechanisms which determine the fracture location in the dynamic tensile testing of steel sheets. For that purpose we have conducted experiments and finite element simulations. Experiments have been performed using samples with six different gauge lengths, ranging from 20 mm to 140 mm, that have been tested within a wide spectrum of loading velocities, ranging from 1 m/s to 7.5 m/s. Three are the key outcomes derived from the tests: (1) for a given gauge length and applied velocity, the repeatability in the failure location is extremely high, (2) there is a strong interplay between applied velocity, gauge length and fracture location and (3) multiple, and largely regular, localization patterns have been observed in a significant number of the experiments performed using the samples with the shorter gauge lengths. Our experimental findings are explained using the finite element simulations. On the one hand, we have shown that variations in the applied velocity and the gauge length alter the processes of reflection and interaction of waves taking place in the sample during the test, which leads to the systematic motion of the plastic localization along the gauge (as experimentally observed, see Fig. 1). On the other hand, we have detected that the emergence of multiple localization patterns requires short and equilibrated specimens with uniform stress and strain distributions along the gauge. We conclude that the experimental and numerical results presented in this paper show that, in the absence of significant material and/or geometrical defects, the ocation of plastic strain localization in the dynamic tensile test is deterministic.

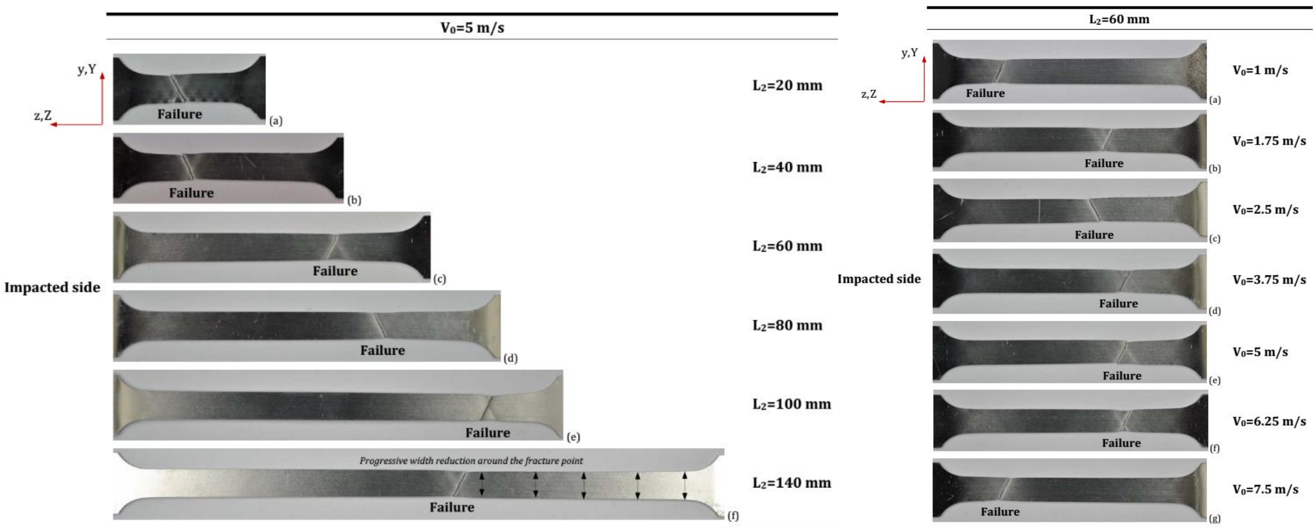

Fig. 1. *Dynamic tensile post-mortem samples. Comparison between samples with different gauge length and different impact velocity.*

* Corresponding author. Tel.: +34 91 6246015; fax: +34 91 624 9430.
E-mail address: avazrome@ing.uc3m.es

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Dynamic Fracture of Ductile Materials

Towards Reliable Shear Fracture Experiments at Low, Intermediate and High Strain Rates

Christian C. Roth[a] and Dirk Mohr[a,b]

[a]*Department of Mechanical and Process Engineering, ETH Zurich, Zurich, Switzerland*

[b]*Impact and Crashworthiness Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA*

Abstract

Determining the strain to fracture of metals under shear dominate-loading conditions is a pressing issue in the field of ductile fracture. Detailed analysis reveals that fracture experiments for pure shear conditions are extremely challenging and likely to produce misleading results due to premature fracture initiation at specimen boundaries. Flat in-plane shear specimens (as extracted from sheet metal) are particularly prone to early failure. In this talk a new family of in-plane shear specimens is presented to address this remaining experimental issue. The new specimens feature a single shear gage section that is formed through two blunt notches. Depending on the plastic material properties, the notch offset is adjusted to maintain shear stress states throughout the entire experiment. Furthermore, design maps are presented to determine the optimal notch shape delaying fracture from the free boundaries. The results from a computational study considering two geometric parameters, three sheet thicknesses and nine generic engineering materials are discussed in detail. It reveals that a group of geometries exists that guarantee failure under shear, irrespective of the material hardening and material thickness, but solely depending on the material ductility. It is also observed that obtaining shear fracture with in-plane shear specimens becomes more challenging with increasing material ductility. To validate the numerical findings, an experimental study is carried out in which loading is applied onto the newly developed specimens using either a universal testing machine or a Split Hopkinson Pressure Bar (SHPB) system with a load inversion device. Several materials are tested over a wide range of strain rates ranging from 0.001/s to several 1000/s and the displacement fields are measured by means of digital image correlation (DIC). Selected experimental results are presented for DP and armor steels providing valuable insight into the effect of strain rate on the ductility of sheet metals for stress state close to pure shear.

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* Corresponding author.
E-mail address:ccroth@ethz.ch

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Dynamic Fracture of Ductile Materials

Spall Fracture Prediction based on a multi-scale Approach for the Behavior of Porous Ductile Materials accounting for Microinertia

C. Czarnota[a], N. Jacques[b], S. Mercier [a],A. Molinari[a], C. Faciu[c]

[a]Université de Lorraine, LEM3, UMR CNRS 7239 Ile du Saulcy, 57070 Metz, France [a]First affiliation, Address, City and Postcode, Country
[b]ENSTA Bretagne, IRDL, FRE CNRS 3744, 2 rue François Verny, 29806 Brest, France
[c]Simion Stoilow, Institute of Mathematics of the Romanian Academy, Bucharest, Romania

Abstract

The fracture of ductile materials is often the result of the nucleation, growth and coalescence of microscopic voids. In dynamic fracture, micro-voids sustain an extremely rapid expansion which generates strong acceleration of particles in the vicinity of cavities**.** These micro-inertial effects are thought to play an important role in the development of dynamic damage in plate impact tests (spall fracture). Due to the interplay between reflected waves, a large tensile stress develops in the target plate, and can lead to the complete fracture of the material in a few microseconds.

To analyse ductile failure under dynamic conditions, a multiscale approach has been proposed where the macrostress is the sum of a quasi-static part and a dynamic part. The dynamic part is related to the rapid expansion of the cavities and can be modeled adopting salient admissible velocity fields. For spherical voids, the velocity field proposed by Rice and Tracey and adopted by Gurson has been selected. A closed form expression for the dynamic part has been obtained [1]. The proposed model has been implemented in Abaqus to analyse spall experiments on tantalum. In our approach, the material is initially free of void, but contains potential nucleation sites for microvoids. Each nucleation site is characterized by its own nucleation pressure. The evolution of the void radii is governed by a hollow sphere model that account for micro-inertia (local radial inertia around the expanding voids)

Simulated free-surface velocity profiles were found to be in agreement with experimental data available in the literature [2]. The present approach is also able to reproduce the porosity map and void size distribution inside the target plate [3]. In the present talk, new results will be presented concerning the stress and strain fields within the target plate. The porosity development within the spall plane affects strongly the wave propagation. Based on the proposed model, the spall strength can be directly captured and it will be shown that the magnitude of pullback velocity measured on the free surface is a signature of damage inception.
Based on the simulations, the validity of the classical formula for the spall strength, based for instance on the acoustic approximation, are discussed.

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