Material Testing for Development and Calibration of Material models for Plastic Deformation and Failure

Amos Gilat and Jeremy Seidt

The Ohio State University Department of Mechanical and Aerospace Engineering
Columbus OH, USA

Abstract

Material testing at various, loading conditions, temperatures, and strain rates is used for studying plastic deformation and failure of materials. The data from such tests is used for developing and calibrating material model that are utilized in numerical codes that are used for simulations of practical applications. The presentation will review experimental techniques used in such testing with emphasis on the integration of Digital Image Correlation (DIC) for measuring full-field deformations and the development of new tests. Of special interest is the testing needed for supporting the new deformation and failure model MAT224 in LS-DYNA®. This material model is based on experimental determination of a failure surface that gives the equivalent plastic strain to failure as a function of stress triaxiality and the Lode parameter. It is done by testing specimens that are subjected to uniform and nonuniform states of stress and deformation and determining the failure state (deformation and stress) from matching the simulation of the test with the DIC and load measurements. Testing can be done at room temperature or, by using a special furnace, at elevated temperatures (up to 850C°). In addition, a new experimental setup in which full-field deformation and full-field temperature are measured simultaneously on the surface of a specimen during a tensile test is introduced. Results from testing specimens made of stainless steel show a significant temperature increase in the neck area in a quasi-static tension test. In most material models (e.g. Johnson Cook) the effect of strain hardening and temperature softening are uncoupled. The data that is typically used for determining the parameters in the models is obtained from experiments where strain hardening and temperature are coupled. The results from the new experimental setup can be used for uncoupling the effect of strain hardening and thermal softening during plastic deformation.

Background

Numerical simulation of the response of materials under loads has reached a level of maturity at which it can be used with confidence for design purposes. Numerical codes like LS-DYNA include many material models for deformation and failure (constitutive relations) that can be selected for specific applications. The various models require input parameters that are specific to the material that is being simulated. The accuracy of the simulations depends on the values of the input parameters which are determined from experimental data.

The focus of the present paper is on the testing configurations and techniques that have been developed recently for the purpose of providing accurate data for determining the parameters in material models for deformation and failure. Of special interest is MAT224 which is a relatively new deformation and failure model in LS-DYNA. The input requires stress strain curves from tests at different strain rates and temperatures and values of equivalent failure strain at various state of stress (various combinations of stress triaxiality and Lode parameter).

Uniaxial Stress Tests at Various Strain Rates and Temperatures

Uniaxial (tension, compression, shear) tests can be done at various strain rates and temperatures. At quasi-static strain rates between 10^{-4} s^{-1} and 1 s^{-1} they are done using a hydraulic machine. At strain rates above 500 s^{-1} they are done using the split Hopkinson bar (SHB) technique. A special machine was developed for testing in tension and compression at intermediate strain rates of 10 s^{-1} to 200 s^{-1}. The technique is a hybrid of a SHB and a hydraulic machine. A specimen that is placed between the end of a long bar and a hydraulic actuator is loaded by the hydraulic actuator, Fig. 1. As the specimen is loaded, a wave propagates to the end of the bar and reflects back. The force in the specimen is measured by strain gages that are placed on the bar and the strain in measured directly on the specimen with DIC. The actual setup is shown in Figs. 2 and 3.

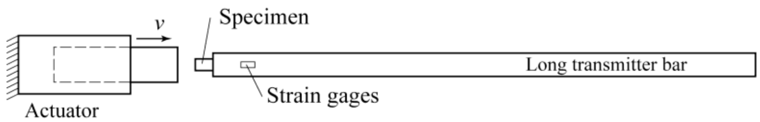

Fig. 1: Schematic of the intermediate strain rate apparatus.

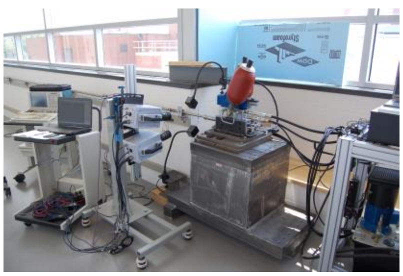

Fig. 2: Intermediate strain rate apparatus.

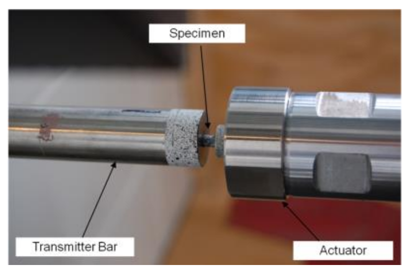

Fig. 3: Intermediate strain rate apparatus.

The bar is more than 40 m long which allows a test duration (until the reflected wave arrives at the strain gages that measure the force) of more than 0.016 s. At a strain rate of 20 s^{-1} it provides enough time for the specimen to deform to a strain of 0.3. Results from tensile testing of HHS at various strain rates are shown in Figs. 4.

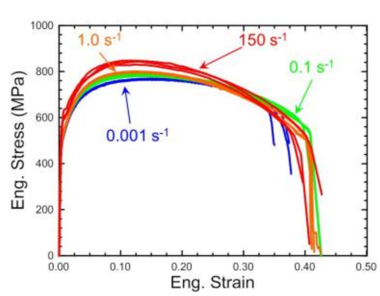

Fig. 4: Tensile stress strain curves for HHS at different strain rates.

Data for Determining the Failure Surface

The data for determining the failure surface is obtained from tension tests of notched flat and notched round specimens with different notch dimensions, plane strain tension experiments with smooth and notched specimens with different notch sizes, and biaxial tension-torsion and compression-torsion tests and punch tests. Digital Image Correlation (DIC) is used in all the tests for a direct measurement of the deformation (full field) on the surface of the specimens. The DIC data together with numerical simulation of the experiments is used for determining the state of stress (triaxiality and Lode parameter) and deformation in the specimens throughout the test and at the instant of fracture. For example, a comparison between DIC experimental data and numerical simulation is shown in Fig. 5. DIC data from tensile testing of flat-notched-specimens with different notch sizes is shown in Fig. 6.

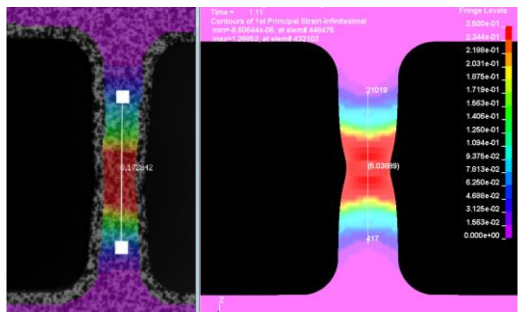

Fig. 5: DIC data and numerical simulation of a tensile test.

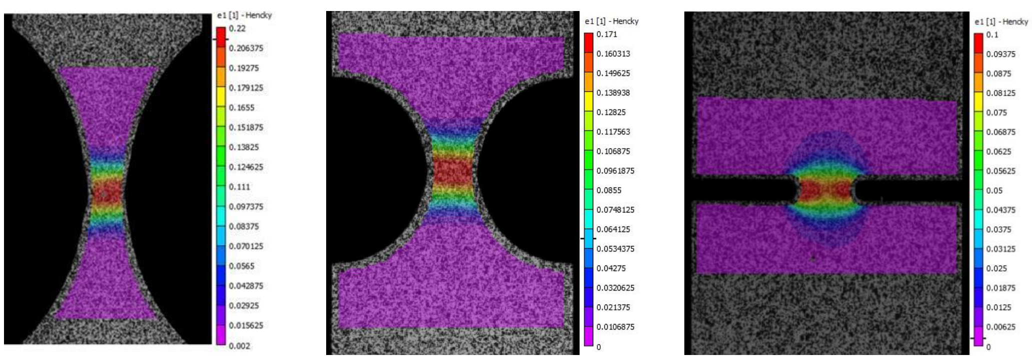

Fig. 6: DIC data from tensile testing of flat-notched-specimens.

Full-Field Deformation and Temperature Measurements

A new experimental setup, in which full-field deformation and full-field temperature are measured simultaneously on the surface of a specimen during tensile tests at various strain rates has been recently developed. The setup consists of a flat thin specimen and visual cameras on one side of the specimen and a high speed IR camera on the other side. The set up for a high strain rate test with the tensile SHB technique is shown is Fig. 7. Synchronized DIC and IR images recorded in a test are shown in Fig. 8. Results from testing a specimen made of stainless steel at a strain rate of about 3000 s^{-1} show that the strain in the necking region of the specimen exceeds 0.6 and the temperature exceeds 300°C. The results from these tests provide data that can be used for uncoupling the effects of strain hardening and temperature softening in plasticity models.

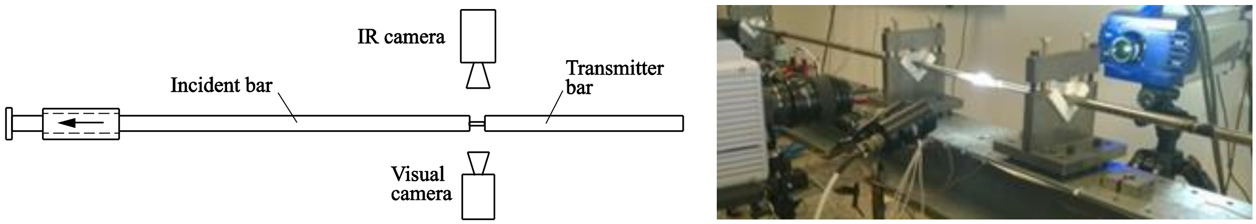

Fig. 7: Tensile Split Hopkinson bar with full-field deformation and temperature measurements.

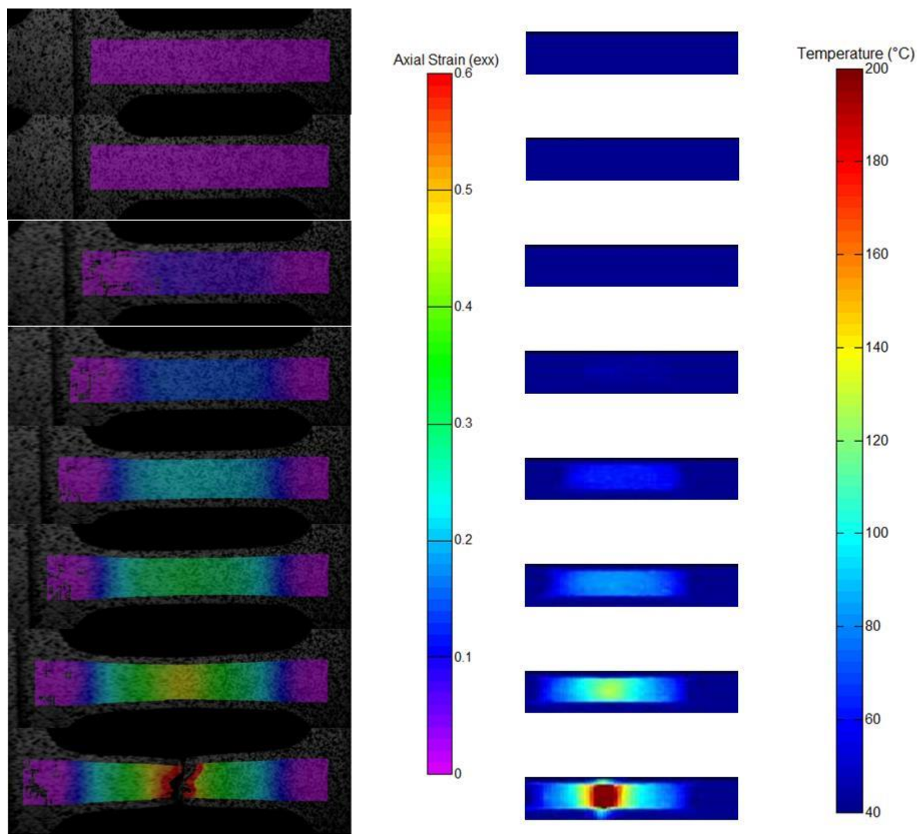

Fig. 8: DIC processed images recorded by the visual camera and IR camera images at different times during the test.

Acknowledgements

The development of the testing techniques for the data needed for MAT224 was supported by the U.S.A. Federal Aviation Administration, Grants No. 06-G-004 and 11-G-003. The authors are grateful to Mr. Bill Emmerling, Dr. Chip Queitzsch, and Mr. Don Altobelli of the FAA. The development of the intermediate strain rate test was done by Mr. Thomas Matrka with support from NASA, Grant No. NNX08AB50A.