Material Testing in Support of the Development and Calibration of Material Models for Forming Simulations

A. Gilat, and J. Seidt
The Ohio State University
Department of Mechanical and Aerospace Engineering, Columbus OH, USA
gilat.1@osu.edu

Abstract. Material testing at various strain rates, temperatures and loading conditions provides data that is used for the development and calibration of constitutive equations (material models) that are utilized in numerical simulations of sheet metal forming. In general, the testing can be divided into characterization tests and validation tests. In characterization tests basic material properties (e.g. yield stress, ultimate stress, failure strain) are determined from a test in which a material coupon is loaded under a well-defined condition (stress, strain rate, temperature, etc.). The data is used for determining the values of parameters in plasticity and failure models. In validation tests a material specimen or a small component is loaded with a more complicated, but well defined, loadings. The test is numerically simulated and the calculated quantities (forces, deformation, failure, temperature, etc.) are compared with measurements. The recent development of the Digital Image Correlation (DIC) technique for full-field measurement of deformation has extended the useful data that can be extracted from traditional characterization tests and provide means for developing new experiments that can be used for obtaining more accurate material models. This paper reviews the advantages of using DIC in traditional tests and presents several new recently developed testing configurations for material coupons and small components. Many of these tests have been used during in the development of a failure surface that gives the equivalent plastic strain to failure as a function of stress triaxiality and the Lode parameter.

1. Background
Numerical simulation of the response of materials under applied loads has reached a level of maturity at which it can be used with confidence for design purposes. Numerical codes 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.

In general, testing in support of the development of accurate materials models can be divided into two groups. In one group are characterization tests that are used for the derivation of the parameters in the material models, and the other group are validation tests. When plastic deformation and failure are involved, the characterization tests consist of uniaxial stress state tests and combined stress state tests. The uniaxial stress tests are tension, compression and shear tests at various strain rates and temperatures. This data is used for obtaining the parameters of the plasticity model. Combined state of stress tests are used for calibrating failure models. The objective is to load material specimens with various combination of stresses and measure the load and deformation at failure. The results from these tests are used for...
verifying the plasticity models for the deformation, and for deriving the values of the parameters in the failure and damage models. The second group of tests are validation tests. These are well instrumented tests in which material specimens are loaded in a non-uniform combined state of stress that are different from the states of stress in the characterization tests. The validation tests can also include tests on small components (e.g., welded or glued connection, channel crush beam). The validation tests are simulated numerically using the constitutive models for plasticity and failure that were developed based on the data from the characterization tests and the simulation results are compared with the experiments.

The Digital Image Correlation (DIC) method for non-contact, full-field measurement of deformation on the surface of a deforming specimen [1] has revolutionized experimental mechanics. It provides means for obtaining new data from traditional characterization tests (e.g. tensile test) and enable the development of new tests on material coupons and components that provide data for obtaining significantly more accurate material models.

The present paper reviews the advantages of using DIC in traditional experiments and presents several new experiments that have recently been developed and are doable only by using DIC. It includes using DIC in the traditional tension test to obtain a true stress strain curve at strains beyond the necking point, a novel intermediate strain rate test, and using full-field deformation and temperature measurements for determining the fraction of plastic work converted to heat (Taylor-Quinney coefficient) in tensile tests at different strain rates.

2. True tensile stress strain curve beyond the ultimate engineering stress
A true tensile stress strain curve can easily be obtained from the engineering curve when the state of stress is uniaxial and the deformation is uniform up to the point that necking starts. Once necking starts, the true stress and true strain cannot be calculated from the engineering values because the deformation localizes in the necking zone and the stress is not a simple function of the force. The true stress strain curve beyond the necking point can be indirectly determined when DIC is used to measure the full-field deformation throughout the test (including the necking portion). This is done by simulating the experiment using a finite element analysis with an assumed extension of the true stress strain curve and comparing the simulation results with the data from the experiment. If the simulated force and deformation match the experimental values, the assumed stress strain curve can be regarded as the material curve. An example of this procedure is shown in Figures 1 and 2. Figure 1, [2], shows assumed extensions of the true stress strain curves for titanium 6AL 4V that were used in a simulation of a high strain rate tensile test, and Figure 2 shows a comparison of the deformation between the finite element simulation and the DIC data.

![Figure 1. Assumed true stress strain curves.](image-url)
3. Intermediate strain rate test

To study strain rate effects uniaxial tension and compression tests are done at various strain rates. At quasi-static strain rates between $10^{-4}$ s$^{-1}$ and 1 s$^{-1}$ tests are usually done using a hydraulic machine. At strain rates above 500 s$^{-1}$ tests are usually done using the split Hopkinson bar (SHB) technique. Testing at intermediate strain rates of 20 s$^{-1}$ to 200 s$^{-1}$ is problematic. Machines that are used for quasi-static tests can deform the specimens faster, but when operating at high speeds the testing machine is not in static equilibrium and the data obtained is noisy (ringing). The availability of DIC enabled the development of a new special apparatus for testing in tension and compression at intermediate strain rates. The apparatus is a hybrid of a SHB and a hydraulic machine, shown schematically in Figure 3. A specimen is placed between the end of a long bar and a hydraulic actuator. The specimen is loaded by the actuator and once loaded a wave starts propagating along the bar toward the free end where it is reflected back (as in the transmitter bar of a SHB apparatus). 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 surface with DIC. The actual setup is shown in Fig. 4.

![Figure 3](image)

**Figure 3.** Schematic of the 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 about 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. The data that is obtained is smooth without any ringing. Engineering stress strain curves from tensile testing of HHS at various strain rates, including a strain rate of 150 s$^{-1}$ are shown in Fig. 5.
4. Simultaneous full-field deformation and temperature measurements during tensile tests

The availability of DIC and new high-speed IR cameras have made it possible to conduct tensile tests in which the full-field deformation and temperature are measured simultaneously throughout the test, including at the necking region during the necking, [3]. The data from such tests can be used for determining the Taylor-Quinney coefficient (β) as a function of strain and strain rate and for determining the strain-hardening and temperature dependent coefficients in material models. The setup consists of a
flat thin sheet specimen, visual cameras on one side of the specimen and a high speed IR camera on the other side. Tests at quasi-static strain rates are done using a servo-hydraulic load frame. As an example, DIC and IR images from a test with a specimen made of stainless steel at strain rate of 200 s$^{-1}$ are shown in Fig. 6. The figure shows synchronized DIC processed images recorded by the visual camera and IR camera images at different times during a test. The figure show nearly uniform deformation and temperature rise at the early part of the test and localized deformation and heating in the necking zone during necking. Quantitative data from this test is shown in Fig. 7. The figure on the top shows the axial strain along the center line of the specimen at different times during the test and the figure on the bottom shows the temperature along the same line at the same times. The figure shows a uniform deformation up to about a strain of 0.3 when necking starts to develop. At that stage the temperature has increased from room temperature to about 80°C. Once the necking starts the deformation localizes with strain exceeding 0.6 and temperature reaching 370°C. An approximate calculation of the Taylor-Quinney coefficient ($\beta$) that is done by calculating the plastic work from estimating the average stress and strain in the middle of the neck shows that $\beta$ changes with strain. At a strain of 0.17 when the strain is still uniform $\beta$ is about 0.6. Once the necking starts and the deformation localizes $\beta$ increases and at the end reaches a value of about 0.9.

Figure 6. DIC (left) and IR (right) images from tensile test of 316 stainless steel at strain rate of 200 s$^{-1}$.

Figure 7. Strain and temperature along the center line of the specimen.

5. Spot weld test

Spot weld joint test is an example of the advantage of using DIC in a component test that is used for validation of plasticity and failure models. A set up for such a test where two DIC systems are used for measuring the deformations on different surfaces of the component is shown in Fig. 8. The data from the experiment includes the history of the applied force and the deformation throughout the test. Example of DIC data is shown in Fig. 8. The figures on the left and in the center show how the relative displacement between any two points of the component can be measured, and the figure on the right shows a processed DIC frame with the strain on the surface during the test. A comparison of the measured force and deformation with the ones obtained from numerical simulation can be used to validate or possibly modify the material models in the numerical code.
Figure 8. DIC data from a spot weld test.

6. Conclusions
The development of the DIC method for measuring the full-field deformation and its integration into material and components testing have improved significantly the ability to develop more accurate materials models for plastic deformation and failure. Full-field DIC measurement of displacement and strains can now be directly compared with results from finite element simulations. This is especially important in situations where the deformations are not uniform. Together with measurements of the applied loads the DIC data can be used to develop, validate and improve material models that are used in the simulations.

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References
[1] Sutton M A, Orteu J J, and Schreier H W, Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications, 2009, New York, NY: Springer
[2] Haight S, Wang L, Du Bois P, Carney K, Kan, C D, Development of a Titanium alloy Ti-6Al-4V material model used in LS-DYNA, 2016, FAA Report DOT/FAA/TC-15/23
[3] Seidt J D, Kuokkala V T, Smith J, Gilat A, Synchronous full-field strain and temperature measurement in tensile tests at low, intermediate and high strain rates 2017 Exp Mec 57 219