Strain Rate and Temperature Dependent Testing in Support of the Development of MAT224 and MAT213

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Abstract

The deformation and failure of metals and composites is known to be affected by strain rate and temperature. Material models in LS-DYNA® account for these effects and material coupon testing is required for determining the input parameters for the models. The present paper presents a new experimental setup that provide means for investigating the coupled effects of temperature and strain rate during plastic deformation, and new strain rate sensitivity data for fibrous composites that was obtained from static and dynamic tests. Although coupled, the effects of strain rate and temperature are usually determined separately in tests at different strain rates and different initial temperatures, neglecting temperature increase that might be taking place during the deformation. In the present paper a new experimental setup is introduced in which full-field deformation and full-field temperature are measured simultaneously during tensile tests in various strain rates (including high strain rates). The results show a significant rise in the temperature in the necking region even at relatively low strain rates. The data from these tests can be used for determining the Taylor-Quinney coefficient and for determining more accurate parameters in the material models. Limited data is currently available on the response of fibrous composites at high strain rates. New data from testing unidirectional T800/F3900 composite at low and high strain rates shows significant strain rate effect in tension and compression in the 90° direction.

Introduction

MAT224 and MAT213 are strain rate and temperature dependent tabulated deformation and failure material models in LS-DYNA for metals and composites, respectively. The models require input data in a tabulated form that is obtained from processed experimental data. The focus of the present paper is on the coupled effect of strain rate and temperature on plastic deformation and on strain rate sensitivity of fibrous composites. Plastic deformation in metals is associated with increase of temperature where the Taylor-Quinney coefficient (β) gives the fraction of work that is converted to heat. During uniform deformation at low strain rates the increase in temperature can be small and neglected since there is enough time for the heat to dissipate, but during uniform deformation at high strain rates and localized deformation at any strain rate the increase in temperature can be significant. Material characterization tests that are used for determining the parameters in the material models usually consist of tensile and/or compression tests at different strain rates and different initial temperatures. Data from a typical test includes measurements of force and strain. Tests are assumed to be isothermal neglecting temperature increase that might be taking place during the deformation. Consequently, the strain hardening is determined to be dependent on the strain rate neglecting softening due to increase of temperature which vary with stain rate. The accuracy of materials models that are determined in this way is limited because in reality the effects of strain rate, strain hardening and temperature are coupled. To provide additional data that could be used for developing more accurate constative models, a new experimental setup has been developed. In this setup full-field deformation and temperature are measured simultaneously on the surface of a specimen subjected to tensile load. The deformation is measured using the DIC technique and the temperature is measured with a high-speed IR camera.

The strain rate sensitivity of fibrous composites has been mostly studied at low (quasi-static) strain rates. Very limited data is available from testing composites at high strain rates. The Split Hopkinson Bar (SHB) technique is the most frequently method used for testing metals in the range of 500 to 5,000 s^{-1}. In this technique a short specimen is placed (or attached) between two metal bars (incident and transmitter). The specimen is loaded by a wave that is generated in the incident bar. A stress strain curve of the material tested is determined from the waves that are recorded in the bars. The technique has been introduced with testing in compression but can also be used for testing in tension and shear. Testing of fibrous composites with the SHB technique requires special attention due to the nonhomogeneous structure of the material, the requirement of specimens of small size, and the brittleness of the material. Small fibrous composite specimens are difficult to machine and attach to the testing apparatus. In many cases a composite specimen fractures at strain of less than 5% and sometimes at strains of the order of 1% or less. Determining such small strains in SHB experiments from the waves in the bars might not be accurate due to the effect wave dispersion and the effects of the specimen boundary and attachment method on the waves. In the present paper specimens made of T800/F3900 composite are tested in compression and tension at high and low strain rates. The high strain rate tests are done using the SHB technique and the low rate tests are don using a hydraulic frame. In all the tests full-field deformation is measured on the surface of the specimen using the DIC technique.

Deformation and temperature measurements in static and dynamic tension tests

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 visual cameras on one side of the specimen and a high speed IR camera on the other side. Tests at quasi-static stain rates are done using a servo-hydraulic load frame. Tests at high strain rates were done using a tensile Split Hopkinson (Kolsky) Bar (SHB) apparatus. Example of DIC and IR images from a test with a specimen made of stainless steel at strain rate of 200 s^{-1} is shown in Fig. 1. 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. 2. 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 start 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 (β) that is done by calculating the plastic work from estimating the average stress and strain in the middle of the neck shows that β changes with strain. At a strain of 0.17 when the strain is still uniform β is about 0.6. Once the necking starts and the deformation localizes β increases and at the end reaches a value of about 0.9.

Results from tensile testing of titanium 6AL-4V at strain rates of 1 and 400 s^{-1} are shown in Figures 3 and 4. Figure 3 shows the engineering stress strain curves from tests at these two strain rates and Figure 4 shows the history of the temperature as a function of strain at the point in the gage section that has reached the highest temperature. In both tests the temperature at the neck exceeds 120°C. The strain when the material reaches this temperature is, however, smaller in the high rate test than in the low rate tests (approximately 0.3 compared to over 0.45).

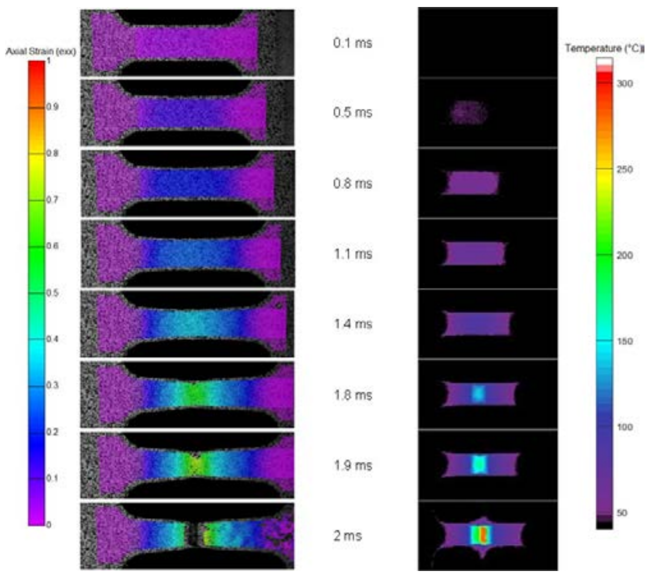

Figure 1: DIC and IR images from tensile test of 316 stainless steel at strain rate of 200 s^{-1}.

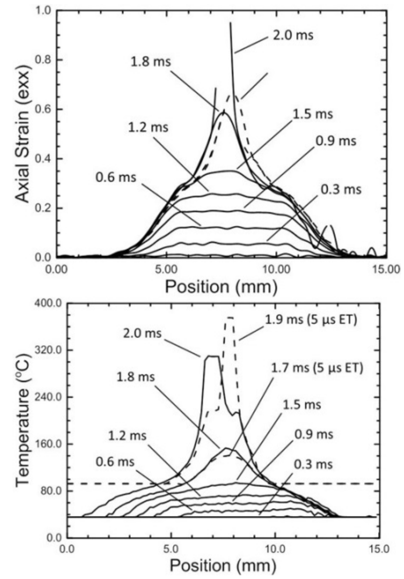

Figure 2: Strain and temperature along the center line of the specimen.

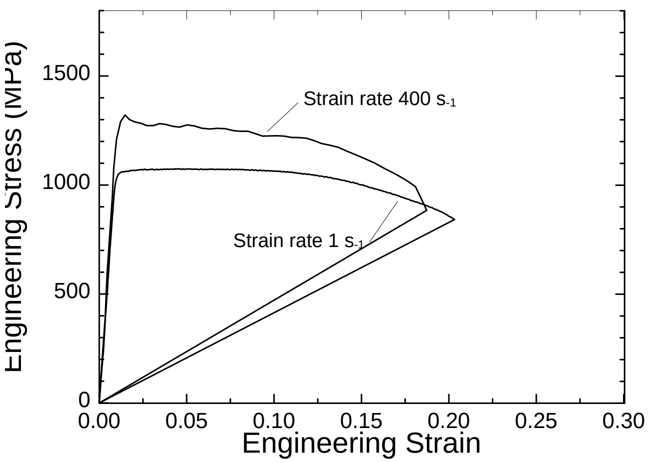

Figure 3: Tensile engineering stress strain curves of Ti-6Al-4V at strain rates of 1 and 200 s^{-1}.

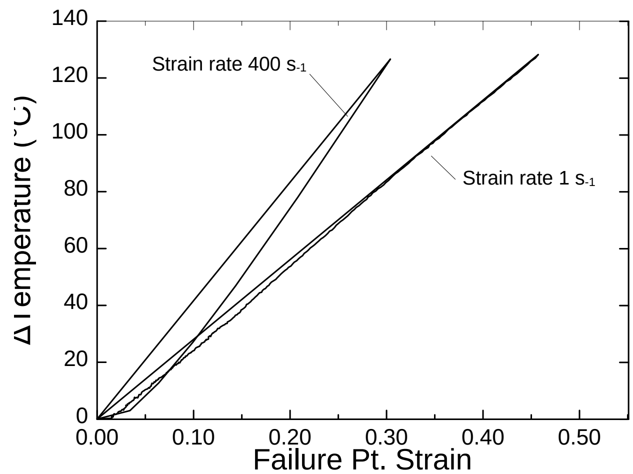

Figure 4: Temperature at the failure point as a function of strain.

The effects of strain rate on the response of T800/F3900 composite

In the present paper specimens made of T800/F3900 composite are tested in compression and tension at low and high strain rates. The high strain rate tests are done using the SHB technique and the low rate tests are done using a hydraulic frame. In all the tests full-field deformation is measured on the surface of the specimen using the DIC technique. The composite specimens are machined from a 3.18 mm thick T800/F3900 unidirectional plate. For the compression tests the specimen is a short small rectangular prism, Figure 5. The prisms are machined in the 0° or 90° directions. To prevent transverse motion of the specimens during the compression tests, titanium platens with a shallow 0.5 mm deep rectangular notch, Figure 6, are attached to the hydraulic frame and to the ends of the input and transmitter SHB bars. The specimen ends are inserted into the notches.

The specimens for the tensile tests are flat 3.18 mm thick with a dog-bone geometry according to ASTM 638-02a, Figure 7. Tensile tests were done in the 90° direction. The gage section is in the middle and the wide tabs are glued into notched aluminium adaptors. For the SHB tests the specimen assembly is glued between the incident and transmitter bars. In the low strain rate tests the specimens are connected via double universal joints to the hydraulic machine.

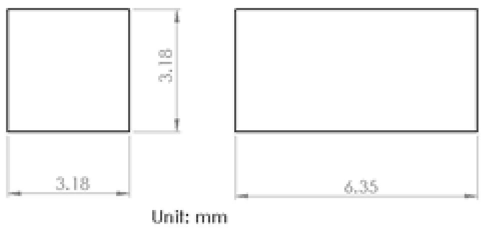

Figure 5: Compression specimen geometry.

Figure 6: Titanium platens

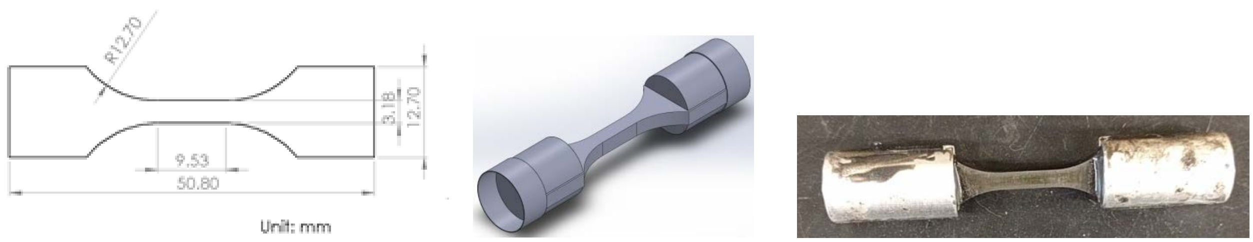

Figure 7: Tensile specimen geometry (left), specimen with adaptors (middle), photo (right).

Results from the compression tests are shown in Figures 8 and 9 for specimens loaded in the 0° and 90° directions, respectively. As can be seen in Figure 8, the response of the composite in the 0° direction is not sensitive to the strain rate, probably since the carbon fibers, which dominate the response in this direction, are known to be strain rate insensitive. Results from testing in the 90° direction, Figure 9, show that in this direction there is a significant strain rate effect. The stress strain response at strain rate of 550 s^{-1} is essentially linear, while an initial linear response is followed by a nonlinear behavior at strain rate of 0.001 s^{-1}. The maximum stress increases with strain rate from about 200 MPa at the low strain rate to about 300 MPa at the high strain rate. The maximum strain, on the other hand, is smaller at the high strain rate (~0.35 compared to ~0.45).

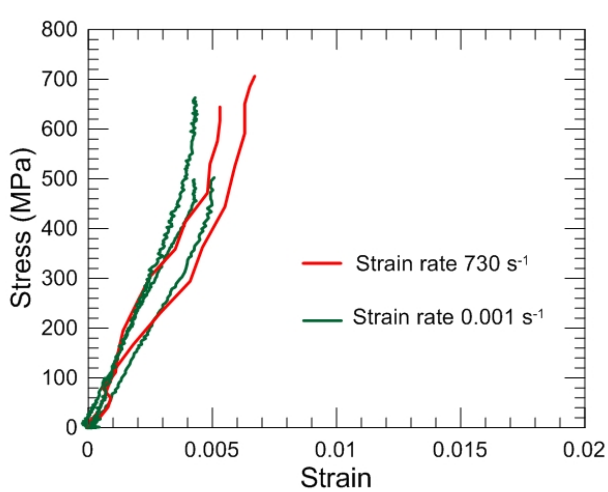

Figure 8: Compression stress strain curves of T800/F3900 composite in the 0° direction.

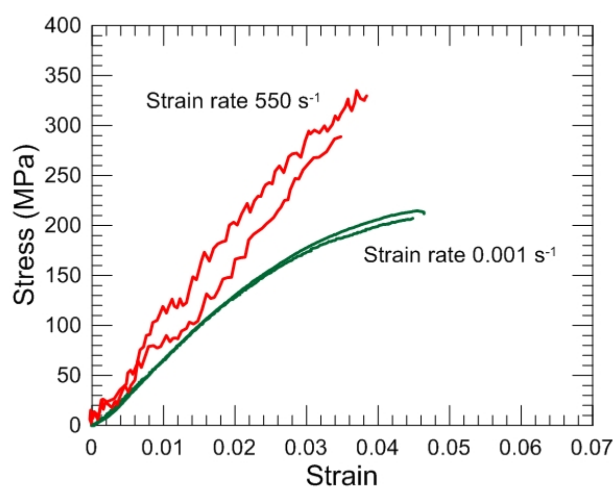

Figure 9: Compression stress strain curves of T800/F3900 composite in the 90° direction.

Results from tension tests of specimens loaded in the 90° direction are shown in Figure 10. The figure shows a significant strain rate effect. The stress strain response at strain rate of 0.001 s^{-1} is essentially linear up to a stress of about 80 MPa and strain of about 0.013 (modulus of approximately 6.25 GPa). At strain rate of 360 s^{-1} the initial response is much stiffer (modulus of about 100 GPa), and then the stress strain curve transitions to be approximately parallel to the curve from the low strain rate curve. The maximum stress in the dynamic test ends up to be slightly higher than in the low strain rate test and the maximum strain is significantly smaller than in the low strain rate (~0.0065 compared to ~0.013).

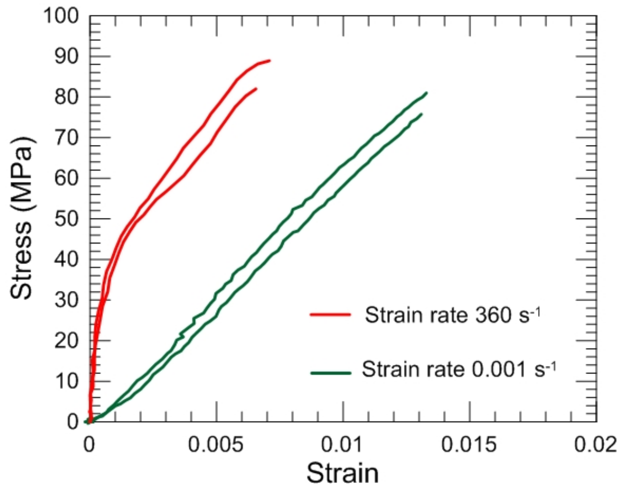

Figure 10: Tension stress strain curves of T800/F3900 composite in the 90° direction.

Conclusions

Accurate simulations of manufacturing processes and response of structures to loading with LS-DYNA requires reliable materials models. The development and calibration of these models depends on the availability of high quality data from coupon material testing. The focus in the present paper is on the dependence of the increase of temperature during Plastic deformation on strain rates and on strain rate effects on the response of fibrous composites. Simultaneous measurements of strain and temperature during tensile tests at various strain rates provide data that can be used for obtaining better (more accurate) material models. Results from tensile testing stainless steel and titanium show significant temperature increase during necking. The response of epoxy-matrix fibrous composites is strain rate sensitive. The split Hopkinson bar technique with digital image correlation for measuring strain can be used for obtaining high strain rate data that is needed for studying the rate effects. Results from testing T800/F3900 composite show significant strain rate effect in compression and tension in the 90° direction.

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