High Strain Rate Testing and Modeling of Polymers for Impact Simulations

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Abstract

The increased use of polymeric materials in impact and high strain rate applications is motivating the use of impact simulations during design. However, simulation of polymer impacts requires difficult-to-measure stress-strain behavior at high strain rates. Even when appropriate data is collected, accurate high strain rate constitutive models need to be fit to the data before being incorporated into a simulation code. This article presents a testing and constitutive modeling process using Veryst's PolyUMod® and MCalibration® to achieve accurate impact simulations using polyether ether ketone (PEEK) as the example material. Low and high strain rate data is presented over a large strain rate range. Validation of the developed material model is performed by simulating a drop test in LS-DYNA® with comparison to measured drop test data.

Introduction

There is an increasing need for accurate impact simulations of polymeric materials due to their increased use in consumer electronics, medical, and transportation industries. Although impact simulation of metal components is well-established, polymeric materials demonstrate more rate-dependence than metals. In addition, lower elastic stiffness, lower deformation resistance, and potentially heterogeneous strain fields makes testing of polymeric materials more difficult.

Veryst has been developing methods to measure, calibrate, and simulate high strain rate deformations in polymeric materials. The following provides a description of those methods using polyether ether ketone (PEEK) as a model material.

Experimental Methods

Low strain rate data was collected using an Admet electromechanical load frame. Cylindrical specimens were used in compression and subsized tension specimens were used in tension. Low strain rate compression tests were performed in a cyclic manner as the generated data permits the characterization of visco-elastic/plastic behavior in a single test. The low strain rate tensile tests were monotonic.

High strain rate data was collected using a Split Hopkinson Pressure Bar (SHPB) system with both compression and tension loading configurations. Both configurations used aluminum incident and transmission bars. A variable pressure gas gun projected a striker bar against the incident bar to produce an elastic wave that passed through a PEEK sample. Different strain rates were imposed using different gas gun pressures. Strain gauges attached to the incident and transmission bars were used to calculate the forces, stresses, and strains at the specimen interfaces based on standard SHPB equations [1]. The compression configuration used cylindrical specimens between the flat faces of the incident and transmission bars. The initial compressive wave passed directly through the cylindrical specimen. In the tensile configuration, cylindrical dogbone specimens were threaded directly into the ends of a set of aluminum incident and transmission bars. Tensile loading was imparted using the reflected tensile wave that was generated after the initial compressive wave reached the end of the transmission bar. The initial compressive wave was carried by a set of aluminum collars.

Experimental Results

Figure 1 provides experimental stress-strain data for PEEK in tension at strain rates of 0.001 and 0.1/s and compression at strain rates of 0.001, 0.1, and 1400/s. The cyclic nature of the low strain rate compression tests is clearly shown by the stress-strain loops. The compressive stress is shown to increase approximately 36% for a given compressive strain from a strain rate of 0.1/s to 1400/s, clearly indicating a strong strain rate sensitivity. Also of note is the increase in compressive yield strength and little change in hardening behavior of this material as compressive strain rate increases.

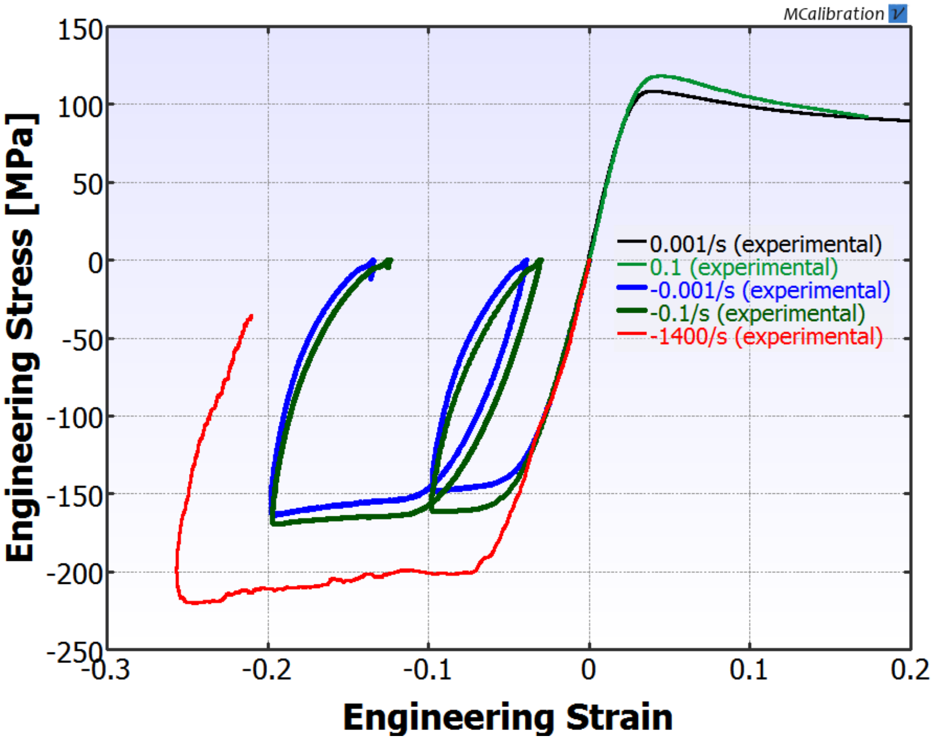

Figure 1 - Stress-strain data for PEEK

During testing it was found that “standard” SHPB methodologies for generating stress-strain data are not reliable for high strain rate tensile loading of PEEK. Figure 2 provides representative stress-strain signals for SHPB tensile testing obtained using the same signal processing method used for SHPB compression; clearly, the high strain rate data demonstrates unacceptable oscillations. There are several issues that complicate the use of this data. First, even though PEEK represents a stiff thermoplastic, the increased tensile specimen gauge length reduces the magnitude of the elastic wave transmitted through the specimen. Second, the end conditions required to rigidly attach the tensile specimens to the aluminum bars introduces additional material interfaces that in turn produce internal wave reflections, distorting the detected wave signals. Third, the transmission of the first compressive wave from the incident bar to the transmission bar introduces both noise and distortion of elastic wave. Finally, both high speed video of the tensile tests and explicit finite element simulations of the SHPB tensile test demonstrate that the deformation field is not homogeneous. Therefore, it is not correct to assume homogenous deformation within the gauge section and one cannot assume either a uniform tensile strain field or accurate stress signal. Consequently, this high strain rate tensile data was not considered in the calibrated material model presented herein. Work is ongoing to improve the high strain rate test methodologies for PEEK and other similar low impedance materials. At this time, the high strain rate tensile test in combination with high speed imaging is only used to determine the failure strain as a function of strain rate.

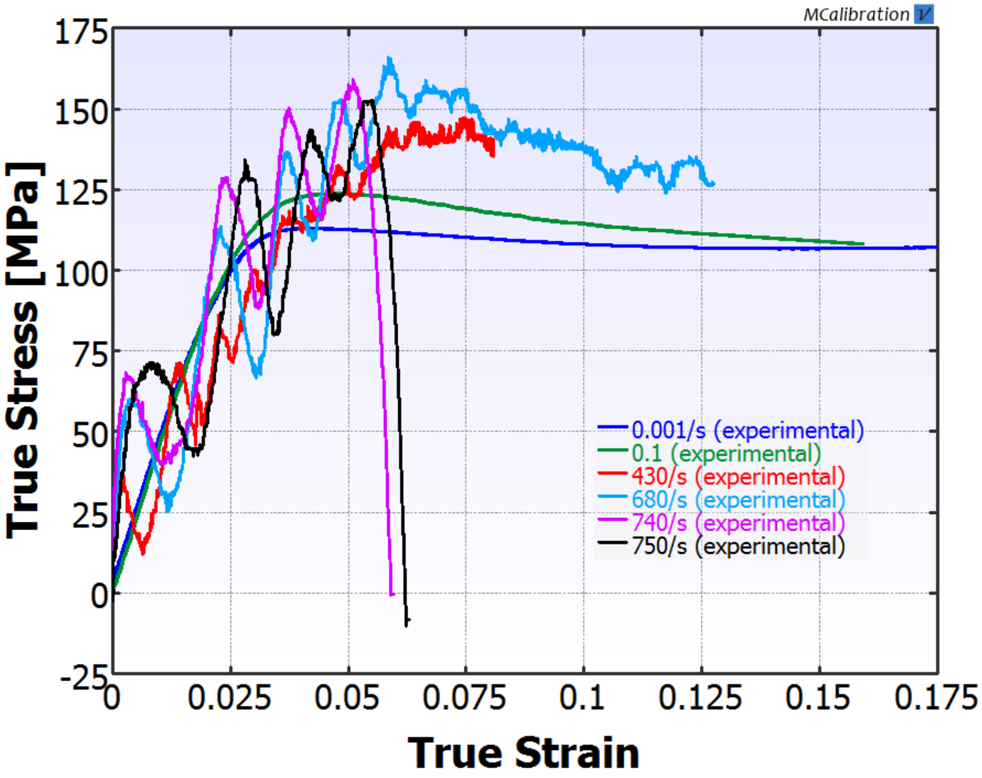

Figure 2 - High strain rate tensile stress-strain determined from standard SHPB methodology for PEEK

Material Model Calibration

In the present work the Three Network Model developed by Bergstrom and Bischoff [2] was chosen. This model is capable of predicting the non-linear visco-plastic response of thermoplastic materials.

Figure 3 presents the calibration of a Veryst Engineering PolyUMod Three Network Model to the data shown in Figure 1. This calibration is done using MCalibration, a Veryst software that uses multiple material tests to calibrate material constants for constitutive models. MCalibration is capable of fitting data to constitutive models provided with commercial finite element codes as well as Veryst specific PolyUMod material models. MCalibration can accommodate variable strain rates within single tests, as its optimization algorithm simulates each test, even at nonconstant strain rates, to achieve the best fit for a specific material model's parameters. As the figure demonstrates, MCalibration is capable of creating an accurate representation of the experimental data using PolyUMod's Three Network Model.

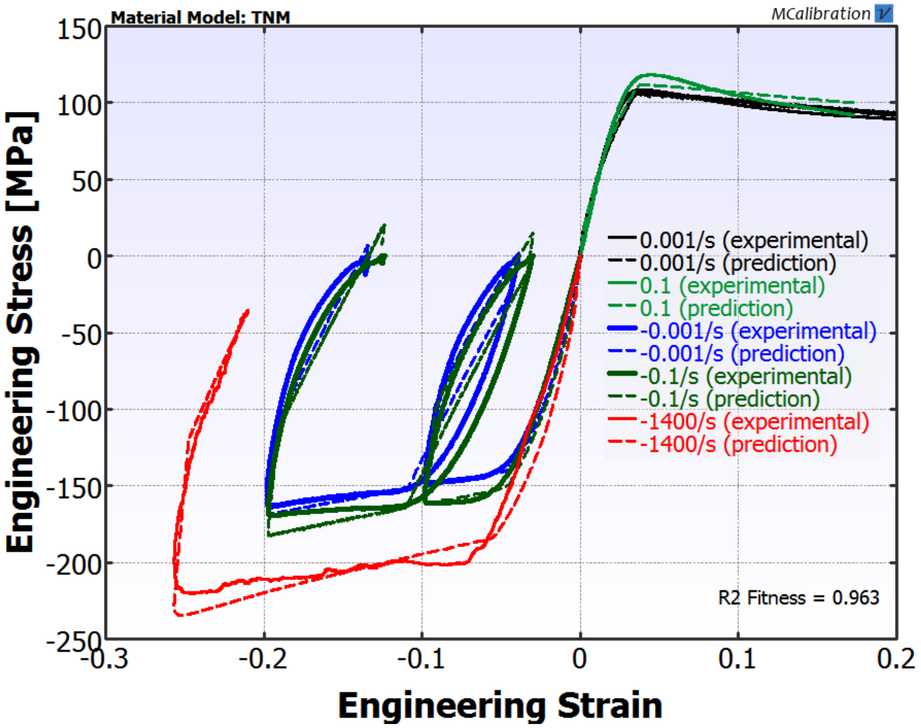

Figure 3 - Fit of Three Network Model to low and high strain rate PEEK data

Material Model Validation

Validation of the calibrated material model was performed via comparison to a conical drop test impact. The drop test consisted of a steel indenter with a mass of 238 grams and a rounded conical tip with an included angle of 92° and 0.28 mm radius. The indenter was dropped from a height of 2280 mm onto a 7.1 mm thick PEEK specimen producing an impact speed of 6690 mm/s as determined by high speed video. A residual impression, as shown in Figure 5(a), remained in the PEEK test specimen with an outer diameter of approximately 3.74 mm and a depth of approximately 0.66 mm. Mild pile-up was observed at the periphery of the impression creating some uncertainty in the measured residual diameter and depth.

An explicit axisymmetric finite element model of the impact test was performed in LS-DYNA using the developed material model. The conical indenter was modeled as a rigid body with mass and initial velocity assigned based on the test conditions. The PEEK sample was modeled using 4-noded axisymmetric elements with an element edge length of 0.05 mm near the indenter contact location; element size was progressively increased towards the boundaries. A substrate was placed under the sample to simulate a rigid mounting surface. A coefficient of friction of 0.4 was assigned at the indenter-sample and sample-substrate interface. Figure 4 shows the model layout where the inset figure shows the mesh layout at the top of the sample near the indenter contact location.

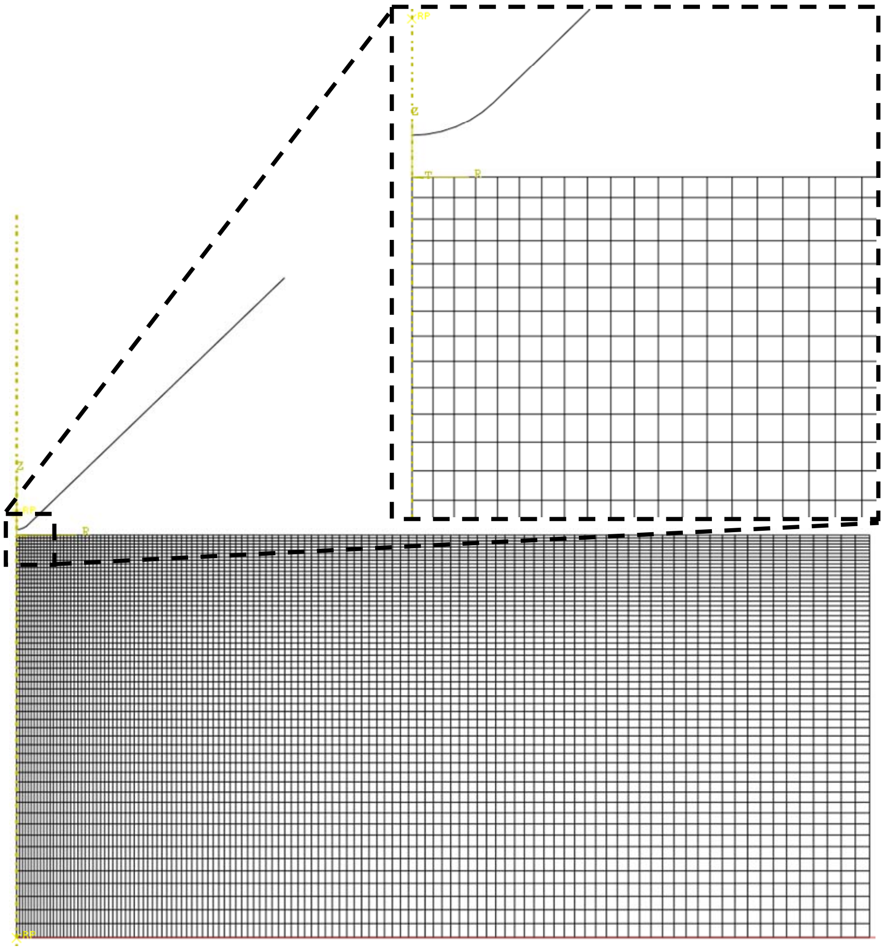

Figure 4 - Finite element mesh

Figure 5(b) demonstrates a predicted indentation profile using the material model calibrated from Figure 3. The finite element model predicts a diameter of 3.68 mm and a depth of 0.97 mm. The error between the measured and predicted diameters is 1.6%, which indicates a robust model; however, the error between the measured and predicted indentation depths is 47%. We believe that the indentation depth error is due to the relaxation behavior of the PEEK. The simulation results showed that the diameter was nearly unaffected by material relaxation. We are continuing to characterize the PEEK relaxation behavior.

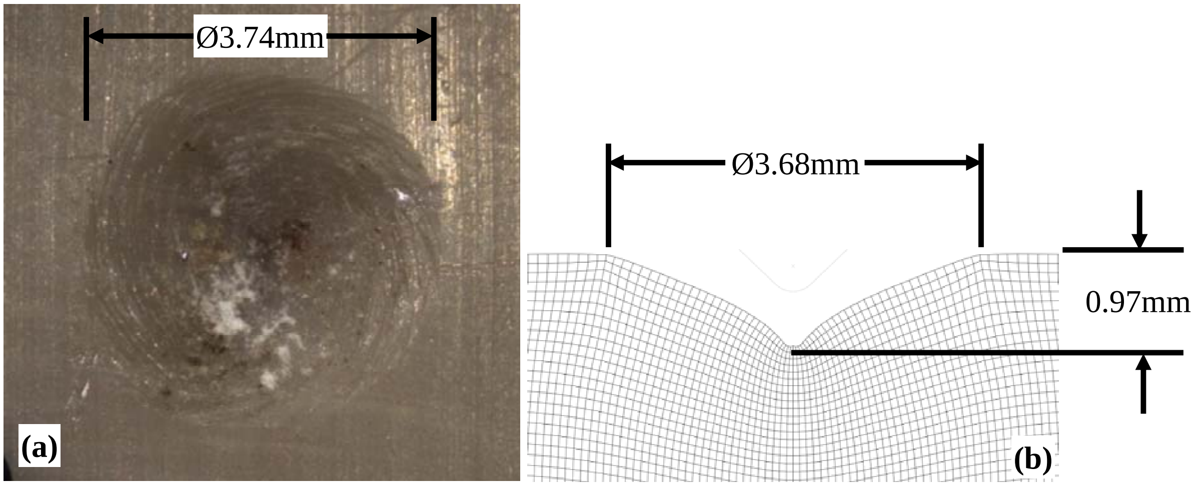

Figure 5 - Comparison of drop test indentation with predicted indentation from finite element simulation

Figure 6 demonstrates the predicted von Mises stress contours inside the specimen at two time stamps. The image on the left, labeled as Full Depth, corresponds to the time when the indenter reaches maximum penetration. The image on the right, labeled as Final Shape, corresponds to the time when relaxation has ceased at the end of the simulation. Comparing the two images reveals a large amount of elastic recovery once the indenter retracts from the specimen surface. A maximum stress of 420 MPa is found beneath the surface of the specimen at full indentation depth, which is in accordance with general elasto-plastic indentation theory [3]. A residual stress of 140 MPa is also found beneath the surface at the completion of the simulation.

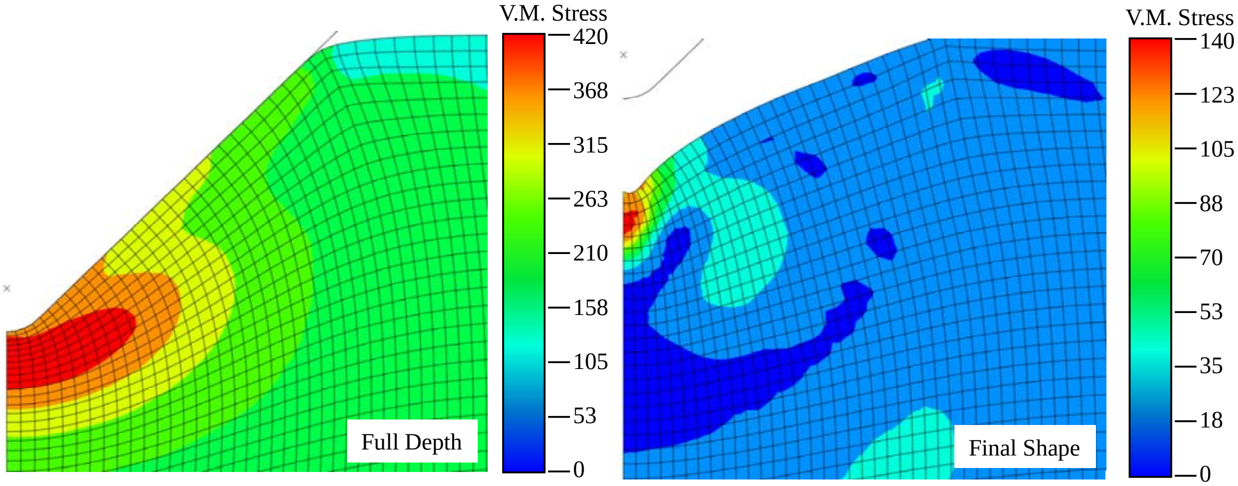

Figure 6 - Subsurface von Mises stress contours

Conclusions

This work has demonstrated the capabilities of Veryst's PolyUMod material library and MCalibration software. A polymer material model was created that accurately predicts the impact deformation of polyether ether ketone. The developed material model shows good agreement to the experimental data; however, some additional work is required to improve the predicted relaxation behavior of this material.

References

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[2] Bergstrom, J.S., and Bischoff, J.E., An Advanced Thermomechanical Constitutive Model for UHMWPE, International Journal of Changes in Solids, 2:31-39, 2010
[3] Johnson, K.L., Contact Mechanics, Cambridge University Press, 1985