High strain rate testing of elastomers and thermoplastic elastomers

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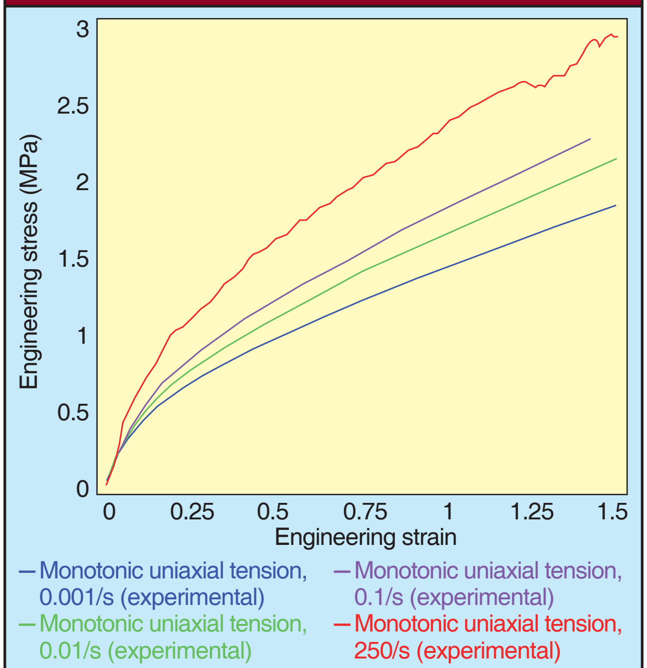
Elastomers and TPEs are used in many different applications and industries, including automotive, aerospace, consumer products, electronics, biomedical devices and heavy industry. These materials are increasingly being used in high strain rate and impact applications. Due to their inherent molecular structure, elastomers and TPEs exhibit rate-dependent response: As the material is deformed faster, the material response changes, becoming stiffer. This effect needs to be taken into account by an engineer when designing a part that experiences high strain rates. Without correctly understanding this rate-dependent behavior, a part can be over- or under-designed, performing poorly during use or increasing production costs due to extraneous material. Figure 1 shows the rate-dependent response of Santoprene, a TPV material made from an EPDM and PP blend. As the strain rate is increased to 250 strain/s, the material is ~60% stiffer at high elongation. In addition to the changing stress-strain behavior of the material, many materials have different failure behaviors at high rates. Most materials become brittle at high strain rates, with some materials undergoing a drastic change.

Understanding how a material behaves is critical to choosing the best material and optimizing the design of a component to the loading conditions in use. Thus, testing a material at multiple strain rates that cover the applied rates is critical. Although quasi-static test methods are well-understood, impact rate testing is a growing field with many test methods. Testing elastomers and TPEs at these rates is difficult; the low sample forces, low density and low wave speed (or acoustic impedance) make testing more difficult. Careful experimental test machine design and selection are necessary to obtain accurate, reliable results. This article aims to introduce and explain the different test methods available to test elastomers and TPEs, as well as explain advantages and disadvantages. Brief discussion is also given on how the data can be used to select and calibrate a material model for use in a finite element (FE) analysis.

Figure 1 - tensile test data for Santoprene; at 150% engineering strain, the material is 60% stiffer



Force and strain measurement

Accurately measuring force and sample strain (or displacement) is critical to a high quality test method and test plan. Modern force and strain measurement systems have made this task easier.

Digital image correlation (DIC) is an increasingly used, advanced method to measure sample strain and displacement. The DIC method uses samples that have a random speckle pattern applied with either paint or ink. Figure 2 shows an exemplar tensile specimen with a speckle pattern. A computer-controlled camera records sample images throughout the test, saving them for post-processing. The sample image is divided into smaller areas, similar to an FE mesh; displacements and strains for each area are calculated using image analysis methods. The individual areas are combined, and full field sample strains and displacements are calculated. The strain history for all the samples can be measured and analyzed.

DIC was originally developed as a single camera system, so the systems could not measure out-of-plane displacements. With a 2D system, the test engineer must use care during test specimen setup; any motion perpendicular to the camera introduces significant error in the calculation. Stereo camera systems and 3D DIC are now common. With these systems, two cameras record the test from two different angles, and full 3D displacement fields are measured, including out-of-plane displacements.

Figure 2 - DIC speckle pattern on an ASTM D638 type IV tensile specimen

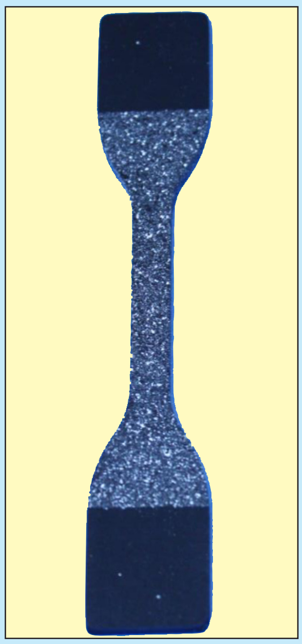
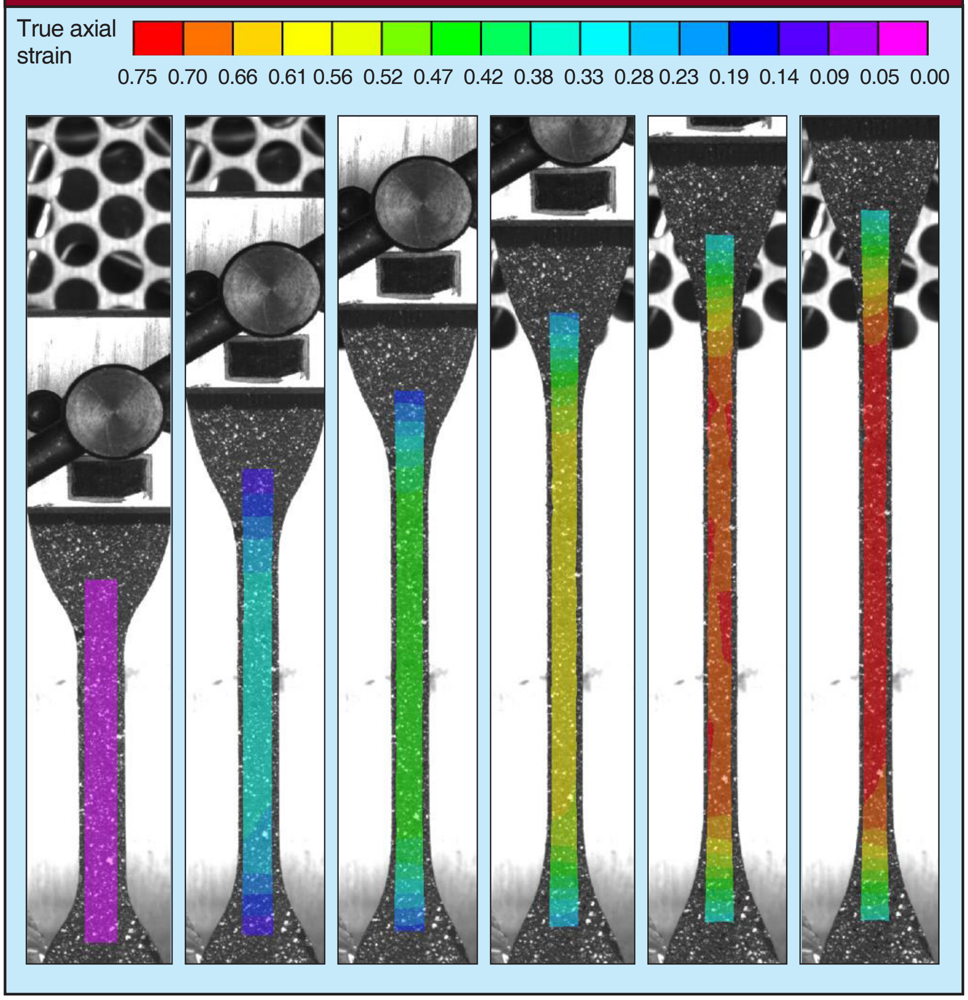


Figure 3 - DIC axial true strain contours of a tensile test on Santoprene at low strain rate



DIC strain measurement has many advantages versus traditional extensometer or laser extensometer systems. DIC systems can measure sample strains up to and in excess of 1,000% strain, as well as accuracy down to 10 microstrain. Additionally, any strain localization or failure effects can be measured throughout the test; if a sample experiences necking or tearing during testing, these values can be measured and analyzed. Further, all strain measurements are made without sample contact, so no effects are introduced due to the measurement system. Last, with one strain measurement system, all strain components are measured. Figure 3 shows DIC strain contours from a tensile test on a TPE material. Multiple commercial DIC software packages exist, as well as open source packages.

Load cells for force measurement can be broken down into two main categories: static load cells and dynamic load cells. Static load cells are used for low strain rate testing, and are usually strain gauge based systems. Typical configurations are the s-style or pancake load cells. These can be either single axis measurements or multi-axis measurements. Dynamic load cells are designed to have a fast response time, and cannot measure static loads. These load cells are typically piezoelectric or piezoresistive, and have response frequencies above 75,000 Hz.

Universal test machines

Universal test machines or universal test systems (UTS) are used for low strain rate testing of polymers, typically up to 10 strain/s. UTS come in two different configurations: servohydraulic or electromechanical machines. Typically, the two systems are interchangeable, although servohydraulic machines are better suited to higher strain rates and fatigue applications. Advantages of UTS are that they are well-characterized and validated, and include complex fixturing and precise control systems. For example, a test engineer can program complex strain histories to test the response of the material with the control system, including loading, unloading, creep or relaxation, and cyclic loading. Unfortunately, only moderate strain rates are achievable in these systems. A typical electromechanical UTS is presented in figure 4. The figure shows compression platens and a temperature chamber in the background.

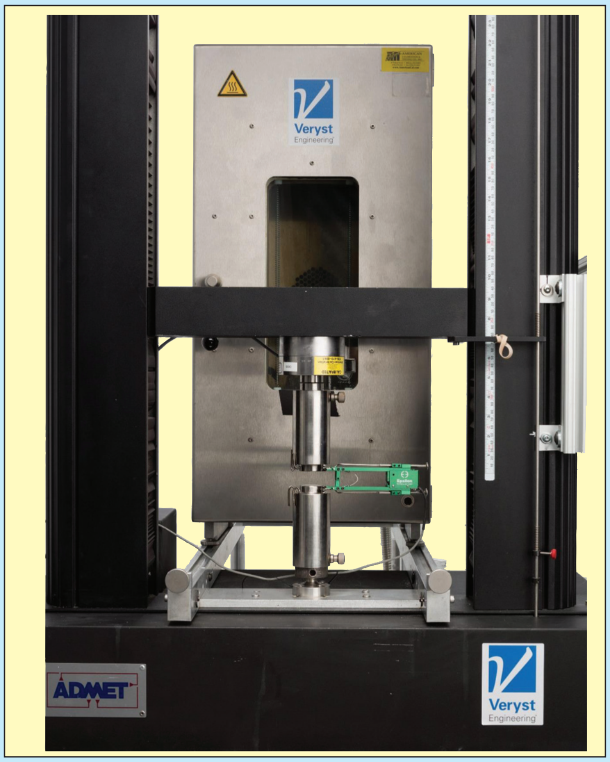
Split Hopkinson pressure bar

The split Hopkinson pressure bar (SHPB), or Kolsky bar, is a dynamic, stress wave based experimental method to measure the high strain rate response of materials up to ~10,000 strain/s. SHPBs can be configured to test in compression, tension, torsion or shear, and have a long history of use in research and development applications.

A schematic of an SHPB is shown in figure 5. The system consists of a pneumatic cylinder, striker, incident bar and transmitted bar. The pneumatic cylinder is charged to a set pressure, and accelerates the striker. The striker transmits a stress wave to the incident bar, and the velocity of the striker is measured. The stress wave travels through the bar, into the sample, and into the transmitted bar. The strain in the incident and transmitted bars is measured with strain gauges, and the bars are made of a well-known material. Sample stress and strain are calculated from the strain gauge measurements, and the applied load and strain history for the sample is calculated.

Careful design of an SHPB is necessary when used for elastomers and TPEs. If the acoustic impedance of the incident and transmitted bars is too high, then very little energy (and deformation) is transferred to the sample. SHPB systems are designed for the materials they are to test: SHPBs for plastics use aluminum bars; SHPBs for elastomers and TPEs typically use PMMA bars. Although the PMMA bars create good material

Figure 4 - exemplar electromechanical test frame for low strain rate testing



response, the PMMA bars are viscoelastic materials. Because the data analysis for the test uses the mechanical response of the bars, this introduces additional complexities and potential errors.

The SHPB is a validated and well-characterized system with high test strain rates, although it does have limitations. Soft materials, like elastomers and TPEs, are more difficult to test and analyze with the SHPB, introducing additional uncertainty in the test data. Additionally, total test strain is limited with the SHPB.

Drop towers

Drop towers are a versatile tool to test elastomers and TPEs up to strain rates of ~1,000 strain/s. A drop tower uses a falling weight to load the sample, and different fixtures are used for tension, compression or shear testing. Figure 6 shows Veryst Engineering's custom built drop tower. In this system, sample strain is measured with a high-speed camera (>100,000 fps) and DIC; sample force is measured with a dynamic load cell. Test strain rate is controlled by changing the height of the falling weight, and materials can be tested in tension up to 1,000% strain.

Figure 5 - split Hopkinson pressure bar (SHPB) schematic

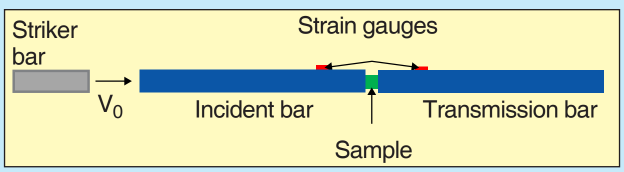
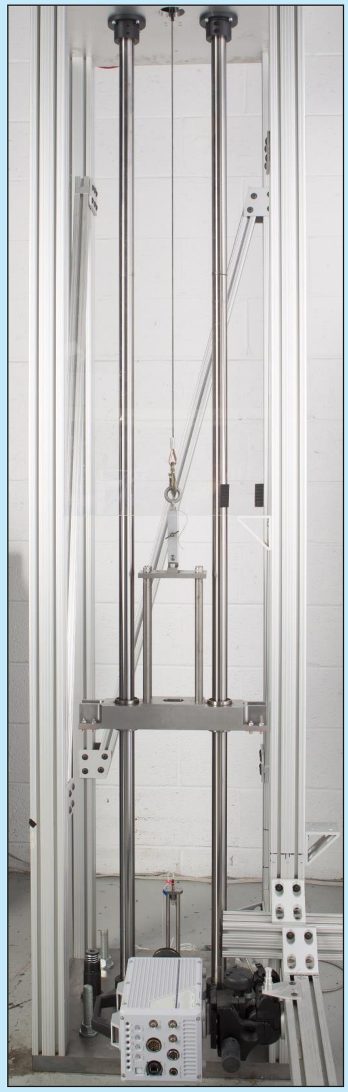


Figure 6 - Veryst Engineering's custom built drop tower



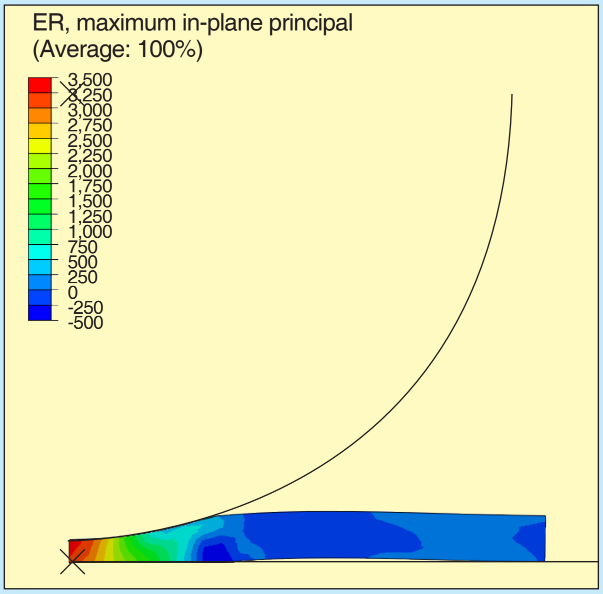
A well-designed drop tower system will provide highly accurate and mostly noiseless material data for all classes of polymers, particularly elastomers and TPEs. In addition, samples can be tested to extremely large strains in both tension and compression. The high-speed camera and DIC allow full field strain measurements and a record of the test. The drop tower is limited in the maximum strain rates achievable, although rates that are applicable to most impact conditions are possible.

Inverse methods

Inverse test methods are attractive when reaching high strain rates with a homogenous strain field is difficult or impossible, which is often true for elastomers and TPEs. Due to their relative softness and low acoustic impedance, at high strain rates the applied strain field may not be uniform. Inverse test methods can overcome this difficulty. In an inverse test method, the force and displacement of the loading are measured, and an FE model is used to simulate the experiment and calculate the material response. A candidate material model is used to perform the simulation, and the simulated force and displacement are compared to the experimental data. Nonlinear search algorithms are then used to minimize the error between the candidate material model and the experimental data.

One example of a common inverse test method is the ball impact or ball drop experiment. A cylinder of the material is placed on a dynamic load cell, and a ball bearing (typically steel) is dropped from a known height. The force on the sample is recorded, and the displacement is calculated from Newton's laws. Figure 7 shows the results of an FE simulation on a rub-

Figure 7 - FE simulation of a ball impact test on a rubber material; the contours show the effective strain rate in the sample, reaching 3,500 strain/s



ber material. In this case, the sample experiences strains in the range of 5,000 strain/s, well above those achievable in a drop tower.

Another example of an inverse test method is the Taylor impact experiment. In this test, a cylindrical specimen is shot from a gas gun at a rigid platen. The original experiment was used to predict yield stress based on the deformed shape of the specimen, but modern load cells and high-speed cameras allow real time measurement of the force and displacement. These data are then used with an FE model to simulate the material response at high rates. Impact rates up to 10,000 strain/s are possible with this method.

Generally, inverse methods enable extremely high strain rate testing of all classes of materials, and are particularly suitable for elastomers and TPEs. Although the experiments can produce clean data, additional data processing is needed to capture the material behavior from these tests. In addition to the high strain rates available, inverse test methods use multi-axial loading. This can be important to validate material models in more complex loading modes, building confidence in the material model.

Material model selection and calibration

Finite element analysis is a powerful tool for the design engineer to understand the stress and deformation the designed component experiences during use. The analysis can be used to validate if the component will perform or needs to be redesigned. An FE analysis has three inputs: component geometry, applied loading and constraints, and material behavior. Geometry and applied loading are well-defined based on load cases, but material response is difficult to accurately capture with complex, advanced materials such as elastomers and TPEs. Advanced tools exist to calibrate advanced material models that capture strain rate dependent material response, including tools built into FE software and MCalibration from Veryst Engineering. MCalibration uses non-linear optimization procedures to match simulated material response to experimental data. The material parameters are then exported to the FE software for simulation, enabling advanced simulations to analyze and design products under real world loading conditions.

Conclusion

Elastomers and TPEs are complicated materials that exhibit strain rate dependent behavior due to their molecular structure. This rate dependent behavior can drastically change the stress-strain response of the material, and can affect designed component behavior. Accurate methods for soft materials like elastomers and TPEs are readily available in multiple loading modes. Each test method offers advantages and disadvantages that need to be considered for each material and test program. A well-designed test plan can provide highly accurate data that can enable a material or design engineer to create a better end product for the user. Last, clean, accurate data enable an engineer to calibrate a material model for use in an FE simulation.