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Bonnie Antoun · H. Jerry Qi · Richard Hall · G.P. Tandon
Hongbing Lu · Charles Lu *Editors*

Challenges in Mechanics of Time-Dependent Materials and Processes in Conventional and Multifunctional Materials, Volume 2

Proceedings of the 2012 Annual Conference on Experimental and Applied Mechanics

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Preface

Challenges in Mechanics of Time-Dependent Materials and Processes in Conventional and Multifunctional Materials, Volume 2: Proceedings of the 2012 Annual Conference on Experimental and Applied Mechanics represents one of seven volumes of technical papers presented at the Society for Experimental Mechanics SEM 12th International Congress and Exposition on Experimental and Applied Mechanics, held at Costa Mesa, California, June 11–14, 2012. The full set of proceedings also includes volumes on Dynamic Behavior of Materials, Imaging Methods for Novel Materials and Challenging Applications, Experimental and Applied Mechanics, Mechanics of Biological Systems and Materials, MEMS and Nanotechnology, and Composite Materials and Joining Technologies for Composites.

Each collection presents early findings from experimental and computational investigations on an important area within experimental mechanics. The Challenges in Mechanics of Time-Dependent Materials and Processes in Conventional and Multifunctional Materials conference track was organized by Bonnie Antoun, Sandia National Laboratories; H. Jerry Qi, University of Colorado; Richard Hall, Air Force Research Laboratory; G.P. Tandon, University of Dayton Research Institute; Hongbing Lu, University of Texas-Dallas; Charles Lu, University of Kentucky, and sponsored by the SEM Time Dependent Materials and Composite, Hybrid and Multifunctional Materials Technical Divisions.

This volume includes chapters which address constitutive, time (rate)-dependent constitutive and fracture/failure behavior of a broad range of materials systems, including prominent researches in both applied and experimental mechanics. Solicited chapters involve nonnegligible time-dependent mechanical response in cases incorporating nonmechanical fields. The sessions are as follows:

- Time-Dependent Model Validation
- Small-Scale and Dissipative Mechanisms in Failure
- Thermomechanics and Coupled Phenomena I
- Strain-Rate and Frequency Effects
- Process Models and High-Temperature Polymers
- Shape Memory Materials
- Time-Dependent Nanoscale Testing
- Time-Dependent and Small-Scale Effects in Biocomposites
- Viscoelastoplasticity and Damage
- Composites, Hybrids, and Multifunctional Materials

Chapters in the following general technical research areas are included:

- Effects of interfaces and interphases on the time-dependent behaviors of composite, hybrid, and multifunctional materials
- Effects of inhomogeneities on the time-dependent behaviors of metallic, polymeric, and composite materials
- Environmental and reactive property change effects on thermomechanical and multifunctional behaviors
- Challenges in time-dependent behavior modeling in metallic and polymeric materials at low, moderate, and high strain rates, and effects of frequency and hysteretic heating
- Challenges in time-dependent behavior Modeling in composite, hybrid, and multifunctional materials – viscoelasto-plasticity and damage
- Modeling and characterization of fabrication processes of conventional and multifunctional materials
- Time-dependent and small-scale effects in micro/nanoscale testing

The organizers thank the presenters, authors, and session chairs for their participation in this symposium.
The opinions expressed herein are those of the individual authors and not necessarily those of the Society for Experimental Mechanics, Inc.

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Contents

Chapter 1
Elastomeric Polymers for Shockwave Mitigation and Extreme Loading Conditions

Roshdy George S. Barsoum

Abstract Recent investigations into blast resistant properties of polymers with high rate sensitivity, have shown that they interact with the underlying substrates in quite different manner than any ballistic material known to the shock community. We are going to discuss in this paper that these polymers have a profound effect on the failure (fracture) mechanism of the substrate: suppression or delay of shear localization (or penetration) mechanisms, and delay of necking instability in ductile metals, in addition to dissipating large amounts of energy through wave reflections. The intrinsic property of the polymer under blast/ballistic/ shock, in addition to its high strain rate sensitivity, is a very large increase of its shear properties, both modulus and strength, under very high pressure and loading rate, which exists under extreme loading conditions. In addition, because these elastomeric polymers are multi-phase of hard and soft domains, at the nano scale, they can dissipate broad bands of frequencies such as those encountered in blast events. We will discuss also research in the development of polymers-by-design to divert and dissipate shockwaves from the head and thus prevent Traumatic Brain Injury—TBI, using molecular dynamics, polymer synthesis and high strain rate testing of shock properties for constitutive models, and the continuum analysis of shockwave propagation.

Building on successful testing of elastomeric polymers in demonstrating its effect on the blast, ballistics performance of steel, ONR initiated efforts to understand the mechanisms involved in extreme loading conditions. The fundamental property of these polymers is *high strain rate sensitivity*, which was shown to be essential in the suppression of shear localization in high strain rate events [1], such as those encountered in blast and penetration mechanics [2]. To fully illustrate the delay or suppression of shear localization, Fig. 1.1 shows the failure mechanism of large scale of uncoated and coated thick steel plates subject to underwater high rate loading. Examination of the fracture in the uncoated plates, show the failure to be the result of shear localization. On the other hand, Fig. 1.2, of small (thin steel) specimens also subject to intense high rate loading, the failure of the uncoated specimens was ductile. It is instructive to know that the % increase in pressure associated with the coated plates vs. uncoated plates was much higher in the case of the shear localization case, than in the ductile failure case. What is more interesting, is that in the case of thick plates, where the failure is governed by shear localization, it did not matter whether the coating is, on the side of the loading (front) or the back side. While in the case of thin plates, the coating was only effective when the coating was on the backside. In Ref. [3], it is argued that the polymer on the front side, focuses the shock, while in the backside it attenuates the shock. No computation was done to prove these arguments, because of the difficulty in performing large deformation nonlinear plasticity combined with shockwave propagation in extremely thin layers. This type of analysis was recently resolved by Fish [4], using multi-scale computational approach with solitons to compute the shockwave

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Fig. 1.1 Thick-high strength steel plates coated with ERC subject to intense underwater high rate loading

propagation and its reflections at interfaces, which provides another mechanism of dissipation. Therefore there are three mechanisms associated with these polymers: (1) in the case of thin plates, as the strain rate increases the polymer hardens significantly, and thus reduces the plastic deformation; (2) in the case of thick plates the thick plates the polymer hardens similarly, but it spreads the localization to neighboring areas and delays shear localization; and (3) the polymer dissipates the shockwave and attenuates it, as shown by the analysis [4] of experiments done earlier at NSWC. The mechanisms of how the high strain rate sensitive polymer can result in delay in shear-localization or ductile fracture and shockwave propagation/dissipation, can be further deployed to further improvements in multi-layered hybrid plates with different materials. ONR is pursuing a new computational approach to perform shear localization analysis of thick high strength, high toughness steel plates.

To further exploit these polymers in a highly complex and formidable problem facing the warfighter, ONR is leading a Basic Research Challenge and applied S&T effort, to develop polymers-by-design to divert and dissipate shockwaves from the head and thus prevent Traumatic Brain Injury—TBI [6].

Protection against TBI is one of the most challenging problems in mechanics, because the brain is the most sensitive instrument we know of, and helmets requires lightweight materials, so that they are worn all the time. Elastomeric polymers, if designed accordingly, can both address shockwaves and ballistic effects. Tests and theoretical developments on polymers, indicate that these polymers can provide the necessary protection against TBI. Investigations into blast resistant properties of polyureas and other multi-phase polymeric elastomers, indicate that they can dissipate broad bands of frequencies such as those encountered in blast events. Recent experiments and multi-scale computations of polymers with underlying substrates, have been shown that polymers absorb shock loading in quite a different manner than any ballistic material known to the armor community.

Fig. 1.2 Thin-high strength steel plates coated with ERC

In this presentation we will discuss efforts on the multi-scale approach addressing constitutive modeling, analysis, and tests of various extreme loading events. To understand interaction between materials and wave propagation at extreme high rate requires multi scale computation, which are in the nano scale space and time. Molecular dynamics, coarse scale modeling, continuum modeling, high rate load testing, and constitutive modeling and large scale computations simulating biofidel models of the head and brain are used in addressing the Traumatic Brain Injury problem [5–8].

Figures 1.3 and 1.4, illustrate the multi-scale computational effort of atomistic-to-continuum behavior of polymers subject to shockwaves and its impending dissipation and diversion of shock energy.

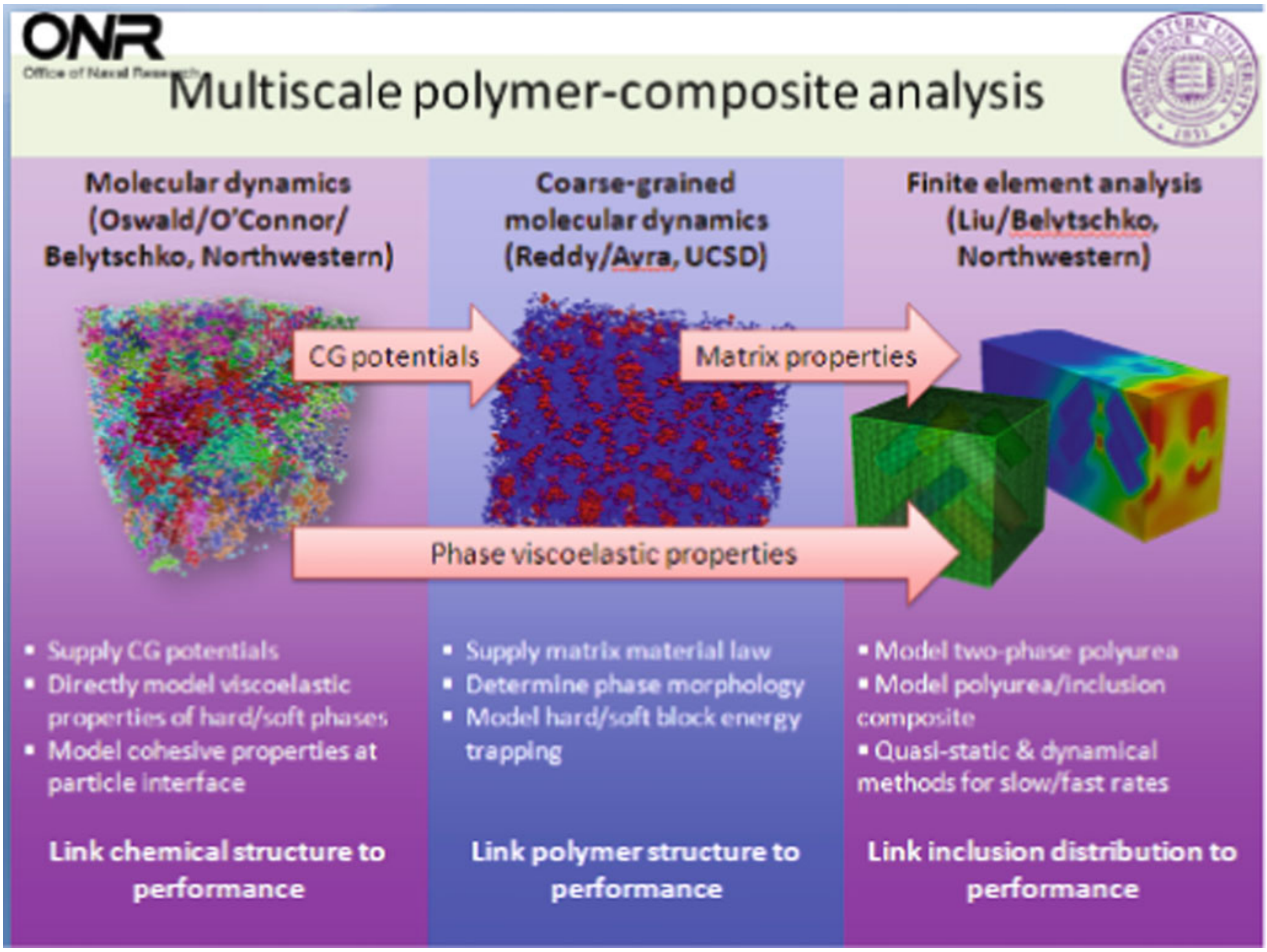

Fig. 1.3 Multi-scale modeling of polymers with nano and micro inclusions to divert shockwaves

1.1 Why Polymers for TBI?

- Polymers are the best hope for protection against TBI for the following reasons:
  - Lightweight and can both improve blast and ballistic protection
  - When combined with other materials, have proven to offer increased protection against blast, shockwave, and fragments.
  - Highly strain rate sensitive and shear mechanical properties increase significantly under combined pressure and high rate.
- Under shock loading, brain tissue is weak in shear, while polymers increase in strength and modulus (both direct and shear stresses).
- Polyureas have multi-scale structures from the nano to the micro and continuum level with complex interactions with all frequencies of shockwaves, thus, in principle, have the potential for absorbing/dissipating harmful effects that result in mTBI.
- Polymers can be design from the molecule up. But what is the design criteria in the case of shock-
- Nano- and micro- particles, and shaped interfaces and layers can be included to dissipate and divert shock-

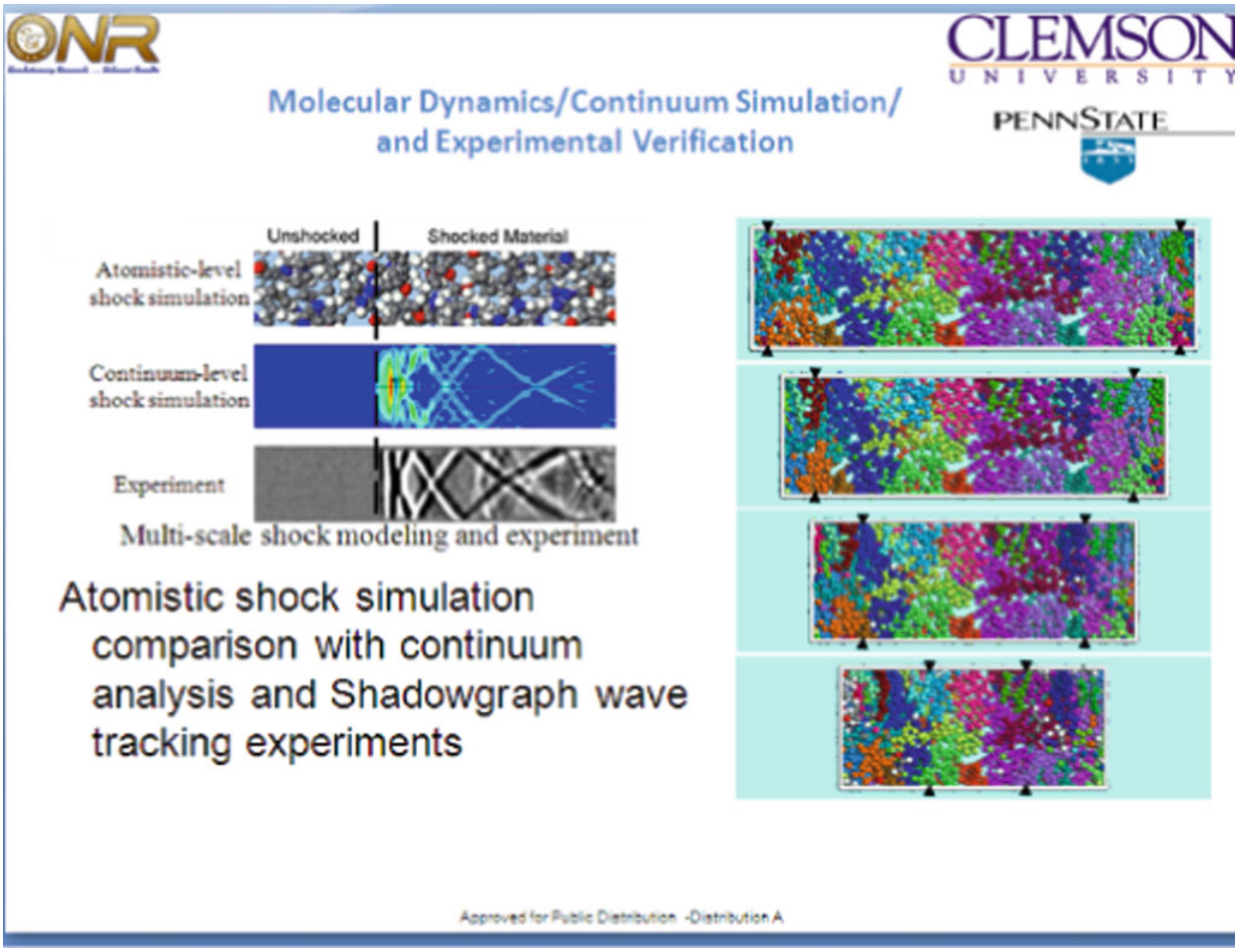

Fig. 1.4 Multi-scale modeling of shockwave reflections at boundaries—comparison between molecular dynamics, continuum mechanics computations and shock testing

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Chapter 2
Temperature Dependent Ductile Material Failure Constitutive Modeling with Validation Experiments

J. Franklin Dempsey, Bonnie R. Antoun, Vicente J. Romero, Gerald W. Wellman, William M. Scherzinger, and Spencer Grange

Abstract A unique quasi-static temperature dependent low strain rate constitutive finite element failure model is being developed at Sandia National Laboratories (Dempsey JF, Antoun B, Wellman G, Romero V, Scherzinger W (2010) Coupled thermal pressurization failure simulations with validation experiments. Presentation at ASME 2010 international mechanical engineering congress & exposition, Vancouver, British Columbia, 12–18 Nov 2010). The model is used to predict ductile tensile failure initiation using a tearing parameter methodology and assessed for accuracy against validation experiments. Experiments include temperature dependent tensile testing of 304L stainless steel and a variety of aluminum alloy round specimens to generate true-stress true-strain material property specifications. Two simple geometries including pressure loaded steel cylinders and thread shear mechanisms are modeled and assessed for accuracy by experiment using novel uncertainty quantification techniques.

Keywords Finite element model • Validation testing • Temperature dependent constitutive model

2.1 Finite Element Material Characterization Modeling

Finite element (FE) analysis with validation testing is performed to predict quasi-static failure initiation of ductile materials when subjected to high pressures at elevated temperature. Two structure types are chosen to envelope load and displacement modes of failure. The structures include a simple stainless steel cylinder (pipe bomb) that that is pressurized and heated and an aluminum Acme thread geometry that is extended and heated to failure.

A unique FE quasi-static temperature dependent constitutive model [1] has been developed and uses a tearing parameter methodology for failure initiation. Model inputs require experimental derived tensile test hardening data taken at temperatures in the range of the desired failure prediction. The structural response is then validated by tests.

The elastic–plastic constitutive model incorporating temperature dependence was developed for use in Sandia's quasi-static finite element modeling software, Adagio [2]. The model requires a temperature dependent true stress-true strain hardening curve definition to failure plus temperature dependent elastic constant specifications. Elastic constants can be obtained in the open literature but the hardening curve data is characterized through experimental tensile tests at elevated temperature [3]. Pipe bomb tensile-test material samples were cut and machined from a common 304L stainless steel tubular stock. The resulting engineering stress strain curves are shown, Fig. 2.1.

Validation-experiment pipe vessels were machined from the same batch of tube stock material to match the tensile test data. As shown, the strength degrades with increasing temperature. From room temperature to 600°C, the ductility at failure decreases. After 600°C, it increases for this particular material.

For each measured stress–strain curve, an advanced optimization technique is used to solve an inverse finite element tensile necking problem to calculate true stress/true strain response and will later be used system model input. An example is presented in Fig. 2.2.

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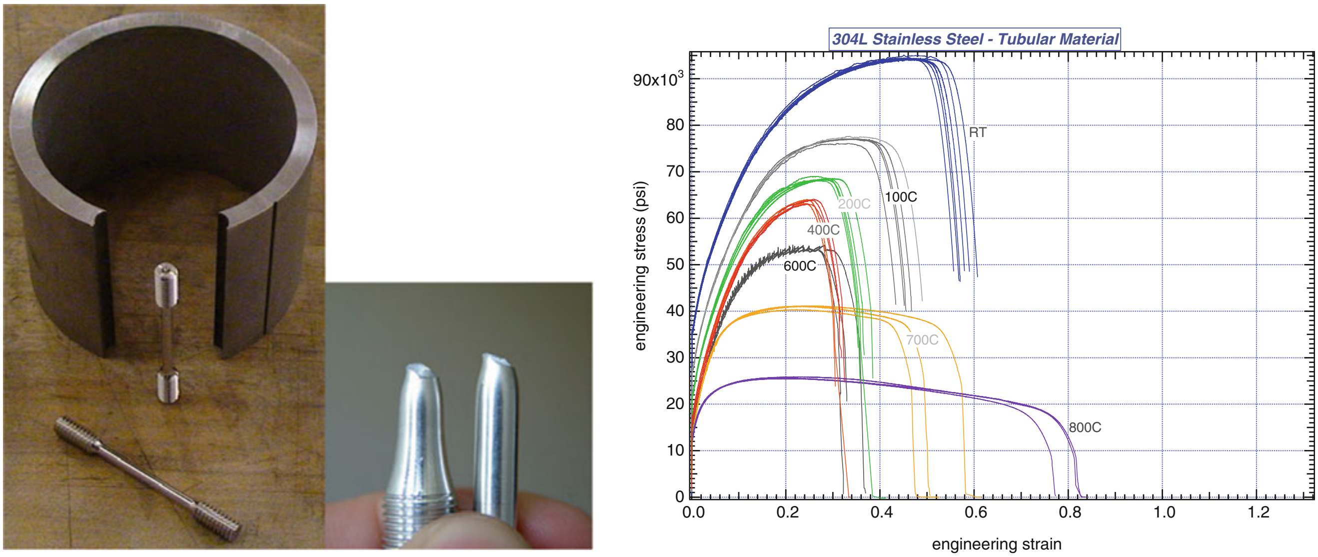

Fig. 2.1 Cylinder tensile-test material samples were cut and machined from the same 304L stainless steel tubular stock that the validation-experiment pipe vessels were machined from. Measured stress–strain response-to-failure curves plotted from cylinder pull-tests at a strain rate of 0.001/s for the labeled temperatures (note: *RT* in the plot stands for "room temperature", nominally 25°C)

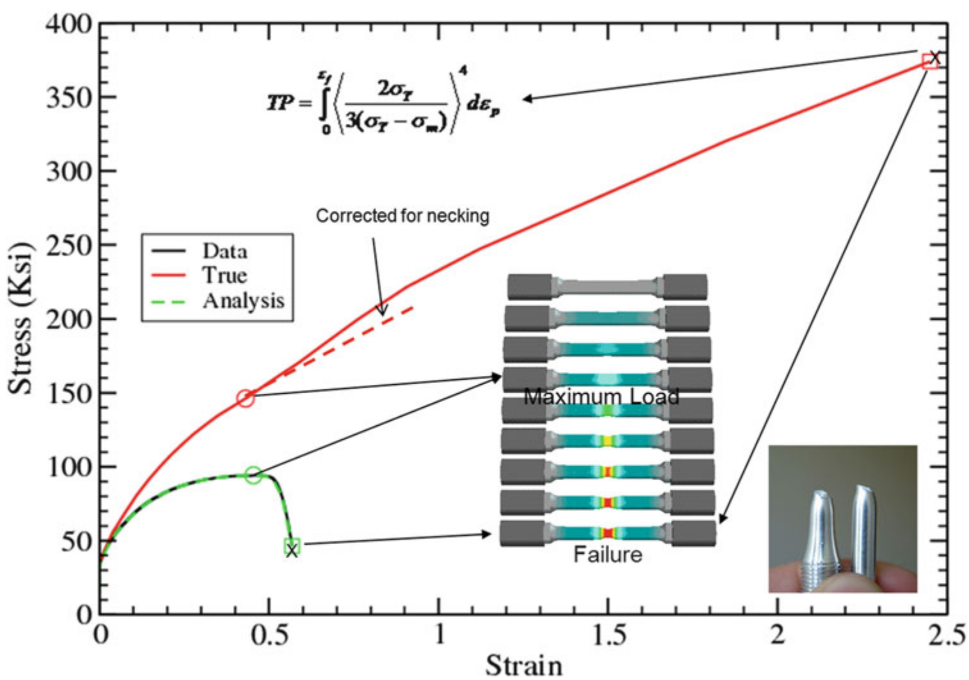

Fig. 2.2 Example of various stress–strain curves pertaining to experimental and modeled response in a given tensile-test. *True* curve is Cauchy-Stress/Logarithmic-Strain "True" curve conditioned to the constitutive model. The curve is inversely calculated using the constitutive model and a FE model of pulled cylinder such that when the curve is used with the constitutive model in the FE simulations the calculated *Analysis* stress–strain curve matches the experimentally measured *black* stress–strain curve from the pull test. See Ref. [8] for the set of derived curves at each temperature

Given the engineering stress strain response of a tensile test [3], the round tensile specimen is modeled using finite elements. A displacement controlled FE calculation is then performed to simulate the tensile test. The simulation predicts no necking through yield but as the specimen begins to harden, true stress/log strain necking response is estimated and checked against the original averaged engineering stress/strain. Iteratively, true stress and log strain can be computed to failure. This is referred to as solving the inverse problem. A tearing parameter method is used to track failure progress. At failure, a critical tearing parameter is calculated to be used in pipe bomb models. This procedure is repeated at every temperature. The inverse problem and solution procedures and results are more fully documented in Ref. [1].

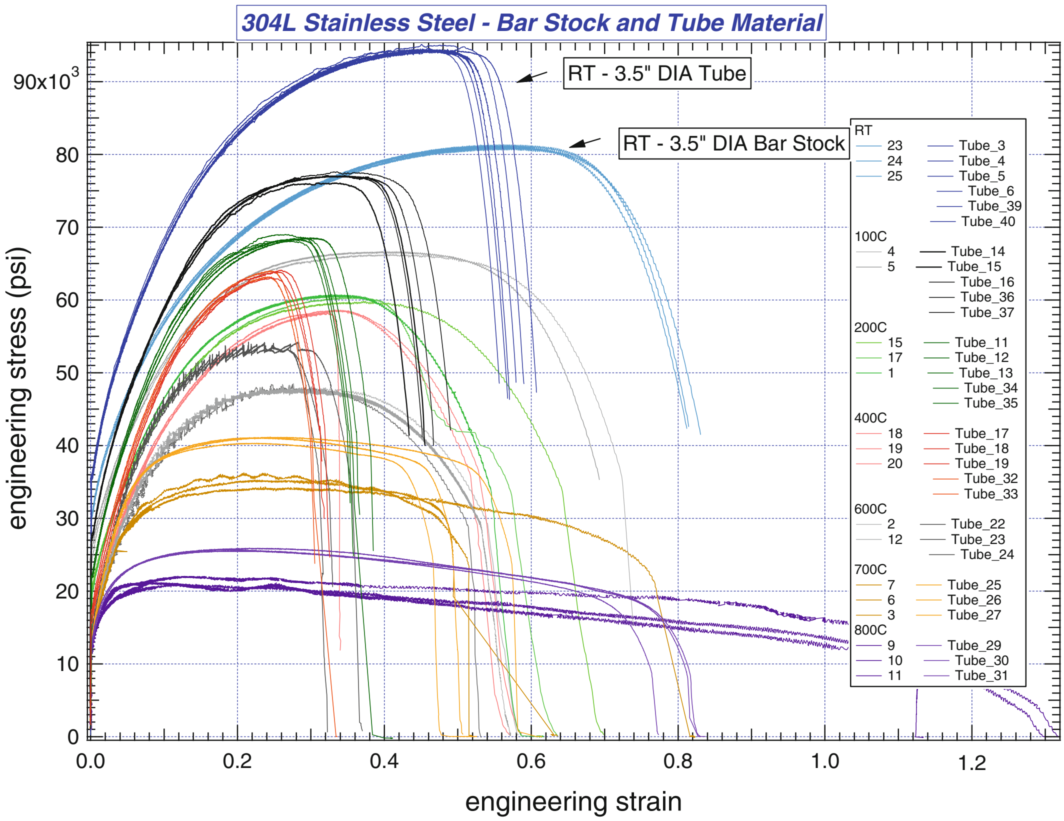

Fig. 2.3 Engineering stress/strain response of 304L bar stock tensile tests through elevated temperature and a comparison of bar stock and tube stock at room temperature

Once the material characterization has been defined for an applicable range of temperatures, it is formatted as input into a thermo-elastic plastic constitutive model and used to predict the failure response of a pressurized cylindrical steel vessel at high temperature. In this case, a critical tearing parameter is used to define a point in which the code will automatically delete elements, thus establishing the pressure, temperature and location of failure initiation.

True stress and log strain response for a given material at elevated temperatures is unique. For example, tensile tests have shown that extruded 304L bar stock has an ultimate strength of nearly 20% less than extruded tubing. It is also about 25% more ductile (Fig. 2.3). Additionally, some aluminum alloys including 6061-T651, 6061-T6, 7075-T651, 7075-T7351, 7079 and 7050-T74 have been tested and characterized to tensile failure at elevated temperature. The 304L tube stock is used for pipe bomb and aluminums for thread shear modeling and simulation.

2.2 Finite Element Validation Modeling

Two quasi-static verification models were created for validation to experiments. They include the pipe bomb pipe bomb and thread shear geometries. Figure 2.4 shows the pipe bomb geometry. Figures 2.5 and 2.6 show the pipe bomb and thread shear finite element models, respectively. Thread shear validation modeling is just beginning; therefore pipe bomb work will be discussed herein.

2.3 Finite Element Modeling to Validation Experiments

The pipe bomb consists of a 3″ O.D tube that is machined down to a 0.020″ wall thickness at the center (Fig. 2.4). Other thicknesses including 0.035 and 0.05 thicknesses are also investigated. It is 14″ in length.