Inelastic Constitutive Equations: Deformation Induced Anisotropy and the Behavior at High Homologous Temperature

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Introduction.

Demand for predictability of performance of energy producing machinery is ever increasing. Modern industrial society demands the safe and reliable operation of these plants. Due to their size and their life expectancy the safety and reliability of steam, gas turbines and other heavy machinery operating at high temperatures cannot be determined by simulated service testing. An engineering stress and lifetime analysis has to be performed long before the actual structure is built. For this purpose a mathematical description of the actual material deformation behavior, the constitutive equation, is needed. These constitutive equations describe a nonlinear physical process, the time-dependent deformation behavior of metals. Previously, nonlinear analyses were not possible in the design office. The advent of almost unlimited and economical computing power has completely changed the picture. As a consequence, the constitutive equations have become limiting factors as their foundation rests with old idealizations that were conceived at the turn of the century (Plasticity. ~1900) or in the 1930s (Creep theory). Plasticity was conceived when carbon steels were the prime structural materials and creep theory was specifically designed for steady energy production lasting decades and not for the cyclic, daily and seasonal energy demands of our technological society. Modern materials and modern demands on energy production pose new challenges for lifetime analyses. The VBO (viscoplasticity theory based on overstress) constitutive equation was invented, developed, experimentally verified and implemented in the Abaqus finite element program by the principal investigator and his students.

This research contributes to the above-described tasks by:

1. Exploring the inelastic behavior of engineering alloys by suitable experiments and by determining the appropriate constants.
2. Formulating material models or constitutive equations suitable for computational use in engineering stress and lifetime analyses.
3. Implementation of these models in finite element programs so that they can be applied to engineering structures.

We have no objection from a patent standpoint to the publication or dissemination of this material.

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Modeling of creep, relaxation and rate sensitivity at high homologous temperature

A high homologous temperature version of VBO was developed earlier by Tachibana and Krempl (1995).¹ This model needed about 20 constants to reproduce rate sensitivity, creep and relaxation. In an application of VBO to the electronic industry a simplified, high homologous temperature VBO model was developed in Refs². 5 and 17. This model required less than ten constants to reproduce the inelastic high homologous temperature behavior of some solder alloys.

This new and simplified model was then applied to the data used by Tachibana and Krempl (1995) with excellent success, see Refs. 3 and 16. The simplified VBO has been shown to reproduce the rate dependent behavior of Alloy 800H and to solder alloys with a minimum number of constants. In the future we will always consider first the simplified version when modeling high homologous temperature deformation behavior.

Dynamic strain aging

Many engineering alloys exhibit dynamic strain aging in certain temperature regions. When this phenomenon is present serrated yielding (Portevin le Chatelier Effect), rate insensitivity (also called neutral rate sensitivity) or negative rate sensitivity are observed together with an increase in strength and a decrease of ductility as the temperature increases. Below and above this temperature region "normal" behavior (positive rate sensitivity and a decrease in strength and an increase of ductility with an increase in temperature) is observed. Virtually every engineering alloy has a region of dynamic strain aging and the subject area has significant engineering importance.

K. Ho, in his thesis, "invented" a simple and elegant way to reproduce negative, neutral and positive rate sensitivity. A number of reports have been written describing the modified VBO, see Refs. 20, 24, 25 and 28. We are not aware that other models have these extended capabilities.

The modification of VBO leading to modeling of neutral and negative rate sensitivity predicted that regular creep and relaxation motions would still be present. Only three papers investigating the anomalous rate dependence in monotonic loading together with creep and relaxation were found. They confirmed the VBO prediction. In his Ph.D. thesis H. Irizarry Quiñones, see Ref. 31, performs an extensive experimental investigation on monotonic rate-dependent loading, creep and relaxation in the dynamic strain-aging regime of Al-Mg. and Al-Mn. alloys. The results confirm the predictions of the modified VBO model.

The capability of the VBO model to incorporate positive, neutral and negative rate sensitivity is unique and will increase the areas of applicability considerably, especially since, to this writers knowledge, other state variable models do not have these attributes.

Polymeric Solids

Through macroscopic, phenomenological experimentation we have established that there are many similarities with the high temperature deformation behavior of metallic

¹ Tachibana, Y and E. Krempl, "Modeling the high homologous temperature deformation behavior using the viscoplasticity theory based on overstress (VBO): Part I. Creep and tensile behavior," *Journal of Engineering Materials and Technology*, Vol. 117, pp. 456-461.

² Ref refers to the appended list of publications.

materials and solid polymers. Of course there are also differences. However, the similarities are sufficient to attempt modeling the rate sensitivity, creep, relaxation and cyclic behavior of solid polymers using VBO. This theory is flexible enough to model specific polymer properties such as the observed large strain recovery after unloading to zero stress. References 8, 9, 11, 14, 15, 18, 25, 26/3, 28 and 29 discuss that subject. A "unified" model for metals and polymers looks very promising and should be pursued further in view of the conceptual simplicity, economies of teaching and industrial applications.

Deformation induced anisotropy

Upon large deformation initially isotropic metals can become anisotropic with the anisotropy dependent on the deformation path. The development of texture is a manifestation of the induced anisotropy. Modeling of this property remains unsolved and is one of the most challenging tasks in materials modeling.

The PI has developed a new idea for modeling the evolution of anisotropy. Frederick-Armstrong type growth laws for the elastic and inelastic compliance tensors are postulated that can reproduce the changing anisotropy. In formulating the finite deformation version of VBO an Eulerian approach has been followed. Recent developments in the kinematics of Eulerian formulations³ are important here and have been used in S. Gomaa's Ph.D. thesis, see Ref. 30. The new development in kinematics, the Frederick-Armstrong law and the structure of VBO make of solution to the modeling of deformation induced anisotropy possible. The feasibility of the approach has been established by Zaini and Gomaa, see Ref. 32 and 30.

Outlook

The research has been identified for use in applications and has also laid the foundations for future research in several new and promising areas.

1. High homologous temperature modeling of tensile, cyclic, creep and relaxation behavior with a minimum number of constants was accomplished for a Nickel based superalloy (800H) and for a PbSn alloy.
2. A completely new way of modeling positive, neutral and negative rate sensitivity has been proposed by K. Ho. This new approach is unique and needs to be evaluated by others. It opens up new ways of modeling the rate dependent behavior of solids.
3. There is a real prospect in describing the inelastic deformation behavior of metals (alloys) and solid polymers with one basic model.
4. A new way of modeling deformation-induced anisotropy has been found and the initial problems have been overcome. This new approach was shown to be feasible and has been implemented in a finite element program.
5. This new approach of modeling deformation induced anisotropy and the method of modeling neutral and negative rate sensitivity can develop into major break-throughs in modeling of inelastic behavior. Due to the novelty of the ideas and due to the complexity of the work it was not possible to completely finish the development. The most promising ideas in the research career of the PI are waiting to be completed.

³ Xiao, H., O. T. Bruhns and A. Meyers, "Logarithmic strain, logarithmic spin and logarithmic rate," *Acta Mechanica* Vol. 134, pp. 89-105.

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Rensselaer Polytechnic Institute
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- 2) "Modeling of Non-proportional Loading of Nylon 66 Using the Viscoplasticity Theory Based on Overstress," K. Ho and E. Krempl.
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29. "Investigating the mechanical properties of Polycarbonate," Fazeel J. Khan, MS, in Mechanical Engineering thesis, Rensselaer Polytechnic Institute, Troy, NY, (December 1998). Mr. Khan is a doctoral student at Rensselaer Polytechnic Institute.
30. "Computational procedures for finite deformation, rate-independent plasticity and viscoplasticity based on overstress," Said Gomaa, Ph.D thesis, Rensselaer Polytechnic Institute, Troy, NY, (Completed thesis defense, degree expected December 1999). S. Gomaa is now with Ansys Corp., Canonsburg, PA.
31. "Rate-dependent properties of Al-Mn and Al-Mg alloys during dynamic strain aging and of OFHC Copper and Type 304 Stainless Steel," Hugo Irizarry Quiñones, Ph.D. thesis, Rensselaer Polytechnic Institute, Troy, NY, (Completed thesis defense, degree expected December 1999). H. Irizarry-Quíñones is now with Bechtel Technical Services, Machinery Apparatus Operations, Schenectady, NY.
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