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Inelastic Deformation and Damage at High Temperature

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Progress Report April 1, 1991 through March 31, 1992Summary

Combined experimental and theoretical investigations into the inelastic deformation and damage behavior of engineering alloys at elevated temperatures are being pursued. The analysis of previously performed strain rate change and relaxation tests on modified 9Cr-1Mo steel showed the need for inclusion of a recovery of state term in the growth laws for the state variables of the viscoplasticity theory based on overstress (VBO). Recovery of state terms were introduced and the experimental results were satisfactorily simulated. The finite deformation theory of VBO has been developed further to include a convected derivative rationale for the choice of the objective stress rate. The reversing direct current voltage drop measurements during low cycle fatigue at elevated temperature were improved. A passive filter bank and new positioning devices for the coils were installed. Tests at 650°C and lasting several days showed excessive, uncontrollable temperature changes. It was decided to drop the test temperature to 538°C which is close to the operating temperature of Type 304 Stainless Steel. The temperature fluctuations in torsion tests were within $\pm 3^\circ\text{C}$ which was considered satisfactory. Testing will continue at 538°C.

Personnel

The principal investigator is Dr. Erhard Krempl, Professor of Mechanics (10% of academic year time), assisted by Brian P. Fitzgerald (BS, Physics, RPI, 1981), PhD candidate (full time); Patrick S. Majors, PhD candidate (full time); and Instrumentation Engineer William R. Mielke (20% time). Brian is in his fourth year on the program and is responsible for the experimental investigation using the reversing DC potential drop method as a potential measure of damage. Pat is in his second year on the program and his theoretical studies cover the finite deformation and modeling of recovery in the context of the viscoplasticity theory based on overstress.

Technical ProgressPublications

"Viscoplasticity Theory Based on Overstress Applied to the Modeling of Cubic Single Crystals," S. H. Choi and E. Krempl, Constitutive Laws for Engineering Materials, Recent Advances and Industrial and Infrastructure Applications, Proceedings of Third International Conference on Constitutive Laws for Engineering Materials: Theory and Applications, Tucson, AZ, January 7-12, 1991, C. S. Desai, E. Krempl, G. Frantziskonis and H. Saadatmanesh, editors, ASME Press, New York, NY, 251-254 (1991).

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"Rate Sensitivity and Short-Term Relaxation Behavior of AISI Type 304 Stainless Steel at Room Temperature and at 650°C; Influence of Prior Aging," M. B. Ruggles and E. Krempl, Transactions of the American Society of Mechanical Engineers, Journal of Pressure Vessel Technology, **113**, 385-391 (1991).

"The Rate(Time)-Dependent Mechanical Behavior of Modified 9Cr-1Mo Steel. I. Experiments at 538°C," M. B. Ruggles, S. Cheng and E. Krempl, SMiRT 11 Transactions, **L06/2**, Tokyo, Japan, 145-150 (1991).

"The Rate(Time)-Dependent Mechanical Behavior of Modified 9Cr-1Mo Steel. II. Isothermal Modeling at 538°C Using Viscoplasticity Theory Based on Overstress," P. S. Majors, E. Krempl and M. B. Ruggles, SMiRT 11 Transactions, **L06/2**, Tokyo, Japan, 157-162 (1991).

"Modeling of Recovery of State Using the Viscoplasticity Theory Based on Overstress," E. Krempl and P. S. Majors, Creep in Structures, 4th IUTAM Symposium, Cracow, Poland, 1990, M. Życzkowski, editor, Springer-Verlag, Heidelberg, Germany, 121-130 (1991).

"A Recovery of State Formulation for the Viscoplasticity Theory Based on Overstress," P. S. Majors and E. Krempl, High Temperature Constitutive Modeling - Theory and Application, MD-Vol. 26, AMD-Vol. 121, A. D. Freed and K. P. Walker, editors, American Society of Mechanical Engineers, New York, NY, 235-250 (1991).

Presentations - Invited

"A Recovery of State Formulation for the Viscoplasticity Theory Based on Overstress," Seminar, Department of Mechanical Engineering, University of Tokyo, Tokyo, Japan, July 23, 1991.

"Viscoplasticity Theory Based on Overstress and Its Application to the Modeling of Metals and Alloys," The Sixth International Conference on Mechanical Behavior of Materials, Kyoto, Japan, July 28-August 2, 1991.

"Modeling of Cyclic Hardening Phenomena Using the Viscoplasticity Theory Based on Overstress," Department of Mechanical Engineering, Hokkaido University, Sapporo, Japan, August 5, 1991.

"A Recovery of State Formulation for the Viscoplasticity Theory Based on Overstress," P. S. Majors and E. Krempl, Workshop on "Modeling of High Temperature Structural Performance of Engineering Materials," Basingstoke, UK, November 4-6, 1991.

Presentations - Contributed

"Viscoplasticity Theory Based on Overstress: The Modeling of Biaxial Cyclic Hardening Using Irreversible Plastic Strain," S.-H. Choi and E. Krempl, ASTM Symposium on Multiaxial Fatigue, San Diego, CA, October 14-15, 1991.

"A Recovery of State Formulation for the Viscoplasticity Theory Based on Overstress," P. S. Majors and E. Krempl, American Society of Mechanical Engineers Winter Annual Meeting, Atlanta, GA, December 1991.

Short Technical Description

Modeling and Theoretical Studies

Modeling has progressed in two different areas which will ultimately be merged. The first area is the development of a recovery of state formulation for the small strain viscoplasticity theory based on overstress (VBO). The second area is the further development of a finite deformation version of VBO.

The present state of a recovery of state formulation for the small strain VBO is summarized by Majors and Krempl (1991). The version presented there was specifically based on the modified 9Cr-1Mo experimental data obtained at Rensselaer under contract with ORNL. The formulation is actually a combination of two recovery terms. An equilibrium stress recovery term following a Baily-Orowan type format is used to aid in the modeling of creep. Using this term, primary, secondary, and tertiary creep can be modeled at stress levels in the quasi-elastic range. The equilibrium stress recovery term does not, however, reproduce the strain rate history dependence which has been observed in the 9Cr-1Mo; therefore, a new recovery term was introduced which influences primarily the isotropic stress through a "recovery modified inelastic strain path length." With the addition of this term, VBO has successfully reproduced strain rate history as well as cyclic loading experiments which were performed on the 9Cr-1Mo material. Strains reached more than 10% and a finite deformation theory will be necessary to model these phenomena adequately.

While the recovery of state formulation was being completed, the existing finite deformation version of VBO was being reevaluated and refined. In the existing version, a modified Jaumann rate is used as the objective rate. It was chosen as a convenient measure. The present study gives a rationale for the choice of the objective rate by using a convected derivative approach in conjunction with a decomposition of the deformation gradient into elastic and inelastic components. The elastic component of motion is now hyperelastic (truly elastic), instead of hypoelastic but has essentially the same characteristics as the previously employed hypoelasticity law. Using a convected derivative argument, the hyperelastic relation can be written in exact rate form, thus implying a unique preferred objective rate for the applied stress, which is related to the postulated constitutive equation for the elastic deformation. A similar logic is then used to suggest a preferred objective rate for the state variable kinematic stress which is associated with the inelastic deformation. This objective rate is derived from the more general case of compressible inelastic deformation and is subsequently specialized for the common assumption of incompressibility. Incorporating hyperelasticity and compressible inelasticity provides for modeling of reversible second order effects (e.g. Poynting effect) and of small volume changes which could accompany dislocation climb at high temperatures. Numerical implementation of the reformulated finite deformation model and comparison to the previous version are underway.

Experimental Studies

The aim of the experimental research is to measure the mechanical response and the changes in potential drop during high temperature biaxial low-cycle fatigue of Type 304 Stainless Steel, an alloy for primary structures in high temperature nuclear reactors. Reversing direct current is used to measure the voltage drop between probes spot welded to the tubular specimen gage section while the specimen is being subjected to axial and torsional loadings in the MTS servohydraulic computer-controlled testing machine. The

voltage drops are in the microvolt range and their changes have to be monitored during the tests performed at elevated temperature and lasting several days. Several torsion tests had been run. Data analysis showed the need for improvement of the experimental techniques. Changes which were subsequently introduced include the installation of a passive filter bank to reduce the electrical interference from the induction heater; continuously adjustable induction heating coil positioning to improve the temperature profile; a complete redesign of thermocouple and voltage probe connections and cabling to reduce electrical noise pick-up; and the installation of a new A/D board for the measurement of voltage drop and thermocouple output.

Several tests were run in torsion at 650°C lasting up to a week. As the test progressed, the temperature profile changed more than $\pm 3^\circ\text{C}$. These large changes could not be avoided and were attributed to changes in the microstructure which in turn caused changes in electrical resistivity and thermal conductivity. Since 650°C is a very high temperature for this material, it was then decided to change the test temperature to 538°C which is close to the intended operating temperature of Type 304 Stainless Steel. In the tests at 538°C, the temperature profile was found to be within $\pm 3^\circ\text{C}$, which was considered to be satisfactory.

Research Plans for the Period August 1, 1992 through July 31, 1993

The theoretical studies will continue with the numerical implementation of the finite and static recovery theory into a computer program capable of simulating numerical experiments which are analogues of the real experiments. The material functions of the theory will be determined from our own tests or from tests found in the literature. Computed results will be compared with experimental data to determine the capability of the theory and to develop it as a constitutive equation suitable for use in stress analysis of high temperature components.

The experimental program will be continued at 538°C and will include torsional, axial, and axial-torsion tests. Also, the potential drop will be monitored on specimens exposed to temperature only (no mechanical loading). This "calibration test" is intended to measure the voltage drop changes due to the exposure to temperature alone (changes in the microstructure may cause resistivity changes). Data analysis will attempt to isolate the damage signal using "calibration tests" and other means. The results will be incorporated into a viscoplasticity theory modified to include damage.

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