Mechanical Testing Using Direct Control of the Inelastic Strain Rate

by E.W. Hart and H. Garmestani

ABSTRACT—A methodology is described for carrying out mechanical tests under direct control of the inelastic strain rate. The method depends on the use of a servohydraulic testing machine and suitable electronic-control circuitry. The technique permits the use of abrupt changes of inelastic strain rate as well as maintenance of constant values of inelastic strain rate. The application of the method to several modes of testing is described.

Introduction

The data for the deduction and validation of the laws of inelastic flow of structural materials are derived from a variety of test configurations. Testing is carried out in uniaxial tension and also in biaxial tension-torsion and tension internal-pressure configurations of thin-walled cylinders. The greatest majority of tests are carried out in uniaxial tension, and the principal tests currently employed maintain one of the test-parameters constant. The controllable test parameters can be extension, true strain, inelastic strain, load, and stress.[1, 2] Other tests have also been devised to examine the transient behavior after an abrupt change in a control parameter.[3-7] These transients can occur in the strain transient 'dip' test; the extension- rate change test; and the load-relaxation test. All the test methods have had a considerable history of application and of theoretical discussion.

It is the purpose of the present, paper to describe and analyze the *controlled inelastic strain-rate test.* Tensile tests under the direct control of inelastic strain have been performed using servohydraulic machines under computer control to investigate the cyclic and monotonic behavior of materials.[8-11] Such tests seem to be important but very little data are reported in the literature. Most prior usage has been restricted to cyclic loading. Elimination of elastic contribution from both specimen and machine compliance becomes important in a variety of other testing configuration including strain-rate-change test.

Due to the experimental difficulty in isolating the plastic and elastic components of strain rate, *the constant plastic-strain-amplitude test* that is commonly performed under total strain or extension control[5-7, 12-13] is the common alternative experiment. The plastic-strain limit test has been used to determine the fatigue life of deformed materials at very low plastic-strain cycles. The accumulated effect of small inelastic strain increments can result in changes in the microstructure of the material. This may effect the ultimate material failure. For a given plastic-strain-limit controlled test the inelastic strain-rate changes from a very low value (during the elastic loading) to a maximum (at the limit of the plastic strain). If the material parameters of interest are rate dependent, this experiment may not be adequate.

As noted above, there are some earlier reported uses of direct control of the inelastic strain rate. The principal earlier work is that of Mughrabi. This work is summarized in Ref. 9. All the work reported there is for cyclic behavior. Furthermore, the experimental details are lacking. In particular, the strain and time resolution of the testing is not available. The other reported work is that of Hart and Garmestani,[8] and that is an internal report that is not easily available.

The work to be described in this paper is a more detailed report of the method and results of Hart and Garmestani.[8, 16] It will be shown that the time resolution of the data points can be better than 1 millisecond, and the strain resolution can be better than 0.2 microstrain for testing with resistance strain gages, and 10 microstrain with an extensometer.

The experimental limitations will be discussed for the different testing configurations. The testing configurations include cyclic loading at constant inelastic strain rate; abrupt changes of inelastic strain from an initial value to a final value; subsequent load relaxation and large inelastic strain and strain-rate experiments. Each of these tests is accompanied by its own stipulations and limitations that should be discussed individually. For example the inelastic strain-rate change test requires fast response of the machine at the time of the abrupt change. A load-relaxation experiment however requires very smooth transition and response with absolutely no drift in the strain response. These requirements can be in contradiction at times. The system is inherently unstable as a result of the introduction of a second closed-loop circuitry. Understanding of these instabilities and their elimination adds another important variable to this mode of testing.

Theoretical Background for the Test

The experimental configuration employs a resistance strain gage mounted directly on the tensile, specimen, and, since the strain gage delivers a signal directly proportional to the total true strain ε_t, the inelastic true strain ε is given to a high accuracy by the relation

$$\varepsilon = \varepsilon_t - e \tag{1}$$

where e is the specimen elastic strain. Furthermore the elastic strain is

$$e = \frac{\sigma}{E} \tag{2}$$

E.W. Hart is Professor, Cornell University, Theoretical and Applied Mechanics, Ithaca, NY 14850. H. Garmestani is Assistant Professor, FAMU/Florida State University, College of Engineering, 2175 Mechanical Engineering, Tallahassee, FL 32316-2175

Original manuscript submitted: December 6, 1991. Final manuscript received: June 25, 1992.

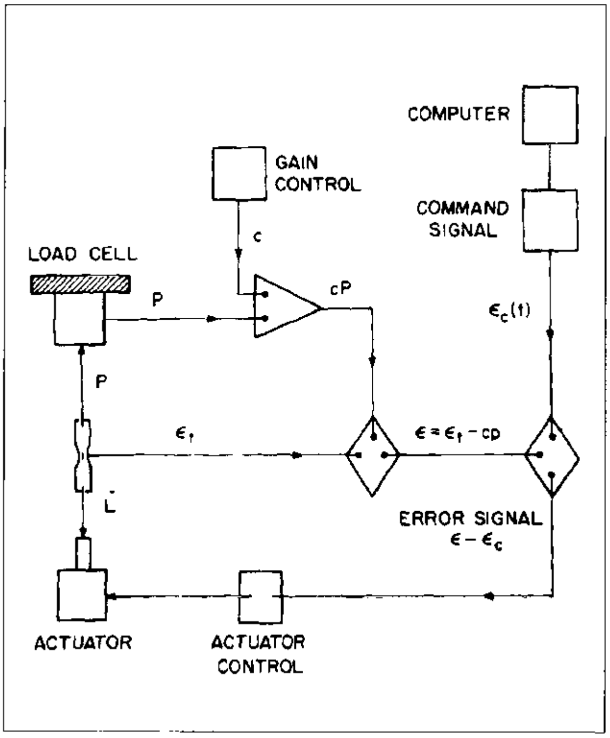

Fig. 1—Schematic diagram for control of inelastic strain in tensile testing

where E is Young's modulus, and σ is the true stress. Since σ is determined by the load P and the specimen geometry, we may express e in terms of the measured P by

$$e = CP \qquad (3)$$

The constant C increases very slightly and the error is proportional to e/A_0E which corresponds to a maximum error of 0.01 percent for experiments performed here. This constant can be elected so that the elastic strain is compared directly with ε_t and so

$$\varepsilon = \varepsilon_t - CP \qquad (4)$$

A general experimental configuration is shown schematically in Fig. 1.

A servohydraulic testing machine with analog circuitry provides a command signal $\varepsilon_c(t)$ that can be compared electronically with the current value of the inelastic strain ε. The difference between ε and ε_c provides an error signal that drives the actuator. The actuator drives the load train so that the error signal is held as close to zero as possible.

The imposed strain rate $\dot{\varepsilon}_c$ is controlled by an analog function generator that is in turn controlled by a digital computer and an analog-digital interface. It is possible to program the command signal so that any command change is effected in a time interval less than 0.01 milliseconds.

Experimental Implementation of the Test

The advancements made in electrohydraulic control systems over the last few decades have led to vast improvements in our ability to control events that occur over very long or short time spans. Application to systems that operate by closed-loop feedback control is growing rapidly. In closed-loop testing machines a signal from a selected feedback control transducer is subtracted from the desired function voltage. The feedback signal transducer can be either load, stroke or strain. The desired function voltage can be selected from a function generator or the computer. The difference between the two signals is amplified and by the action of the proper electronics causes the selected parameter to follow the desired control signal.

The testing machine employed in the present work is an Instron Model 1321 tension-torsion servohydraulic machine. A general layout of the original, unmodified closed-loop test system is shown in Fig. 2. The system operation, starts with the active feedback sensors. Both stress and strain measurements are taken from bridge circuits whose output is amplified by machine signal conditioners. The method of controlling constant inelastic strain rate requires that a signal proportional to the load-cell feedback

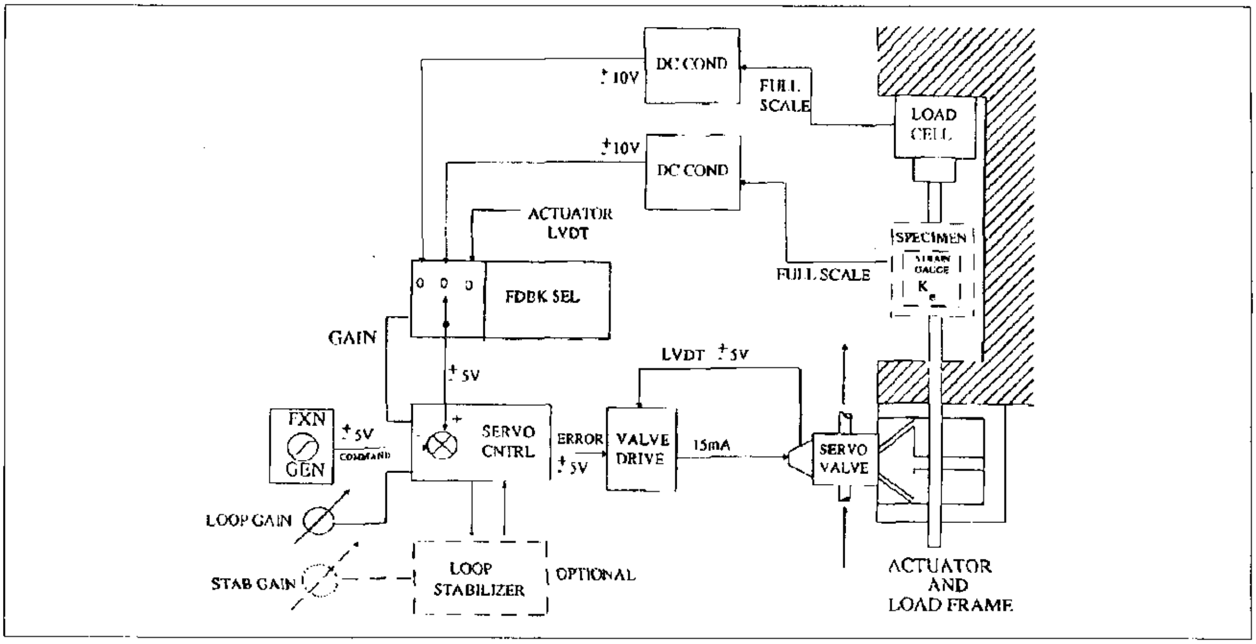

Fig. 2—Schematic diagram of a regular servohydraulics closed-loop system. Common in most tensile testing machines like MTS or Instron

be subtracted from the strain-gage input signal in real time arid that the resultant difference be used as the active feedback signal. The general modified system is depicted in Fig. 1. Regardless of the actual feedback parameter used, it is the command function that determines the steady-state characteristics at the servocontroller output. This constitutes a system with an additional closed-loop circuit. There are other closed loops inherent within the system. The valve controller is part of an inner feedback loop that is used to assure accurate positioning and optimal response to the servocontroller output (error signal).

To use the modified test system for constant inelastic strain-rate testing, a thorough understanding of the system's input constraints is required. Among the critical parameters that must be considered for this test method are: specimen cross section, feedback loop gain, Young's modulus, command strain rate, and maximum actuator velocity. For instance, the maximum actuator velocity is vital to system stability because, prior to the onset of plastic material deformation, the servocontroller output error signal is steadily Increasing. If the actuator velocity is allowed to increase in a corresponding fashion past a critical level, the system may break into oscillations at the onset of plastic strain because of the rapidly changing error signal.

To measure the elastic modulus some preliminary tests were required. One of the problems associated with the measurement of the elastic modulus is the contribution of anelasticity to the total strain. Anelasticity is a viscous phenomenon[14, 15] and its contribution to the total strain can be effectively reduced by making the measurements at high frequency. Calculating the total strain using a viscoelastic model can yield

$$\varepsilon_t = \frac{\sigma}{E} + \frac{1}{\mu}\left[\sigma - f(\dot{\varepsilon})\right] \tag{5}$$

where μ is the anelastic modulus, and f is the anelastic parameter that depends on the inelastic strain rate. As the inelastic strain rate $\dot{\varepsilon}$ is increased, the second term becomes negligible. A Nicolet digital oscilloscope data-acquisition system was used to measure the elastic modulus as the, slope of the stress-strain curve. The variation of elastic modulus from several tests shows an error of two percent. The elastic modulus determined using this method can then be used in the closed-loop circuit to control the inelastic strain rate directly.

A circuit design to generate an analog output proportional to the difference between load and total strain is shown in Fig. 3. It consists of resistive and capacitive circuit elements and five operational amplifiers including a voltage follower that is tapped off the unmodified strain feedback signal to limit sensors. This circuit was connected to the strain-controller circuit of an Instron Model 1321 tension/torsion tester and operated with a Unit gam. The operational amplifier IC1 provides the total strain signal for measurement and limit detection (if desired).

The inelastic strain-rate-controlled circuit consists of 14 discrete components that were added for specific applications during the development of the system.[14] For use with the Instron 1321 system, connection of circuit was made by splicing it between two buffer amplifiers on the strain-controller board. This adaptation, which places a 100-Kohm load at the output of an amplifier that had been connected to two voltage follower circuits (input impedance approximately 400 Mohms) may have some detrimental effects on system performance. For these reasons, all system modifications should be connected between the control boards at output points that are designed to be less susceptible to load differentials than internal circuitry.

The servohydraulic gain circuitry improves the dynamic response of the machine independent of the additions that are introduced here. The time response of the machine should correspond to the expected theoretical requirement or the type of test performed. As an example, one of the problems associated with any kind of abrupt change in a control parameter is the overshooting associated with the change. This is a direct result of the response of the machine that relates to the internal machine gain

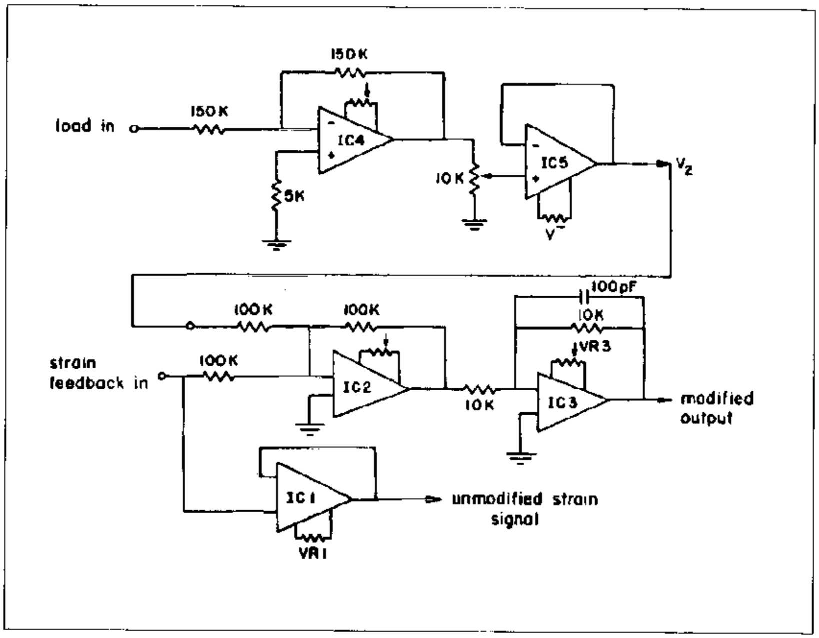

Fig. 3—Schematic diagram of the electronic feedback circuitry

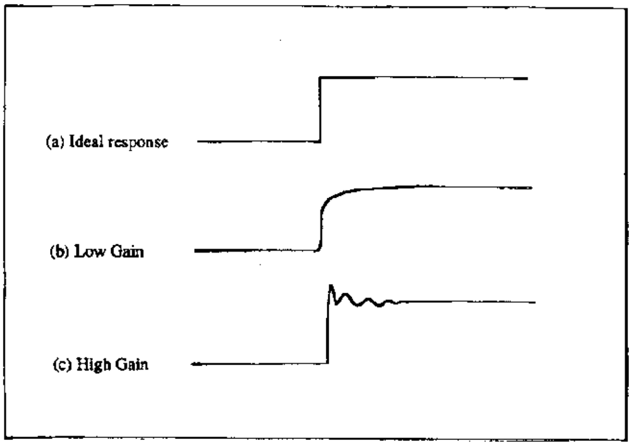

Fig. 4—Machine response due to different gain settings

circuitry. Increasing the gain results in an Increase in machine dynamic response. However this results in an overshoot in the stress history. On the other hand decreasing the gain or adding an integrator will result in a slow response. Figure 4 shows these two extremes.

Some Test Applications

The general experimental behavior of inelastic control machines can best be discussed with the kind of experiments that are of interest. Three different kinds of experiments are discussed here. These are: cyclic loading at constant inelastic strain rate; abrupt changes of $\dot{\varepsilon}$ from an initial value $\dot{\varepsilon}_i$, to a final value $\dot{\varepsilon}_f$; subsequent relaxation of σ when $\dot{\varepsilon}_f = 0$. This last experiment is a new kind of load relaxation performed under constant inelastic strain.

The first attempts to implement the circuit that uses constant inelastic strain rate as a control parameter yielded excellent experimental results.[8] For these experiments, strain gages were mounted on the specimen to obtain very high strain resolution. The strain gage and the load-cell gage were excited by a high precision d-c power supply for high stability and resolution. The strain measurement had an accuracy of about 10^{-7} at strain rates of about 4×10^{-5} S-1 or higher. At inelastic strain rates of 10^{-5} S-1 or less the strain was controlled within 5.0×10^{-7} strain. The data were electronically integrated over 60 Hz to reduce the noise. It was then recorded at 33 millisecond time intervals with an a/d data rate of 1 kHz.

The strain precision and accuracy can test understood by reference to Fig. 5. Here a strain rate change of a factor of four has been imposed in' the' middle of the test. The accuracy of the test can be seen in the strain scale that is in microstrain. The variation in strain is about 5.0×10^{-7} strain as can be seen from the figure. The strain-rate change occurred with no discontinuity in strain. The sharp transition in the inelastic strain rate is a measure of the success of the test.

Inelastic Strain-rate Cyclic Loading

Cyclic stress-strain curves are useful for assessing the durability of structures and components subjected to repeated loading. It has long been realized that only the plastic component of the total strain is the determining factor in material failure. The response of a material subjected to cyclic inelastic loading has the form of a hysteresis loop. The different loops are obtained using the incremental step test. One specimen is subjected to a series of blocks of gradually increasing and decreasing strain amplitude. After a few cycles the material stabilizes. The use of strain gages has proved to be ideal for cyclic loading at small inelastic strain (less than 5000 $\mu\ \varepsilon$) with direct control of inelastic strain rate. The use of clip-on gage transducers restricts the experiments to tests that require an accuracy of only 10^{-4} strain. At inelastic strain cycle amplitudes of 100-1300 $\mu\ \varepsilon$ and strain rates of ~10^{-5} (S-1) very stable cyclic loops were obtained for both aluminum (Fig. 6) and nickel (Fig. 7) representing two materials of a soft and hard nature. Complex cyclic histories can also be obtained with a proper computer interface (Fig. 8).

Great care must be taken to ensure adequate temperature-compensation, gage alignment, and bond strength when strain gages are used. In addition the use of strain gages in the plastic range requires careful attention to hysteresis and nonlinearities.[18] Since one of the interesting features of the inelastic strain-rate-controlled test is its ability to isolate the hysteresis effect, it is important to make sure that the observed hysteresis is not a result of strain-gage nonlinearities. Independent tests using calibrated extensometers showed that strain-gage nonlinearities are negligible for the strains up to 3000-4000 $\mu\ \varepsilon$. One advantage of using strain gages in the tensile test is the familiar option of bending-moment compensation obtained by mounting the gages in pairs on opposite sides of the specimen.

Inelastic Strain-rate Change Test

Abrupt strain-rate change tests are used commonly to measure the strain-rate sensitivity and transient behavior of materials.[19, 20] The experiment involves an abrupt change in the controlled

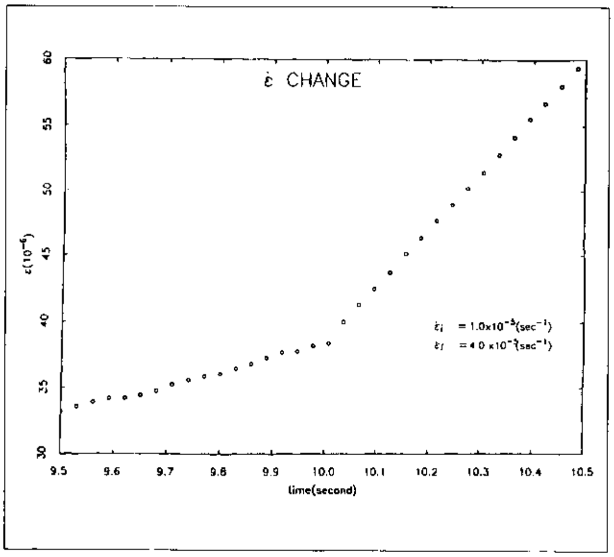

Fig. 5—Abrupt change of inelastic strain rate. High purity aluminum

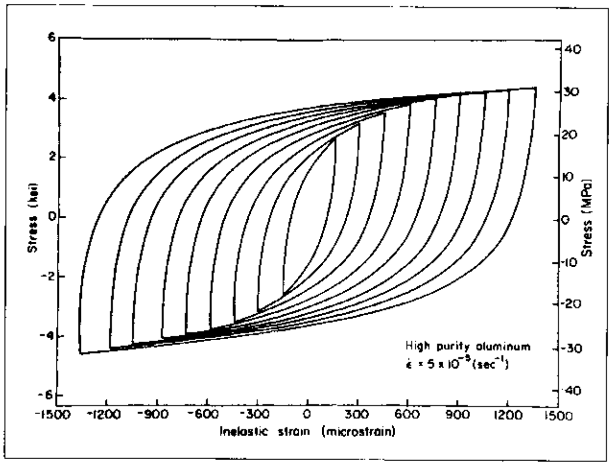

Fig. 6—Subsequent cyclic curves of increasing inelastic strain amplitude for a constant inelastic strain rate experiment. High purity aluminum

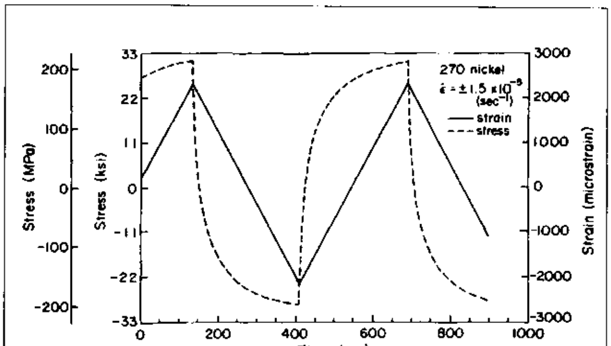

Fig. 7—Closed-loop inelastic strain rate test. 270 nickel

inelastic strain. The stress data are then plotted in time as the output of the experiment. Direct measurement of total strain and stress and a plot of the calculated inelastic strain will ensure the accuracy of the test. Depending on the stiffness of the machine and the specimen the servohydraulic gain has to be adjusted. Figure 9 shows the different behaviors obtained after an abrupt change in the inelastic strain rate. Increasing the gain results in an increase in machine time response. However this results in an overshoot with the stress response. On the other hand decreasing the gain and adding an integrator will result in a slow response. Figure 10 shows an abrupt change of inelastic strain rate by a, factor of 40. The test was performed on a high-purity aluminum specimen. The strain resolution once strain gages are used is about 10^{-7} strain at strain rates of about 10^{-4} (S-1'). Notice the discontinuity in the stress history which is a result of the abrupt change in inelastic strain rate. Such discontinuities represent some internal state of the material.[16] The same discontinuity is also present in Fig. 12.

Load-relaxation Experiments

The load-relaxation test is conventionally performed by loading a specimen in tension or compression to some predetermined load and extension, and subsequently recording the load as a function of time at fixed cross-head position. The best testing requires a rather stiff machine (to minimize the time of the experiment), and good temperature stability and control.[2,3,16] The relaxation time is inversely proportional to the stiffness of the machine plus the specimen. Constant total strain load-relaxation testing reduces the time of relaxation by about a factor of 10 (for a final strain of 10^{-9} S-1). A constant inelastic strain load-relaxation test depends only on the inelastic property of the material under deformation. This test is novel and is not found In the prior literature.

For tests for which the inelastic strain is kept constant for long periods of time (~ days) good strain resolution is vital to the success of the experiment. Strain gages are best for such experiments. The load-relaxation test at constant inelastic strain rate requires the same precautions as the inelastic strain-rate-change tests. However in this test the relaxation part requires a lower gain for better stability. It is sometimes better to perform the test at the higher gains and relax the 'specimen at the lower gain. Application of a very low gain results in a drift in the electronics feedback signal for normal hydraulics machines. Figure 11 shows such behaviors for the different gain settings. Figure 12 shows a load-relaxation experiment from an initial inelastic strain rate of 10^{-5} (S-1). The inelastic strain plotted is the measured value and it can be controlled with a resolution of 0.1 microstrain or better.

Constant Inelastic Strain-rate Test

With the modifications introduced here for the inelastic strain circuitry and the use of clip-on extensometers, very large inelastic strain (up to failure) and inelastic strain rates (up to 10^{-1} S^{-1}) can be obtained. Figure 13 is the result of such tests for high-purity aluminum at different strain rates.

Discussion

The main question about the controlled inelastic strain- rate, testing is whether or not the intended control can be carried out. The reason for such a question can be seen in the equation

$$\dot{\varepsilon}_I = \frac{\dot{\varepsilon}}{1 - \frac{1}{E}\left(\frac{d\sigma}{d\varepsilon_I}\right)} \qquad (6)$$

obtained by differentiating eq (1). It is clear that to hold the inelastic strain rate ($\dot{\varepsilon}$) constant requires the machine to be capable of indefinitely large values of $\dot{\varepsilon}_I$. Of course the values of $\dot{\varepsilon}_I$ are eventually limited by the extension-rate capabilities of the machine. There is then always a small region for which eq (6) will not be satisfied. Fortunately in almost all tests that region is very small compared to the times for which eq (6) is satisfied. This point is also discussed by Mughrabi.[9]

The use of strain gages results in severe limitations in the operating temperature range. Most strain gages are designed for

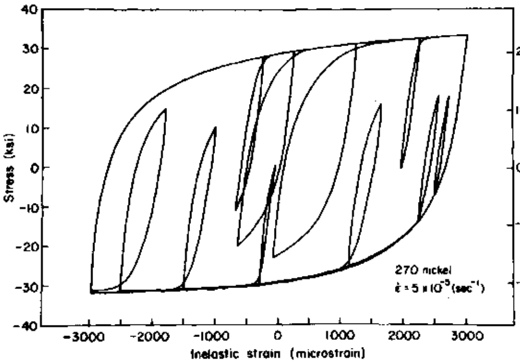

Fig. 8—Complex loading history for cyclic reloading experiments performed within the inelastic strain amplitude. 270 nickel

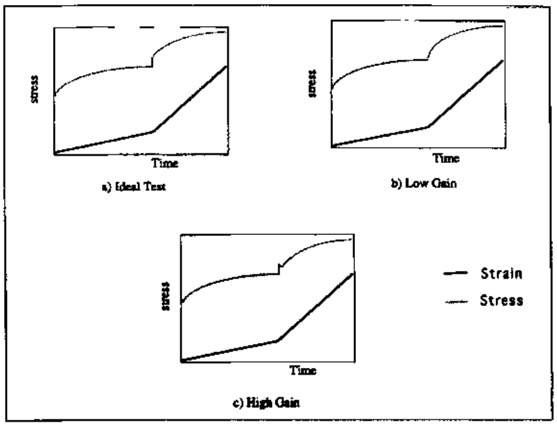

Fig. 9—Schematic diagram for the controlled inelastic strain rate change test at different gain settings

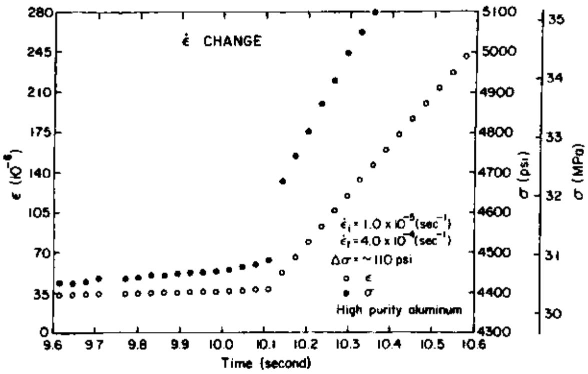

Fig. 10—Abrupt change of inelastic strain rate by a factor of 40. High purity aluminum

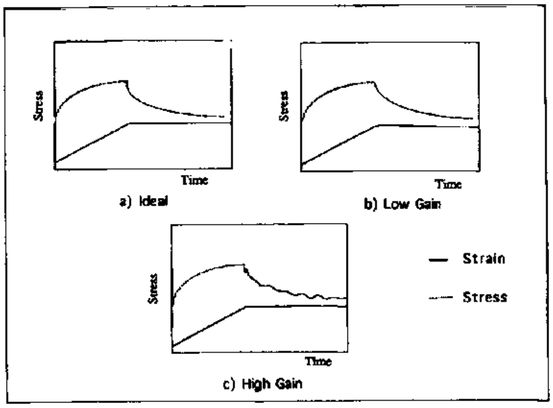

Fig. 11—Schematic diagram of the controlled inelastic strain rate load relaxation test at different gain settings

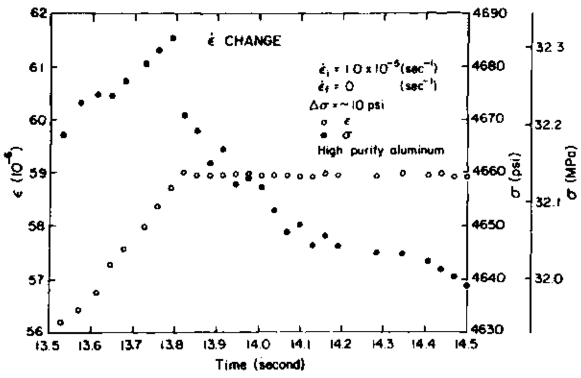

Fig. 12—Abrupt change of the inelastic strain rate to zero. High purity aluminum

room-temperature operation. High-temperature extensometers are used as alternatives to strain gages for high.temperature use but they result in very low strain resolution (10^{-5}).

Conclusion

Controlled inelastic strain-rate experiments have been successfully performed. We describe several test configurations. The most important of these are the tests with constant inelastic strain rate and abrupt change of inelastic strain rate. The limitations of the test are few and are discussed above.

Acknowledgment

The work reported here was supported by the National Science Foundation through the Material Science Center of Cornell University. We wish to acknowledge helpful discussions with Profs. C.Y. Li and A. Ruina and technical assistance by Mr. Jason Cortell from Cornell University and John Siemon from Yale University.

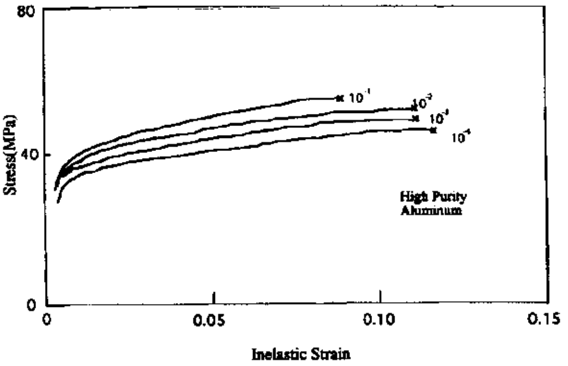

Fig. 13—Controlled inelastic strain rate experiments until failure. High purity aluminum

References

1. Hart, E.W., "Theory of the Tensile Test," Acta Met., **15**, *351-355 (Feb. 1967).*

2. Lee, D. and Hart, E.W., "Stress Relaxation and Mechanical Behavior of Metal", Met. Trans., **2**, *1245-1248 (April 1971).*

3. Hart, E.W. and Solomon, H.D., "Load Relaxation Studies of Polycrystalline High Purity Aluminum," Acta Met., **21** *295-307 (March 1973).*

4. Ahlquist, C.N and Nix, W.D., Acta Met., **19**, *373 (1970).*

5. Yoshinaga, H.Z., Horita, and Kurishita, H., Acta Met., **29**, *1815-1824 (1981).*

6. Champion, H.O., Duesbery, M.S. and Saimoto, S., "Elimination of Machine Transient Effects During Plastic Strain Rate Changes," Scripta Met., **17**, *135-140 (1983).*

7. Bayerlein, M., Christ, H.-J. and Mughrabi, H., "A Critical Evaluation of the Incremental Step Test,"

8. Hart, E.W. and Garmestani, H., "Uniaxial Tensile Testing With Direct Control of the Inelastic Strain Rate," MSC Report No. 6465, Cornell Univ. (Sept. 1988).

9. Mughrabi, M., "Neure Ergebnisse der Ermudungsforschung mit praktischer Relevans - Grundlagenaspekte der Wechselverformung," Berichtsband DGM-Fachkonferenz Werkstoffverhalten und Bauteilbemessung, Karlsruhe, DGM Informationsgesellschaft Oberusel, S.49-65 (1987).

10. Christ, H.J. Springer-Verlag, Berlin, ISBN3-540-53962 (1991).

11. Zarte, R., Petry, F., Crist, H.J. and Mughrabi, H., ASTM, San Diego (Oct. 1991).

12. Mughrabi, M., Herz, K. and Stark, X., "Cyclic Deformation and Fatigue Behavior of α-iron, Mono- and Polycrystals," Int. J. Fract., **17** *(2). (April 1981).*

13. Baker, J.P., Lisiecki, L.L. and Weertman, J.R., "Methods of Extending the Performance of Commercial Materials-Testing Machines in Plastic Strain-Limit Control," J. Exp. Tech., 26 (Oct. 1988).

14. Zener, C.M., Elasticity and Anelasticity of Metals, Univ. of Chicago Press (1948).

15. Hart, E.W., Trans. ASME, J. Eng. Mats. & Tech., **98**, *193 (1976).*

16. Garmestani, H., "An Experimental Investigation of Transient Deformation Using Controlled Inelastic Strain Rate Experiments," PhD Thesis (May 1989).

17. Siemon, J., "Modification of a Closed Loop Tensile Test System for Constant Plastic Strain Rate," Special Investigation, Yale Univ. (Dec. 30, 1988).

18. Rees, D.W.A., "The Sensitivity of Strain Gauges When Used in the Plastic Range," Int. J. Plasticity. **2** *(3), 295-309 (1986).*

19. Alden, T.H. and Gibeling, J.C., Proc. 6th Int. Conf. of Strength of Metals and Alloys, Ed. R.C. Gifkins, Pergamon Press, Oxford, 741 (1982).

20. Alden, T.H. "Load Relaxation in Aluminum: I. Theory of Plastic Deformation. II. Plastic Equation of State," Met. Trans., 8A, 1675-1687.