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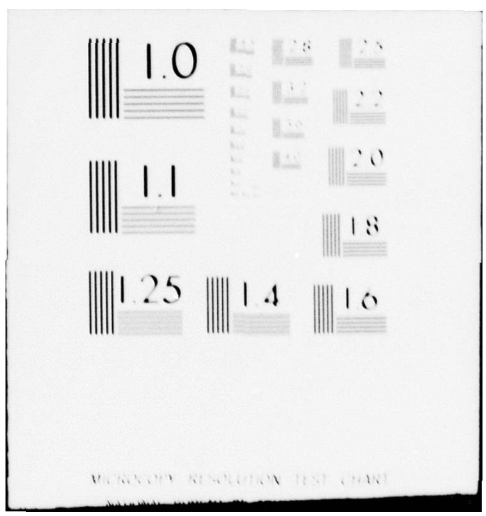
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AMMRC TR 78-37

BIAXIAL TESTING TECHNIQUES OF THIN-WALLED TUBULAR SPECIMENS

JAMES H. RAINEY, RONALD A. SWANSON, and SHUN-CHIN CHOU
BALLISTIC MISSILE DEFENSE MATERIALS PROGRAM OFFICE

September 1978

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Watertown, Massachusetts 02172

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ABSTRACT

A biaxial testing technique of a thin-walled tubular specimen is described. The specimen was loaded with a combination of axial tension/compression and internal/external pressure. The technique can be used to test tubular specimens of any material. The yield surface of 2014-T651 aluminum was determined to illustrate the testing technique and data analysis.

CONTENTS

I. INTRODUCTION

The response of materials under multiaxial stress states beyond the elastic range is an essential part of the mechanical properties required by designers of structures. This report describes a technique to test material in the form of a thin-walled tube under axial and tangential (hoop) stresses. A brief description of the mechanical testing machine and information of an automated data acquisition and control system are presented. The automated control parameter determination and some experimental data of aluminum alloy 2014-T651 are also discussed.

II. TESTING TECHNIQUES

The equipment (Figure 1) required to perform the biaxial testing of tubular specimens can be described in three major components: namely, the medium strain rate machine, intensifier system, and data acquisition and control system.

The medium strain rate machine (MSRM) is used to generate the axial tensile or compression stress, while the intensifier system provides the tangential (or hoop) tensile or compression stress in a tubular specimen. The data acquisition and control system records and stores all data and generates command signals for both machines.

A. Medium Strain Rate Machine

The MSRM is a dual-mode test machine capable of generating 140,000 pounds axial tension or compression. The two modes of operation are an open loop system, and a closed loop servohydraulic system. The open loop system has the capability of strain rates from 1 to 50 sec^{-1}, but it is not normally used in biaxial testing. The closed loop system will produce strain rates from 10^{-5} to 10^{-1} sec^{-1}.

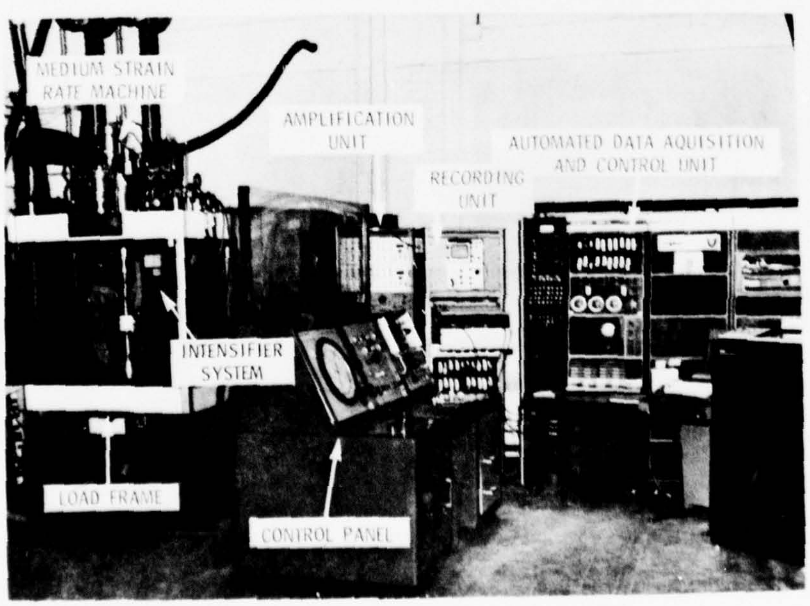

Figure 1. Automated materials characterization system.

The MSRM control panel gives the operator a selection of four different feedback control modes: load, displacement, strain, and optional. Therefore, with proper command inputs, tests at constant rates of load, displacement, and strain are performed. The operator may select one of many different load cells to achieve the best control over the desired testing range. The machine is equipped with a 15-gpm hydraulic power supply and a 15-gpm servovalve. Various fail-safe and limiting devices which either display a warning light or cause a machine shutdown are incorporated into the control system.

The MSRM load frame is designed for a stiffness greater than 15×10^6 lb/in. and has a total machine stretch of 0.005 inch at 140,000 lb load.

B. Intensifier System

The closed loop servohydraulic intensifier system used for the biaxial internal and external pressure testing is capable of generating a pressure of 100,000 psi. The intensifier vessel has a 1-inch inside diameter with an 8-inch length giving a volume of about 6 cubic inches. A Haskell air-driven pump is used to fill the intensifier system with Stoddard solvent as the pressurizing fluid. This fluid has a freezing point well in excess of seven kilobars.

The intensifier control panel gives the operator a selection of four different feedback loops: load, strain, displacement, and optional. With the proper command input, constant rates are possible under closed loop control. In essence, the intensifier system is a testing machine by itself. Different pressure transducers can be used so that the best control is available over the pressure range of interest. Pressure control is used in the optional mode. System pressure is also monitored using a precision Heise gage with a capacity of 100,000 psi. The intensifier uses the same hydraulic power supply as the medium strain rate machine.

C. Data Acquisition and Control System

The computer configuration consists of a central processor, 4K words of basic memory plus 12K words extended memory, real-time clock, relay register, 1.6 million word disk, two magnetic tape drives, teletype and line printer, display screen, multiplexed analog-to-digital converter (16 channels), and three digital-to-analog converters. The system interface includes eight active filters and scaling amplifiers.

The digital computer has a central processor which uses its memory to hold the operating system, to store programs during execution, and for temporary storage of data.

Command signals are generated by the central processor and sent to the digital-to-analog converters at a predetermined interval by the real-time clock. The converter changes binary numbers (12BITS), which are the internal information base of the computer, to an analog voltage (± 10V) that is acceptable to the servocontroller of the test machines. The controllers operate in a closed-loop mode generating a signal which drives the electrohydraulic servovalves. The servovalves regulate the flow of oil from the hydraulic power supply, to the test machine actuators, which deform the specimen. The specimen load, pressure, strains, and displacements are continuously monitored and input into the computer. These analog signals are filtered to remove noise and scaled to match the input range of the analog-to-digital converter. The multiplexer selects one of the 16 channels for input to the analog-to-digital converter according to the program. A sample-and-hold circuit holds the value while it is converted to a binary number for input into the central processor. The data are stored in memory, then either displayed on the screen, printed, or stored on magnetic tape or disk. A second command signal may now be sent to other machines through a different digital-to-analog converter channel, based on the data received from the first signal. The real-time clock is used to determine sampling intervals, command intervals, and signal events. The teletype or console is used to input programs and parameters to the central processor. The magnetic tape units and disk provide fast access mass storage for programs and data. The relay register is used for additional control of the test machines and external equipment.

D. Specimen Configuration and Grip Fixtures

The thin-walled biaxial tubular specimen configuration shown in Figure 2 is designed for both internal and external pressure testing. The specimen designated as 601066-02 has a shorter gage length and overall length in comparison with the 601066-01 specimen. The shorter specimen is used to prevent premature buckling failure before the material reaches its yield stress when the specimen is subjected to compression in both axial and tangential directions.

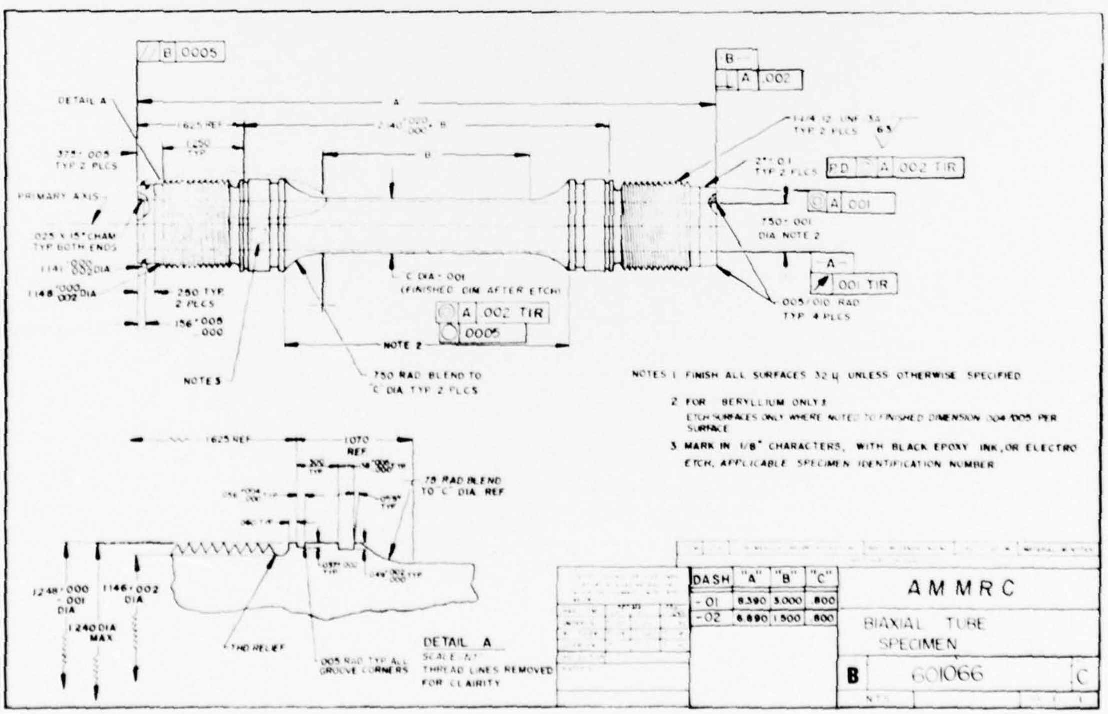

Figure 2. Specimen configuration for internal and external pressure tests.

In order to maintain the stress state in the specimen as close to a state of plane stress as possible, the wall thickness at the gage length is 0.025 inch, which results in an 8% difference in the tangential stress at the inner and outer radii.

The tensile tangential stress is created through the use of an internal plug assembly as shown in Figure 3, while the compression tangential stress is generated with a sleeve arrangement as shown in Figure 4. The external pressure assembly is shown in Figure 5. The pressurized fluid in the plug or sleeve is controlled by the intensifier system, and the pressure inside the plug or sleeve is contained by the use of "O" rings at both ends of the assembly.

The other precaution one must take in testing tubular specimens is that it is essential to maintain a homogeneous strain field in the gage section. This can be accomplished by a precise alignment procedure. A threaded collar containing eight bolt holes is threaded on each specimen end, having approximately 0.25 inch of the specimen exposed. The taper on the exposed ends of the specimen allows an initial alignment of the specimen with respect to the loading frame (see Figure 6). Bolts are then inserted through the collar and threaded to the load frame. While tightening bolts to the load frame, the two axial strain gages on the specimen are monitored to assure that, first, no bending moment is induced through uneven tightening of the bolts; and secondly, zero axial load is maintained. This procedure works very well as test results show that both axial strain gages record nearly identical strains until the specimen approaches failure.

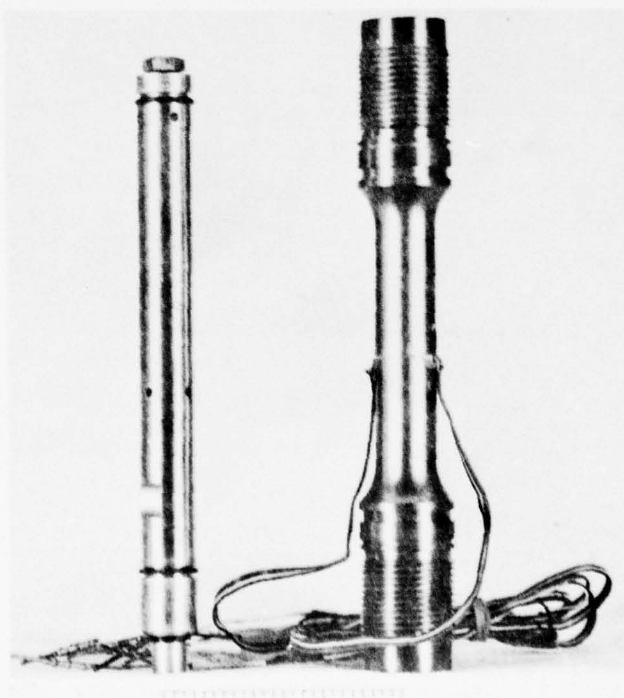

Figure 3. Biaxial internal plug and specimen.
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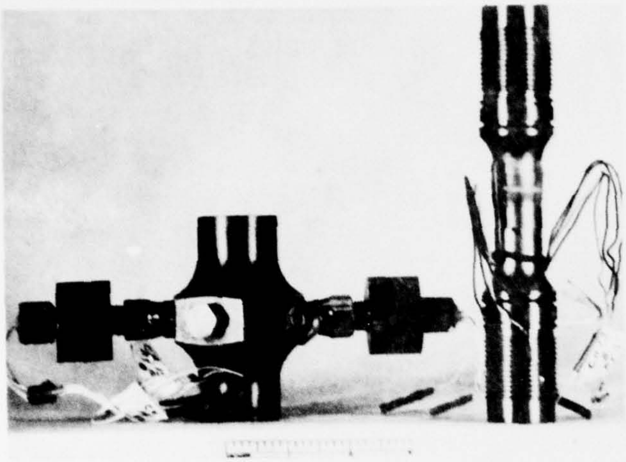

Figure 4. Biaxial external pressure sleeve and specimen.
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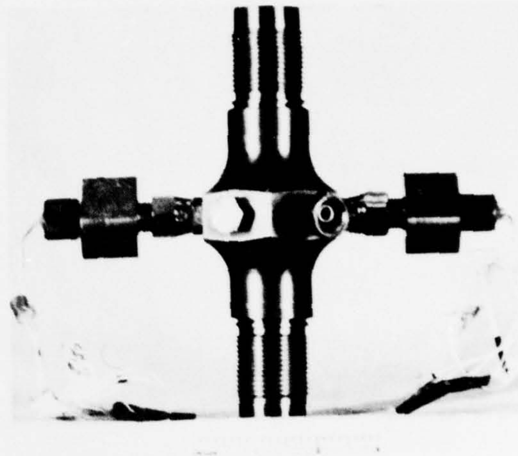

Figure 5. Biaxial external specimen assembly.
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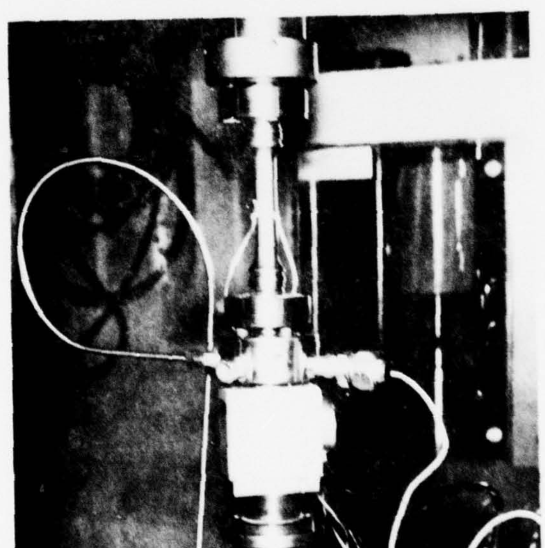

Figure 6. Grip arrangement for biaxial internal pressure test.

E. Specimen Strain Gaging

All biaxial specimens are instrumented with EP08-062TT-120, 90° "tee" rosette strain gages to measure the axial and tangential strains simultaneously. The gaging area is prepared in accordance with the manufacturer's instructions for the particular adhesive being used. Gages are bonded to the specimen with EPY-350 adhesive using a clamping pressure of 10 to 15 psi, and cured for two hours at 350 F. A protective coating of flowable, room temperature curing silicone rubber is used to protect the strain gages from environmental and handling damage. The detailed procedure for gaging specimens can be found in Micro Measurement Instruction Bulletin No. B-127-3, B-130-3, and B-137-2.

At the beginning of this study, four sets of "tee" rosette strain gages were used. They were located at the center of the gage section and placed 90° from each other along the circumference of the tubular specimen. However, since the alignment procedure described in the last paragraph creates a very good homogeneous strain field, it was decided that two sets of "tee" rosette strain gages are sufficient to measure the strain field in the tubular specimen. Test results reported are average values of the two sets of rosette strain gages located diametrically from each other.

F. Testing Control Parameters

Since the medium strain rate machine and intensifier system have separate servohydraulic mechanisms, the axial and tangential stresses (or strains) can, in principle, be controlled at different rates. This operation requires the use of a more sophisticated control theory because the material deformations are interrelated through the Poisson's effect. In this study, each test was carried out along a proportional load path which provides a constant effective strain rate in terms of either axial or tangential strain rate (see the mathematical formulation in the next section), that is, the ratio of the axial and tangential stresses is a constant throughout a test. As described in the section on "Data Acquisition and Control System," the signals from load cell and strain gages were magnified by the gage conditioning units; therefore, it would be logical to use the dominant strain as the control parameter. If the dominant strain is not controlled, it is possible that machine "runaway" might occur and the specimen would fail prematurely. For the case when the ratio of axial stress to tangential stress ($R=\sigma_A/\sigma_\theta$) is greater than or equal to unity, the axial strain is the control parameter and the computer program sends the command signal to the intensifier system to either increase or decrease the internal (or external) pressure so that a constant stress ratio will be maintained. On the other hand, when $R<1$ the tangential strain will be the control parameter and the axial load is determined through the computer program. This procedure provides the stress ratio within 1% of a desired value.

III. DATA ANALYSIS

The biaxial test data presented here are in the form of effective stress-strain curves to illustrate strain hardening behavior and yield and failure stresses in the two-dimensional stress space. The data are presented in terms of the axial and tangential stresses σ_A and σ_T; the corresponding strains are ε_A and ε_T.

Before discussing experimental results a definition of yield must be made. The definition used here is based on the square root of the second invariant of the stress deviator $\sqrt{J_2}$ plotted against the square root of the second invariant of the strain deviator $\sqrt{I_2}$, where in this study,

$$\sqrt{J_2} = \frac{1}{\sqrt{6}} [(\sigma_A - \sigma_T)^2 + (\sigma_T - \sigma_R)^2 + (\sigma_R - \sigma_A)^2]^{\frac{1}{2}}$$

$$\sqrt{I_2} = \frac{1}{\sqrt{6}} [(\varepsilon_A - \varepsilon_T)^2 + (\varepsilon_T - \varepsilon_R)^2 + (\varepsilon_R - \varepsilon_A)^2]^{\frac{1}{2}}$$

and σ_R is the radial stress and ε_R the radial strain.

The axial and tangential strains ε_A and ε_T are measured strain gage values on the outside surface of the tubular specimen. The radial strain ε_R through the wall of the tube is calculated using elasticity equations during elastic loading and the assumption of incompressible flow for the plastic components of strain after "yield."

The stresses are calculated from the axial load and the pressure. In the case of a tubular specimen subjected to axial load and internal pressure, the axial stress σ_A is

$$\sigma_A = \frac{F}{\pi(r_o^2 - r_i^2)}$$

where F is the axial load and r_o, r_i are the outer and inner radii and $r_o \geq r \geq r_i$ and the tangential stress σ_T is

$$\sigma_T = \frac{P_i r_i^2}{r_o^2 - r_i^2} \left(1 + \frac{r_o^2}{r^2}\right)$$

where P_i is the internal pressure.

In the case of a specimen subjected to axial load and external pressure, the vertical component of the hydraulic pressure acting on the surface of the fillet at both ends must be taken into consideration when the axial stress is calculated

$$\sigma_A = \frac{F}{\pi(r_o^2 - r_i^2)} + \frac{P_o (r_s^2 - r_o^2)}{(r_o^2 - r_i^2)}$$

where r_s = shoulder radius of the specimen (Figure 2) and P_o = external pressure. For specimen used in this study r_s = 0.624 inch.

The tangential stress

$$\sigma_T = - \frac{P_o r_o^2}{r_o^2 - r_i^2} \left(1 + \frac{r_i^2}{r^2}\right) .$$

Once the deviatoric stress-strain curves are obtained, yielding is defined as the intercept of a line drawn parallel to the initial linear portion of the curve at 0.2% strain offset.

As it was discussed in the last section, all tests presented here are performed under proportional load conditions. In these tests, one strain rate was controlled to be constant while the second servo was used to maintain a constant stress ratio. Selection as to which direction would be maintained at constant strain rate was usually determined by the dominating stress. It will be shown below that tests performed under these control conditions also have a constant effective (or deviatoric) strain rate. The effective strain rate is defined as

$$\dot{\varepsilon}^P_{eff} = \frac{1}{\sqrt{6}} \left[\left(\dot{\varepsilon}^P_A - \dot{\varepsilon}^P_T\right)^2 + \left(\dot{\varepsilon}^P_R - \dot{\varepsilon}^P_T\right)^2 + \left(\dot{\varepsilon}^P_R - \dot{\varepsilon}^P_A\right)^2 \right]^{\frac{1}{2}}$$

where the superscript P denotes plastic strain, and the dot indicates rate of change.

We further assume the Prandtl-Reuss flow rule

$$d\varepsilon^P_A / S_A = d\varepsilon^P_T / S_T = d\varepsilon^P_R / S_R$$

or

$$\dot{\varepsilon}^P_A / S_A = \dot{\varepsilon}^P_T / S_T = \dot{\varepsilon}^P_R / S_R$$

where S's are deviatoric stress components, and given as follows:

$$S_A = \sigma_A - 1/3\ (\sigma_A + \sigma_T + \sigma_R) = 1/3\ (2\sigma_A - \sigma_T)$$

$$S_T = \sigma_T - 1/3\ (\sigma_A + \sigma_T + \sigma_R) = 1/3\ (-\sigma_A + 2\sigma_T)$$

$$S_R = - 1/3\ (\sigma_A + \sigma_T)$$

with $\sigma_R = 0$.

The flow rule then becomes

$$\frac{\dot{\varepsilon}^P_A}{1/3(2\sigma_A - \sigma_T)} = \frac{\dot{\varepsilon}^P_T}{1/3(-\sigma_A + 2\sigma_T)} = \frac{\dot{\varepsilon}^P_R}{-1/3(\sigma_A + \sigma_T)} .$$

If we define the stress ratio, $\beta \equiv \sigma_T/\sigma_A$, we have

$$\frac{\dot{\varepsilon}^P_T}{\dot{\varepsilon}^P_A} = \frac{2\sigma_T - \sigma_A}{2\sigma_A - \sigma_T} = \frac{2\beta - 1}{2 - \beta} \equiv \alpha$$

which gives $\dot{\varepsilon}^P_T = \alpha \, \dot{\varepsilon}^P_A$.

The assumption of incompressibility provides

$$\dot{\varepsilon}^P_A + \dot{\varepsilon}^P_T + \dot{\varepsilon}^P_R = 0$$

and

$$\dot{\varepsilon}^P_R = -(1+\alpha)\, \dot{\varepsilon}^P_A \quad .$$

Then substitution into the definition of effective strain rate yields

$$\dot{\varepsilon}^P_{eff} = \dot{\varepsilon}^P_A \,(1+\alpha+\alpha^2)^{\frac{1}{2}} \quad .$$

Thus, for a selected proportional load path $\beta = \sigma_T/\sigma_A$ and a prescribed constant strain rate $\dot{\varepsilon}^P_A$, the effective strain rate can be determined.

Two computer programs were written for the purpose of testing tubular specimens under biaxial stress states. The program "BIAX" was written to automatically record the axial load from the load cell, the pressure from the pressure transducer, and the axial and tangential strain values from the two sets of strain gages on the specimen. These values were stored on a magnetic tape through analog-to-digital converters. The program "BIANDV" was written to calculate the deviatoric stress, strain, and strain rate from the data recorded on the magnetic tape, and the results were printed on the line printer. A plotting routine was also included in "BIANDV," so the deviatoric stress-strain curve was automatically plotted on an X-Y recorder for each test.

The listing of these two programs are given in the Appendix.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The described biaxial testing technique was used to determine the yield surface of aluminum alloy 2014-T651 on the axial and tangential stress (σ_A, σ_T) plane. The tubular specimens were machined from 2- and 3-inch-thick rolled plates of 2014-T651 aluminum. Yield surface is shown in Figure 7. In the first quadrant (i.e., $\sigma_T > 0$, $\sigma_A > 0$) some specimens failed before reaching the 0.2% offset, but in the plastic region; in these cases, yield was defined as the maximum stresses reached during the test. The experimental data were also fitted to a quadratic equation with the least-square method

$$A\sigma_A^2 + B\sigma_A\sigma_T + C\sigma_T^2 + D\sigma_A + E\sigma_T = k^2$$

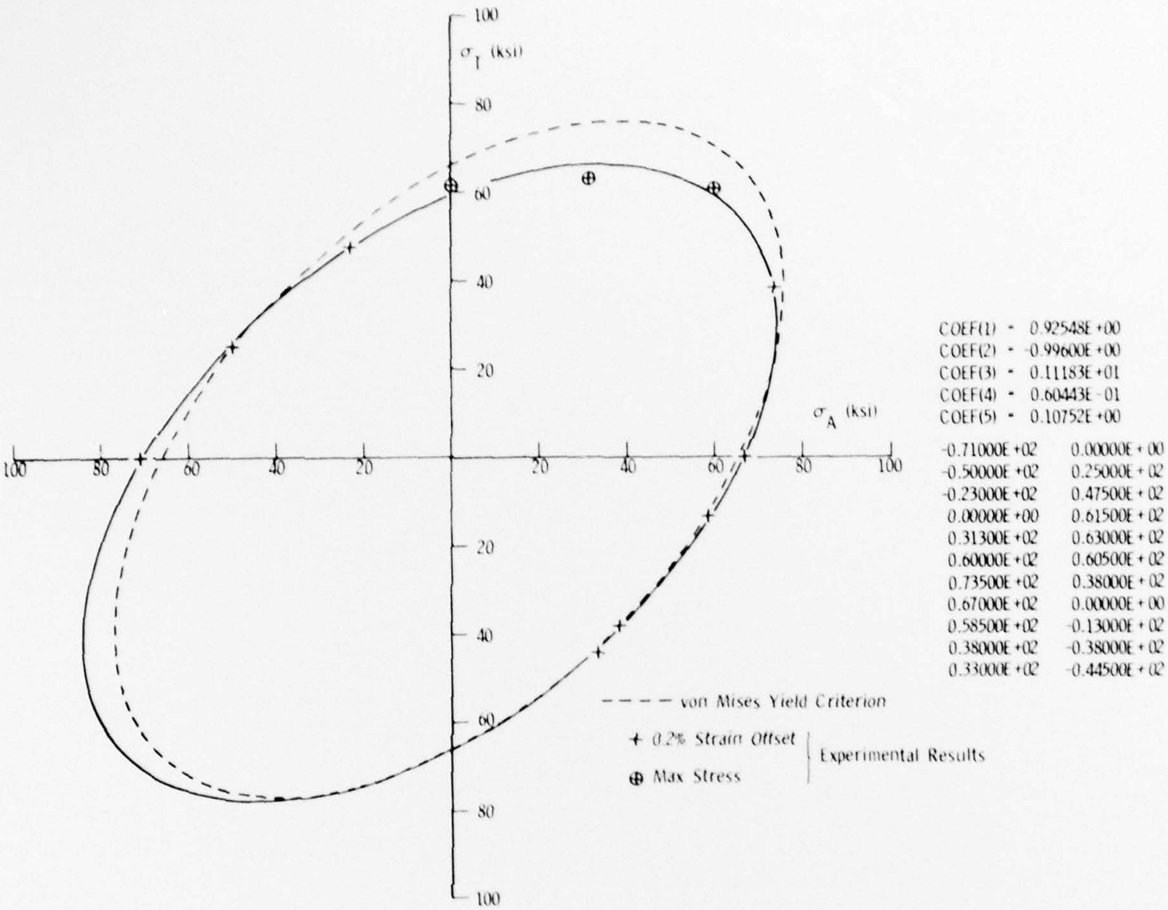

Figure 7. Yield surface for 2014-T651 aluminum alloy.

where k is the yield stress, 67 ksi, in simple tension. The coefficients are given as follows:

A = 0.925
B = -0.996
C = 1.118
D = 0.060
E = 0.107

which indicates that the behavior of the material agrees reasonably well with the von Mises yield criteria. Furthermore, the experimental results presented in this report were compared with results obtained by other investigators, e.g., Reference 1, and they agree very well. This comparison serves as a verification of the testing techniques and data analysis procedure presented here.

1. REID, R., J., JONES, A. H., and GREEN, S. J. *Characterization of 2014-T651 Aluminum Alloy.* Terra Tek, Salt Lake City, Utah, Contract DAAG46-74-C-0019, Final Report, AMMRC CTR 74-68, November 1974.

APPENDIX. BIAX AND BIANDV PROGRAMS

```
DS/8   FORTRAN IV   3.03

       C       PROGRAM BIAX      TAKES IN 6 CH OF DATA
       C
       C   RATIO LESS THAN 1.0
       C
       C      LOAD CONTROL ON AXIAL DIRECTION
       C
       C      STRAIN CONTROL ON THETA DIRECTION
       C
       C      FIGURES LOAD COMMAND FROM PRESSURE READING
       C
       C
       C   RATIO GREATER THAN 1.0 OR EQUAL
       C
       C      STRAIN CONTROL ON AXIAL DIRECTION
       C
       C      PRESSURE CONTROL ON THETA DIRECTION
       C
       C      FIGURES PRESSURE COMMAND FROM LOAD READING
       C
       C
              DIMENSION A(256),B(256),C(256),D(256),E(256),F(256),PLTBUF(200)
              DIMENSION DATBUF(50),STC(2)
       C
       C       SET UP DATA FILE
       C
              DEFINE FILE 1(6,256,U,L)
              T=1HT
              Y=1HY
              DA1=-1
              CALL DTOA(1,DA1)
              DA2=-1
              CALL DTOA(2,DA2)
              WRITE(4,1059)
         1059 FORMAT(' IF EXTERNAL PRESSURE PUT ACTIVE GAGE IN
             1' ,/,'  DUMMY LOCATION  - POSITIVE FEEDBACK ',//)
         1000 FORMAT(' TEST NUMBER IS = ',$)
         1001 FORMAT(' DATE IS ',I3,I3,I5,//)
         1002 FORMAT(' LOAD CAL - LBS -  ',$)
         1003 FORMAT(' PRESS. CAL - PSI = ',$)
         1004 FORMAT(' INSIDE DIA.  = ',$)
         1005 FORMAT(' OUTSIDE DIA. = '$)
         1006 FORMAT(' TOTAL TEST TIME (SEC) ',F12.2)
         1007 FORMAT( ' COMMAND SATURATED : TEST TERMINATED ')
         1008 FORMAT(' THETA STRAIN RATE CONSTANT ',/,
             1' AXIAL LOAD CONTROLLED BY AXIAL STRAIN FEEDBACK ',/)
         1009 FORMAT(' AXIAL LOAD  : TYPE  T OR C  =',$)
         1010 FORMAT(' STRESS RATIO = ',$)
         1011 FORMAT(' AXIAL LOAD SATURATED: TEST TERMINATED ')
         1012 FORMAT(' SAVING DATA ON UNIT 1 ')
         1020 FORMAT(' DO SET UP NOW :  WHEN SET PUT GAGED SPECIMEN TO RUN ',/,
             1' HIT RETURN KEY',/)
         1021 FORMAT(' TYPE RETURN TO GO ')
         2000 FORMAT(2A4)
         2001 FORMAT(I10)
         2002 FORMAT(1A1)
```

```
C
C       TEST NUMBER
C
        WRITE(4,1000)
        READ(4,2000) TEST1,TEST2
        CALL DATE(J1,J2,J3)
        WRITE(4,1001) J1,J2,J3
C
C       LOAD CALIBRATION
C
        WRITE(4,1002)
        READ(4,2001) XLCAL
C
C       PRESSURE CALIBRATION
C
        WRITE(4,1003)
        READ(4,2001) PCAL
C       INSIDE DIAMETER
C
        WRITE(4,1004)
        READ(4,2001) DI
        RI=DI/2.
C
C       OUTSIDE DIAMETER
C
        WRITE(4,1005)
        READ(4,2001) DO
        RO=DO/2.
C
C       STRESS RATIO   AXIAL/THETA
C
        WRITE(4,1010)
        READ(4,2001) RATIO
   21   CONTINUE
C
C       AXIAL LOAD - TENSION OR COMPRESSION
C
        WRITE(4,1009)
        READ(4,2002) AXIAL
        WRITE(4,1060)
 1060   FORMAT(' INTERNAL PRESSURE ? Y OR N =  ',$)
        READ(4,2002) INT
        IF(INT.EQ.Y) GO TO 22
        WRITE(4,1061)
 1061   FORMAT(' SHOULDER DIA. = ',$)
        READ(4,2001) DS
        RS=DS/2.
C
C       SHOULDER AREA
C
        AS=3.14159*(RS**2-RO**2)
        CONE=PCAL*AS/511.
C
C       STRAIN GAGE INFORMATION
C
```

```
   22 DO 401 I=1,2
      WRITE(4,1073) I
 1073 FORMAT(' #',I2,' RES.   = ',$)
      READ(4,2001) RG
      WRITE(4,1072) I
 1072 FORMAT(' #',I2,' G.F.   = ',$)
      READ(4,2001) GF
      WRITE(4,1074) I
 1074 FORMAT(' #',I2,' SHUNT = ',$)
      READ(4,2001) RS
      STC(I)=(1-RS/(RS+RG))/GF
  401 CONTINUE
C
C        COMPUTATIONS FOR EFFECTIVE STRAIN RATE
C        AND TEST TIME
C
      IF(RATIO.GE.1) BET=1./RATIO
      IF(RATIO.LT.1) BET=RATIO
      IF(AXIAL.NE.T.AND.INT.EQ.Y) BET=-BET
      IF(AXIAL.EQ.T.AND.INT.NE.Y) BET=-BET
      WRITE(4,1070)
 1070 FORMAT(' EFFECTIVE STRAIN RATE = ',$)
      READ(4,2001) EFF
      ALP=(2*BET-1)/(2.-BET)
      EDOT=EFF/SQRT(1.+ALP+ALP**2)
      WRITE(4,1071) EDOT
 1071 FORMAT(' CONTROLLED S.R. = ',F12.5)
      IF(RATIO.GE.1) TIME=STC(1)/EDOT
      IF(RATIO.LT.1) TIME=STC(2)/EDOT
      WRITE(4,1006) TIME
   31 WRITE(4,1021)
C
C       HIT RETURN KEY TO START TEST
C
      READ(4,2000) CONT
      INDA1=1
      IF(AXIAL.NE.T) INDA1=-1
      IF(AXIAL.NE.T) CALL DTOA(1,0)
      R=RO
      AA=3.14159*(RO**2-RI**2)
      TT=(RI**2*(RO**2+R**2))/(R**2*(RO**2-RI**2))
      IF(INT.NE.Y) TT=(RO**2*(RI**2+R**2))/(R**2*(RO**2-RI**2))
      CONV=2048*XLCAL/(AA*TT*PCAL*511*RATIO)
      NOAAD=8
      NPTS=256
      CALL CLRPLT(200,PLTBUF)
      KK=TIME/20.+1
      NOA=2048
      NTPTS=(KK*2048)*8
      CALL REALTM(DATBUF,50,8,8,NTPTS)
      CR=(KK*2048)/TIME
C
C       INITIALIZE DATA TO ZERO
C
      DO 300 I=1,256
```

```
      A(I)=0.0
      B(I)=0.0
      C(I)=0.0
      D(I)=0.0
      E(I)=0.0
      F(I)=0.0
  300 CALL PLOT(1,.65,.5)
      CALL CLOCK(0,CR)
      DO 301 I =1,256
      IF(I.EQ.256) NDAAD=7
      DO 302 J=1,NDAAD
      CALL SSW(5,ISNS5)
      IF(ISNS5.EQ.1) GO TO 100
      AAA=0.0
      CC=0.0
      DO 303 K=1,KK
      CALL SSW(0,ISNS0)
      IF(ISNS0.EQ.1) GO TO 304
      IF(K.NE.KK) GO TO 304
C
C       RAMP ON CONTROL GAGE
C
      IF(RATIO.LT.1) GO TO 380
      DA1=DA1+INDA1
      CALL DTOA(1,DA1)
      GO TO 304
  380 DA2=DA2+1
      CALL DTOA(2,DA2)
C
C       SAMPLING ROUTINE
C
  304 A(I)=ADB(X)
      B(I)=ADB(X)
      C(I)=ADB(X)
      D(I)=ADB(X)
      E(I)=ADB(X)
      F(I)=ADB(X)
      IF(INT.EQ.Y) C(I)=-C(I)
      IF(INT.EQ.Y) D(I)=-D(I)
      IF(INT.NE.Y) A(I)=(A(I)*XLCAL/511.+ABS(C(I))*CONE)*511./XLCAL
      AAA=AAA+A(I)
      CC=CC+C(I)
  303 CONTINUE
C
C       AVERAGE DATA BEFORE STORAGE
C
      A(I)=AAA/KK
      C(I)=CC/KK
      IF(RATIO.GE.1.0) GO TO 383
C
C       COMMAND TO MSRM
C
      SIGZ=(XLCAL/(AA))
      SIGT=ABS(C(I)*PCAL*TT)*RATIO
      DA1=SIGT/SIGZ*4.
```

```
          IF(AXIAL.NE.T) DA1=-DA1
          IF(INT.NE.Y) DA1=DA1+C(I)*CONV*511./XLCAL*4.
          IF(ABS(DA1).GT.2047) GO TO 900
          CALL SSW(0,ISNS0)
          IF(ISNS0.EQ.1) GO TO 313
          CALL DTOA(1,DA1)
          GO TO 313
C
C          COMMAND TO INTENSIFIER
C
      303 DA2=ABS(A(I)*CONV)
          IF(DA2.GT.2047) GO TO 900
          CALL SSW(0,ISNS0)
          IF(ISNS0.EQ.1) GO TO 313
          CALL DTOA(2,DA2)
      313 CONTINUE
     302  CONTINUE
C
C          PLOT AXIAL VS THETA STRESS ON SCOPE
C
          CALL PLOTR(1,A(I)*1.5/1024.+.65,C(I)/1024.+.5,1)
     301  CONTINUE
          GO TO 100
     800  CONTINUE
          WRITE(4,1011)
          GO TO 100
     900  WRITE(4,1007)
     100  CONTINUE
C
C          DUMP DATA TO TAPE
C
          WRITE(4,1012)
          L=1
          WRITE(1'L)A
          L=2
          WRITE(1'L) B
          L=3
          WRITE(1'L) C
          L=4
          WRITE(1'L) D
          L=5
          WRITE(1'L) E
          L=6
          WRITE(1'L) F
          WRITE(4,1008)
     1008 FORMAT(' RETURN TO END PROG. & REMOVE SOFTWARE CLAMP')
          READ(4,2001) GO
          CALL RCPEN(0)
          CALL RCPEN(2)
     103  CALL EXIT
```

```
OS/6  FORTRAN IV  3.03

      C  PROGRAM BIANOV   ANALYSIS OF 6 CH OF BIAX
      C
      C   RATIO LESS THAN 1.
      C
      C       STRAIN CONTROL ON AXIAL DIRECTION
      C
      C       STRAIN CONTROL ON THETA DIRECTION
      C
      C       FIGURES LOAD COMMAND FROM PRESSURE READING
      C
      C   RATIO GREATER THAN 1.
      C
      C       STRAIN CONTROL ON AXIAL DIRECTION
      C
      C       PRESSURE CONTROL ON THETA DIRECTION
      C
      C       FIGURES PRESSUR COMMAND FROM LOAD READING
      C
      C
      C      COMPUTES DEVIATORIC STRESS-STRAIN CURVE
      C
      C      PLOTS DEVIATORIC STRESS-STRAIN CURVE
      C
      C
      C      USES SUBROUTINE XYREC
      C
      C
0002          DIMENSION A(256),B(256),C(256),D(256),E(256),F(256)
0003          DIMENSION RS(4),RG(4),STC(4)
0004          COMMON/G/A,B,C,D,E,F
0005          DEFINE FILE 1(6,256,U,L)
0006          Y=1HY
      C
      C       READ DATA FROM TAPE
      C
0007          L=1
0010          READ(1'L) A
0011          L=2
0012          READ(1'L) B
0013          L=3
0014          READ(1'L) C
0015          L=4
0016          READ(1'L) D
0017          L=5
0020          READ(1'L) E
0021          L=6
0022          READ(1'L) F
      C
      C        CROSS PLOT DATA ON SCOPE
      C
      C        RETURN TO EXIT FROM PLT6
0023          CALL PLT6
0024     1000 FORMAT(' TEST NUMBER IS ',2A4)
0025     1001 FORMAT(' DATE IS ',I3,I3,I5,//)
0026     1002 FORMAT(' LOAD CAL - LBS ')
```

```
 1003 FORMAT(' PRESS. CAL -  PSI ')
 1004 FORMAT(' INSIDE DIA. ')
 1005 FORMAT(' OUTSIDE DIA. ')
 1006 FORMAT(' TOTAL TEST TIME (SEC) ')
 1010 FORMAT(' STRESS RATIO ')
 1011 FORMAT(' INTERNAL PRESSURE ? ',$)
 1021 FORMAT(' TYPE RETURN TO GO ')
 2000 FORMAT(2A4)
 2001 FORMAT(I10)
 2002 FORMAT(1A1)
C
C       INPUT CALIBRATION VALUES
C
      WRITE(4,1000)
      READ(4,2000) TEST1,TEST2
      CALL DATE(J1,J2,J3)
      WRITE(4,1001) J1,J2,J3
      WRITE(4,1002)
      READ(4,2001) XLCAL
      WRITE(4,1003)
      READ(4,2001) PCAL
      WRITE(4,1004)
      READ(4,2001) DI
      RI=DI/2.
      WRITE(4,1005)
      READ(4,2001) DO
      RO=DO/2.
      R=RO
      WRITE(4,1011)
      READ(4,2002) INT
      WRITE(4,1010)
      READ(4,2001) RATIO
      WRITE(4,1006)
C
C       INPUT STRAIN GAGE INFORMATION
C
      READ(4,2001) TIME
      WRITE(4,1101)
      READ(4,2001) GF
 1101 FORMAT(' GAGE FACTOR ')
      DO 12 I=1,4
      WRITE(4,1102) I
 1102 FORMAT(' #',I2,' GAGE RES. ')
 12   READ(4,2001) RG(I)
      DO 13 I=1,4
      WRITE(4,1103) I
 1103 FORMAT(' #',I2,' SHUNT RES. ')
 13   READ(4,2001) RS(I)
      DO 14 I=1,4
 14   STC(I)=(1-RS(I)/(RS(I)+RG(I)))/GF*1E6
C
C       SETUP FOR DETERMINING PRINCIPLE STRESSES
C
      AA=(RI**2*PCAL/S11)/(RO**2-RI**2)
      IF(INT.NE.Y) AA=(RO**2*PCAL/S11)/(RO**2-RI**2)
```

```
      SIG1C=(ALCAL/511.)/(3.14159*(RO**2-RI**2))/1000.
      SIG2C=AAA*(1.+(RO**2/R**2))/1000.
      IF(INT.NE.Y) SIG2C=AA*(1+RI**2/R**2)/1000.
      SIG3C=AAA*(1.-(RO**2/R**2))/1000.
      IF(INT.NE.Y) SIG3C=AA*(1-(RI**2/R**2))/1000.
C
C     DETERMINE IF TWO AXIAL OR TWO TRANSVERSE
C       GAGES DIFFER BY MORE THAN 5% OF CALIBRATION VALUE
C
      DO 20 I=1,256
      E1=B(I)*STC(1)
      E2=C(I)*STC(2)
      E3=E(I)*STC(3)
      E4=F(I)*STC(4)
      DEA=(ABS(E1)-ABS(E3))
      DET=(ABS(E2)-ABS(E4))
      DE1=.05*STC(1)*511
      DE2=.05*STC(2)*511
      IF(DEA.GT.DE1) GO TO 21
      IF(DET.GT.DE2) GO TO 22
 20   CONTINUE
      GO TO 27
 21   WRITE(4,1104) I
      GO TO 27
 22   WRITE(4,1105) I
 1104 FORMAT(' AXIAL GAGES DIFFER THAN MORE THAN 5% AT PT =',I3)
   27 WRITE(4,1141)
 1141 FORMAT(' MODULUS  X10**6 PSI ')
      READ(4,2001) EMOD
      WRITE(4,1142)
 1142 FORMAT(' POISSONS RATIO = ')
      READ(4,2001) U
      EMOD=EMOD*1000000.
 1105 FORMAT(' THETA GAGES DIFFER MORE THAN 5% AT PT =',I3)
 23   J=1
      DO 30 I=1,256
      IF(I.NE.J.OR.ISNSC.EQ.1) GO TO 40
      WRITE(3,5000)
 5000 FORMAT(1H1)
      WRITE(3,1000) TEST1,TEST2
      WRITE(3,1001) J1,J2,J3
      WRITE(3,1106)
 1106 FORMAT(' AXIAL   THETA   RADIAL  AXIAL   THETA',
     1'   TIME   STRAIN     DEV     DEV    DEV ')
      WRITE(3,1007)
 1007 FORMAT(' STRESS  STRESS  STRESS  STRAIN  STRAIN',
     1'   SEC    RETE     STRESS  STRAIN  RATE  ',//)
      J=J+52
C
C       COMPUTE PRINCIPLE & DEVIATORIC STRESSES
C
   40 S1=SIG1C*A(I)
      S2=SIG2C*C(I)
      S3=SIG3C*C(I)
      E1=((B(I)*STC(1))+(E(I)*STC(3)))/2./511.
```

```
      E2=((D(I)*STC(2))+(F(I)*STC(4)))/2./511.
      T1=(S2-S3)**2
      T2=(S3-S1)**2
      T3=(S1-S2)**2
      SIGD=(1/SQRT(6))*SQRT(T1+T2+T3)
C
C      COMPUTE RADIAL STRAIN AND DEVIATORIC STRAIN
C
      E(I)=SIGD
      E3=1/EMOD*(S3*1000.-U*(S1+S2)*1000.)*100.
      F1=((E2-E3)/100.)**2
      F2=((E3-E1)/100.)**2
      F3=((E1-E2)/100.)**2
      EED=(1/SQRT(6))*SQRT(F1+F2+F3)*100.
      F(I)=EED
      TM=(TIME/256)*I
      TI=TIME/256
      CALL SSW(0,ISNS0)
      IF(I.GT.15) GO TO 50
      SR=0.0
      WRITE(3,1130) S1,S2,S3,E1,E2,TM,SR,SIGD,EED
      GO TO 30
 50   IF(RATIO.LT.1) SR=(D(I)-D(I-15))*STC(2)/(TI*15)/100./511.
      IF(RATIO.GE.1) SR=(B(I)-B(I-15))*STC(1)/(TI*15)/100./511.
      IF(RATIO.LT.1) GO TO 37
 1130 FORMAT(3F8.2,2F8.3,F8.2,F9.5,2F8.2,F8.5)
   37 CONTINUE
      IF(S2.EQ.0.0) GO TO 888
C
C      DETERMINE EFFECTIVE STRAIN RATE
C
      RAT=S1/S2
  888 IF(S2.EQ.0.0) RAT=S1*99999
      IF(RATIO.GE.1) BET=1./RATIO
      IF(RATIO.LT.1) BET=RATIO
      IF(RAT.LT.0) BET=-BET
      ALP=(2.*BET-1.)/(2.-BET)
      DEV3=SR*SQRT(1.+ALP+ALP**2)
      IF(ISNS0.EQ.1) GO TO 30
      WRITE(3,1130) S1,S2,S3,E1,E2,TM,SR,SIGD,EED,DEV3
 30   CONTINUE
   32 WRITE(3,5000)
C
C      PLOT DEVIATORIC STRESS-STRAIN CURVE ON
C       X-Y RECORDER
C
      WRITE(4,1143)
 1143 FORMAT(' X-Y PLOT X=CH#0, Y=CH#1,  YES OR NO ')
      READ(4,2002) PLOT
      Y=1HY
      IF(PLOT.NE.Y) CALL EXIT
      CALL XYREC
      STOP
      END
```

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