FCP Report No. 27

# MATERIAL CHARACTERIZATION OF A 1% NICKEL STEEL; MONOTONIC AND CYCLIC STRESS-STRAIN BEHAVIOR AND STRAIN-LIFE RESPONSE

by

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## Abstract

Monotonic and cyclic stress-strain behavior and strain-life resistance of a 1% nickel steel at 188HB are reported. The material cyclically hardens and exhibits a behavior comparable to most high strength low alloy steels of similar hardness. Periodic incremental overstraining reduces life by approximately an order of magnitude.

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## FOREWORD

This is the fifth in a series of reports on materials of interest to sponsors of the Fracture Control Program. A 1% nickel steel at 188HB supplied by Clark Equipment Company, which will be referred to herein as IN-787*, is characterized in this report. As in previous reports, the format includes reduced material characterization sheets as well as original laboratory records. However, all data acquisition and reduction were accomplished via a computerized material test facility with a ±10 metric ton load capacity. Only selected records are presented.

## PROCEDURE

Specimens of the design shown in Fig. 1 were supplied ready for testing. Specimens used for the constant strain cycling were not precycled prior to testing.

## RESULTS

### Stress-Strain Behavior

On the data sheet for material characterization are listed results from the monotonic stress-strain tests. Comparison of these results from the 188HB samples of IN-787 to results of SAE 950XK at 183HB given in FCP Report No. 25 illustrate a marked similarity with the exception of the true toughness. As a general trend, a steel having a greater true toughness would exhibit superior impact resistance and notch fatigue resistance.

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*IN-787 is a trade name of International Nickel Corporation.

The cyclic stress-strain behavior of IN-787 is also shown on the data sheet. Cyclic strain hardening is apparent at all strain levels on the companion specimen and incremental step strain curves. The precycled tension test shows slight cyclic softening at all strain levels. To avoid confusion, it is recommended that the precycled tension test be ignored and the cyclic stress-strain curve from companion specimen data be employed to interpret cyclic properties.

## Strain-Life Resistance

Results of the constant strain amplitude tests are given near the back of the report. Three specimens each were tested at four different strain levels to ascertain any scatter in the life results. Three additional specimens were periodically overstrained by 1% every $10^5$ reversals. Comparison of these overstrained results to those tested at a comparable constant amplitude of 0.0018 shows a decrease in life of approximately an order of magnitude.

## Conclusions

From monotonic and cyclic stress-strain results, it is concluded that IN-787 is similar to most high strength low alloy steels of comparable hardness and cleanliness. Because of greater true toughness, IN-787 may exhibit superior impact and notched fatigue resistance but further testing would be necessary to support this assertion.

Attention is called to the order of magnitude decrease in life due to periodic overstraining since this is a common occurrence in ground vehicle components.

# DATA SHEET FOR MATERIAL CHARACTERIZATION

Material: IN-787†

Condition: Hot rolled

Matrix Hardness: 188±8HB

Converted from: $R_B$

## Monotonic Properties:††

| | |
|---|---|
| Modulus of Elasticity, E | $29.8 \times 10^3$ ksi |
| Yield Strength, 0.2% $S_y$ | 65.7 ksi |
| Ultimate Strength, $S_u$ | 90.2 |
| Red. in Area, % RA | 76.4 |
| True Fracture Strength, $\sigma_f$ corr. for necking | 178.0 ksi |
| True Fracture Ductility, $\epsilon_f$ | 1.45 |
| Strain Hardening Exponent, n | 0.14 |
| Strength Coefficient, K | 138.7 ksi |
| True Toughness, $U_p$ | 232.0 in-lb/in$^3$ |

††Average values of two test specimens

## Cyclic Properties:

| | |
|---|---|
| Yield Strength, 0.2% $S_y'$ | 72* ksi |
| Strain Hardening Exponent, n' | 0.13* |
| Strength Coefficient, K' | 163* ksi |
| Fatigue Strength Coefficient, $\sigma_f'$ | 191** ksi |
| Fatigue Ductility Coefficient, $\epsilon_f'$ | 1.4** |
| Fatigue Strength Exponent, b | -0.10 |
| Fatigue Ductility Exponent, c | -0.68 |
| Transition Fatigue Life, $2N_t$ | $10^4$ rev |

*From companion specimen results.

**Intercept values of best-fit line to companion specimen results.

## Composition:

| | | | |
|---|---|---|---|
| w/o C | = 0.04 | w/o Mo | = 0.25 |
| w/o Si | = 0.25 | w/o Cu | = --- |
| w/o P | = 0.007 | w/o Ni | = 1.02 |
| w/o S | = 0.016 | w/o Va | = --- |
| w/o Mn | = 0.51 | w/o Al | = 0.02 |
| w/o Cr | = 0.67 | w/o B | = 0.0013 |

†Trade name of International Nickel Corporation.

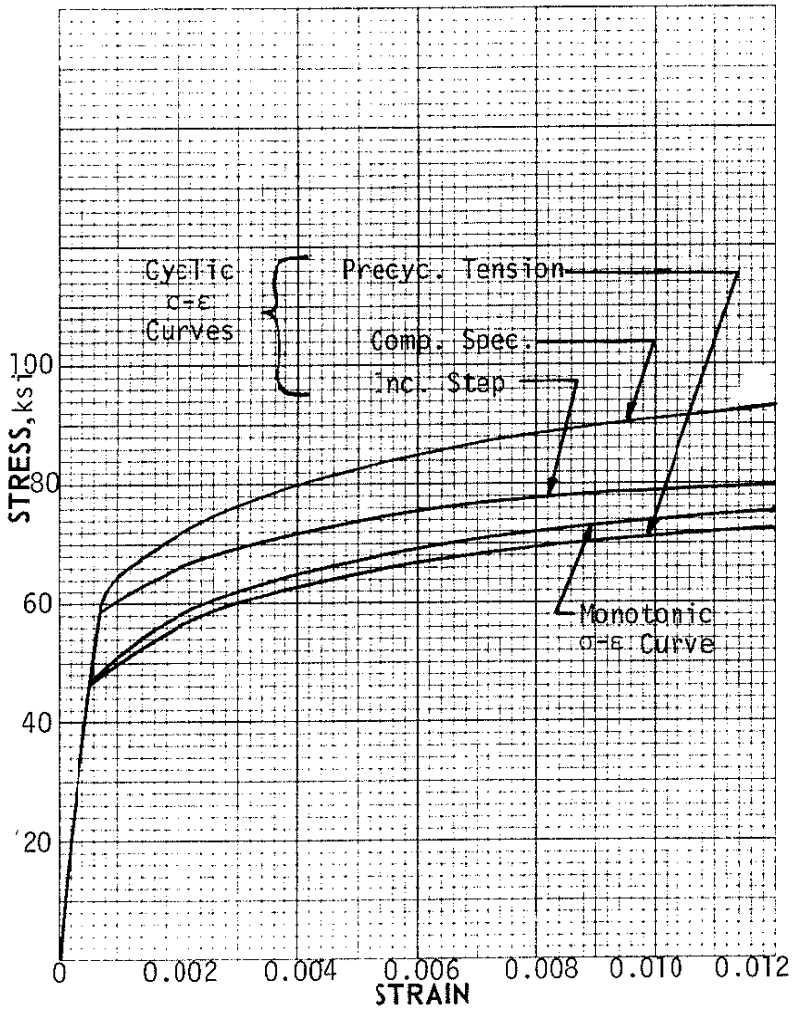
## Comments:

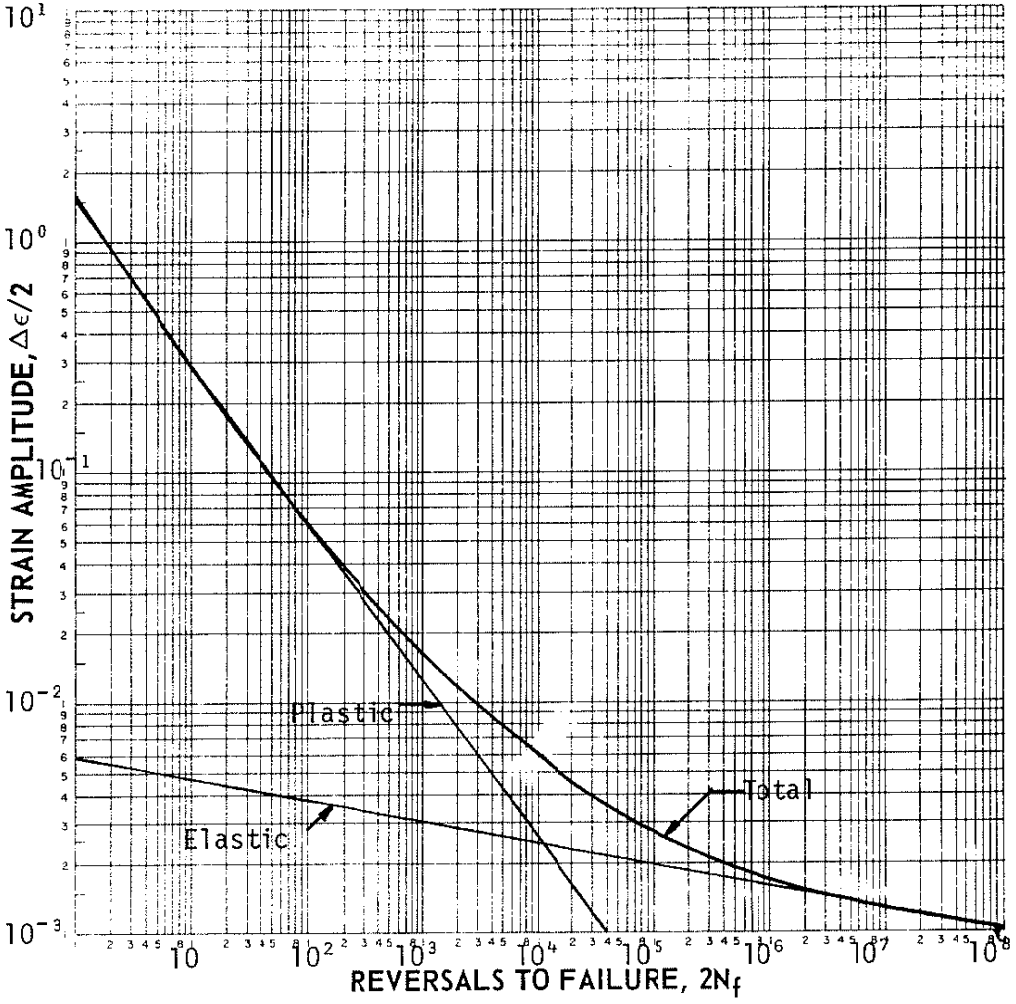
(1) Specimens machined from material parallel to to rolling direction.

(2) Periodic incremental overstraining every $10^5$ rev by ±1% of samples tested at ±0.0018 strain, reduced life by approximately an order of magnitude when compared to samples tested at the same strain amplitude without overstraining (i.e. $2N_f = 8.9 \times 10^5$ rev compared to $10^7$ rev runouts).

**Material:** IN-787 **Hardness:** 188±8HB

**Condition:** Hot rolled



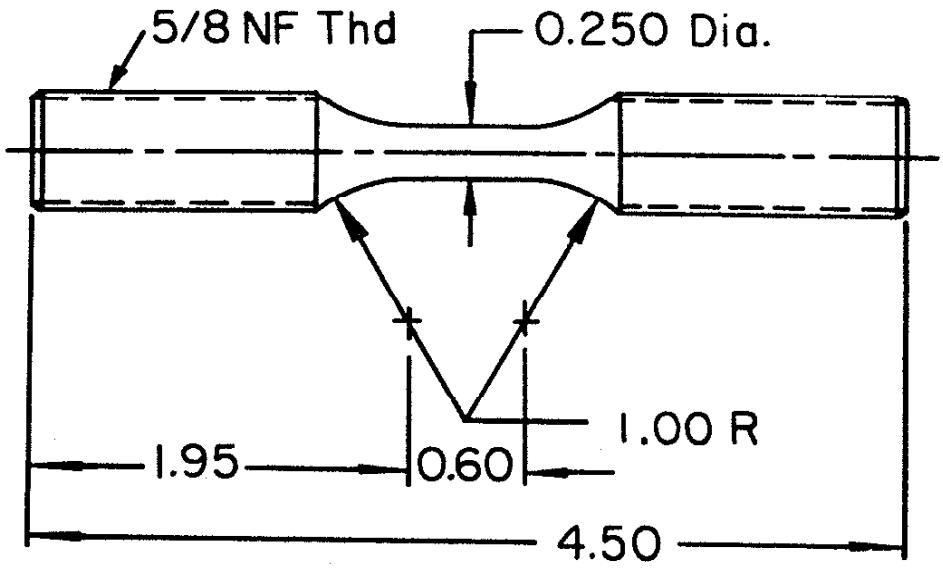
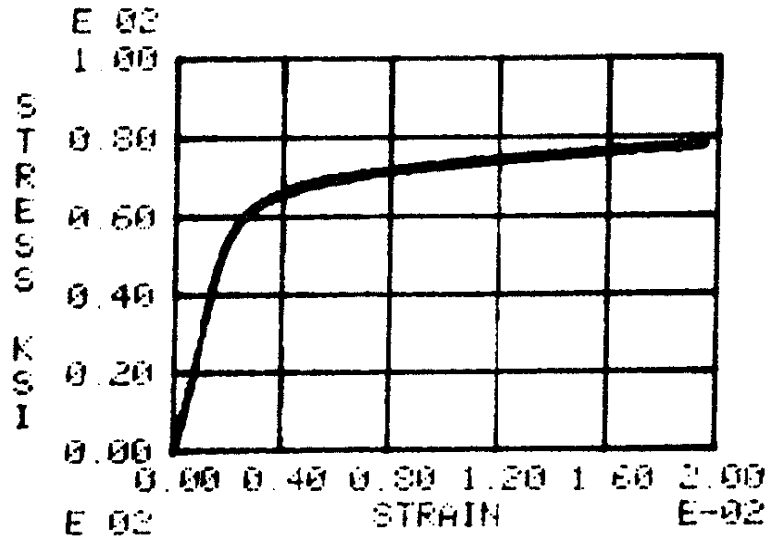



FIG. 1 - SPECIMEN DESIGN
(All dimensions in inches)

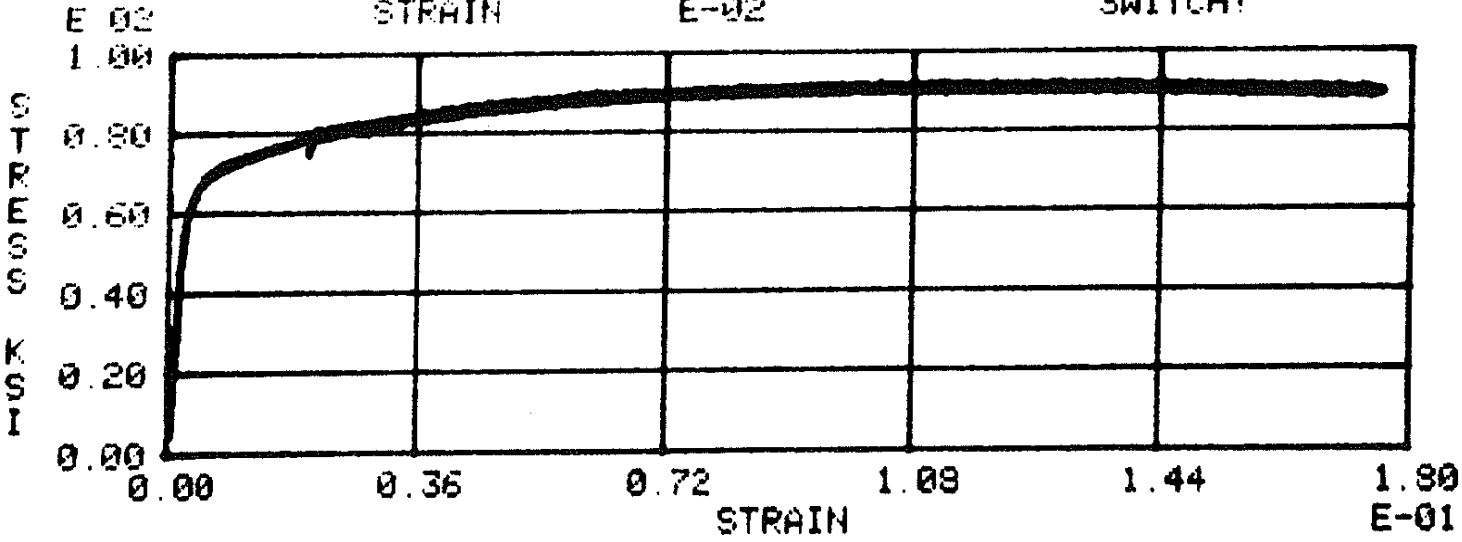
# MONOTONIC TENSION TESTS

MONOTONIC TENSION TEST OF NICUAGE SPECIMEN # 04
STRAIN RATE = 5.000000E-04 18-NOV-76 RONZ

TEST IN STRAIN CONTROL

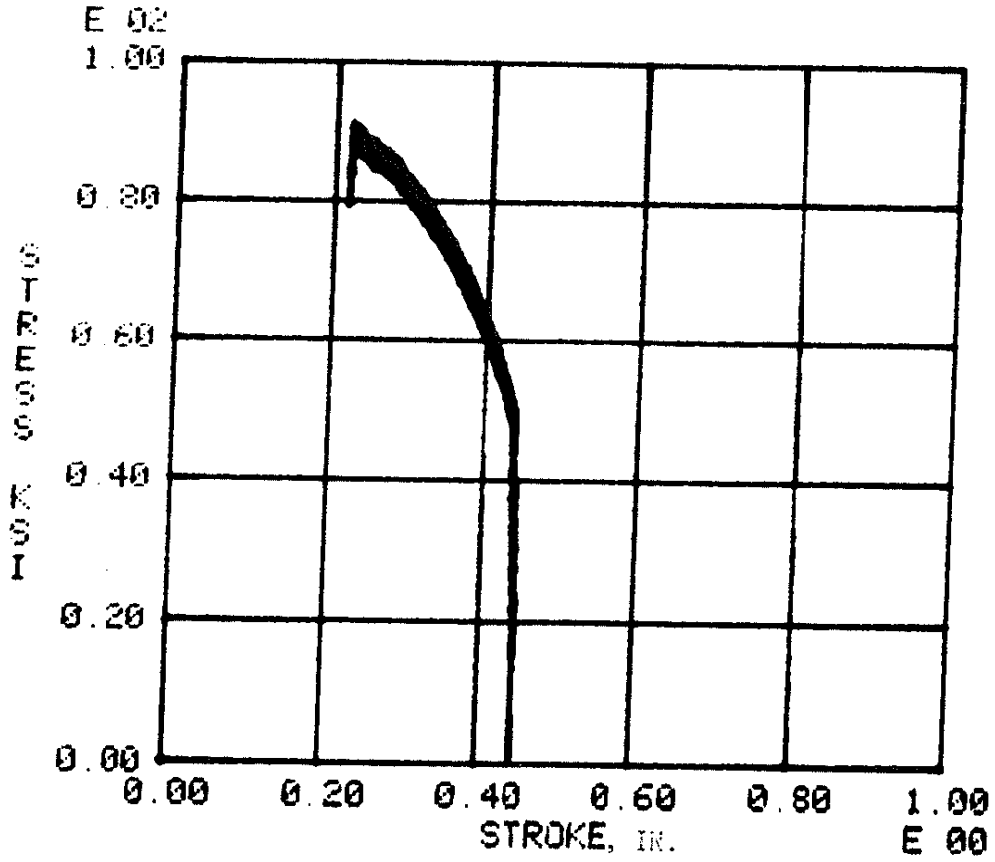



SWITCH?

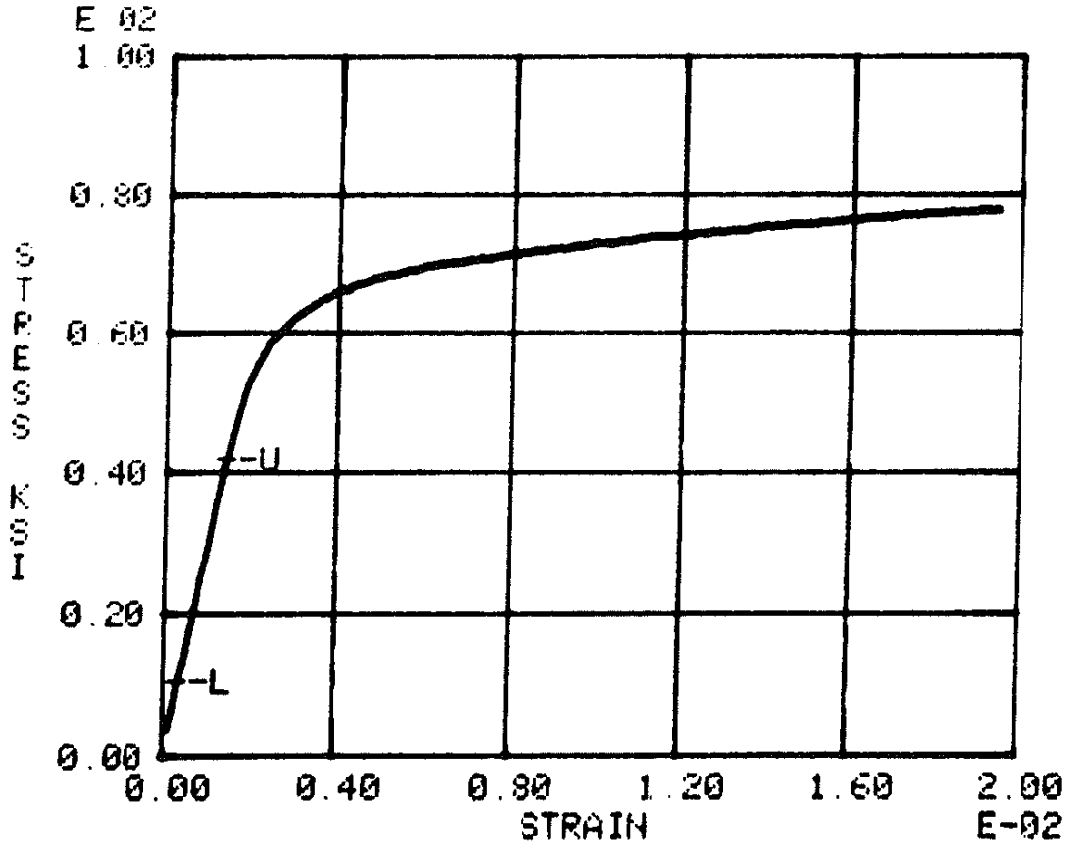


MONOTONIC TENSION TEST OF NICUAGE SPECIMEN # 04
STRAIN RATE = 5.000000E-04 18-NOV-76 RONZ

TEST IN STROKE CONTROL



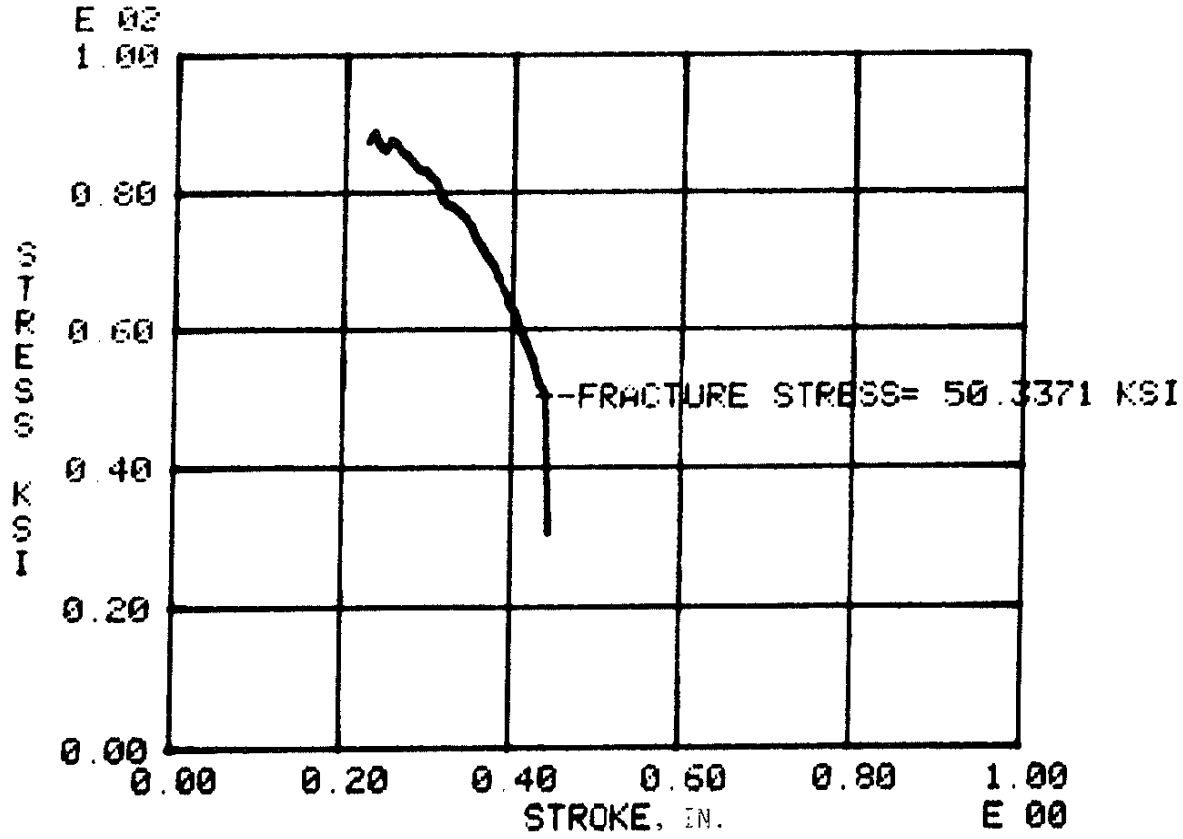
```
MONOTONIC TENSION TEST OF NICUAGE SPECIMEN # 04
     STRAIN RATE =  5 000006E-04 18-NOU-76    PON2

INPUT LOWER STRESS FOR MODULUS FIT? 10
INPUT UPPER STRESS FOR MODULUS FIT? 45

ELASTIC MODULUS = 30072.5 KSI ( 10  POINTS)
IS THIS OK? Y
```



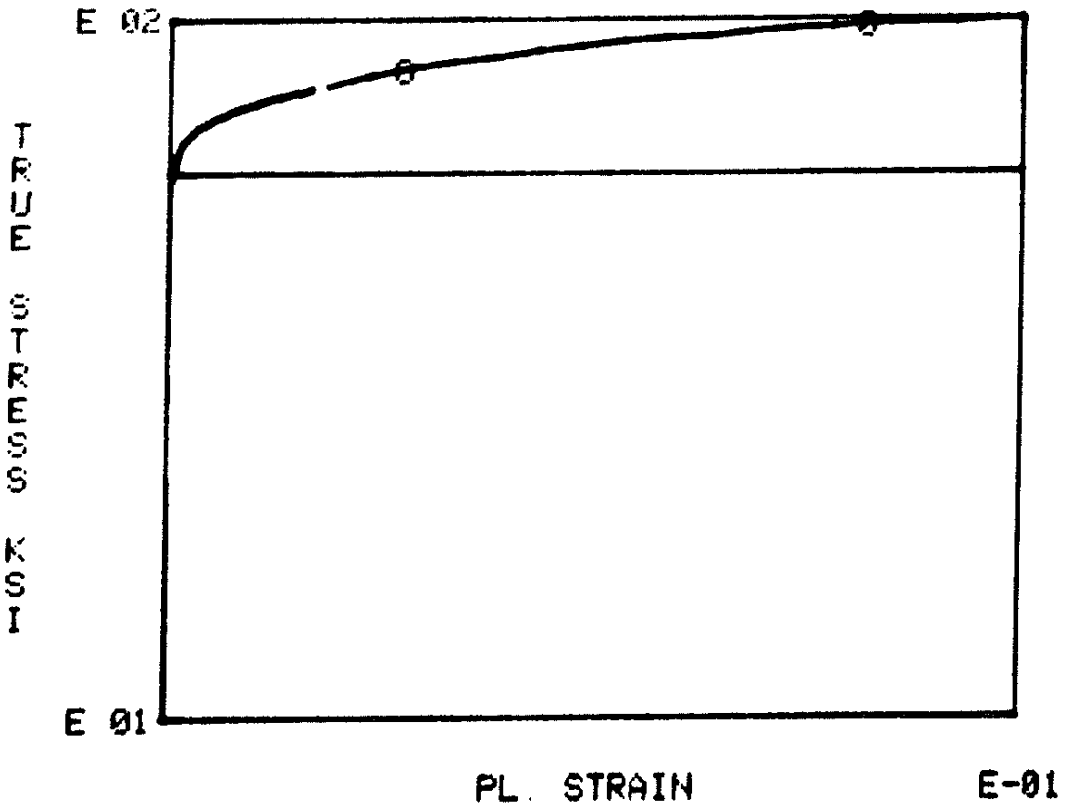
MONOTONIC TENSION TEST OF NICUAGE SPECIMEN # 04
STRAIN RATE = 5 000000E-04 18-NOU-76 RONZ

PLACE CURSORS ON FINAL FRACTURE POINT

IS THIS OK? Y



```
MONOTONIC TENSION TEST OF NICUAGE SPECIMEN # 04
     STRAIN RATE =  5.000001E-04 18-NOV-76     RONZ

INPUT LOWER PL. STRAIN FOR N,K FIT? .02
INPUT UPPER PL. STRAIN FOR N,K FIT? .08

          N= .140595      K= 140.157 KSI
IS THIS OK? Y
```



MONOTONIC TENSION TEST OF NICUAGE SPECIMEN # 04
STRAIN RATE = 5.00000E-04 18-NOV-76 RONZ

SUMMARY OF MONOTONIC TENSION PROPERTIES

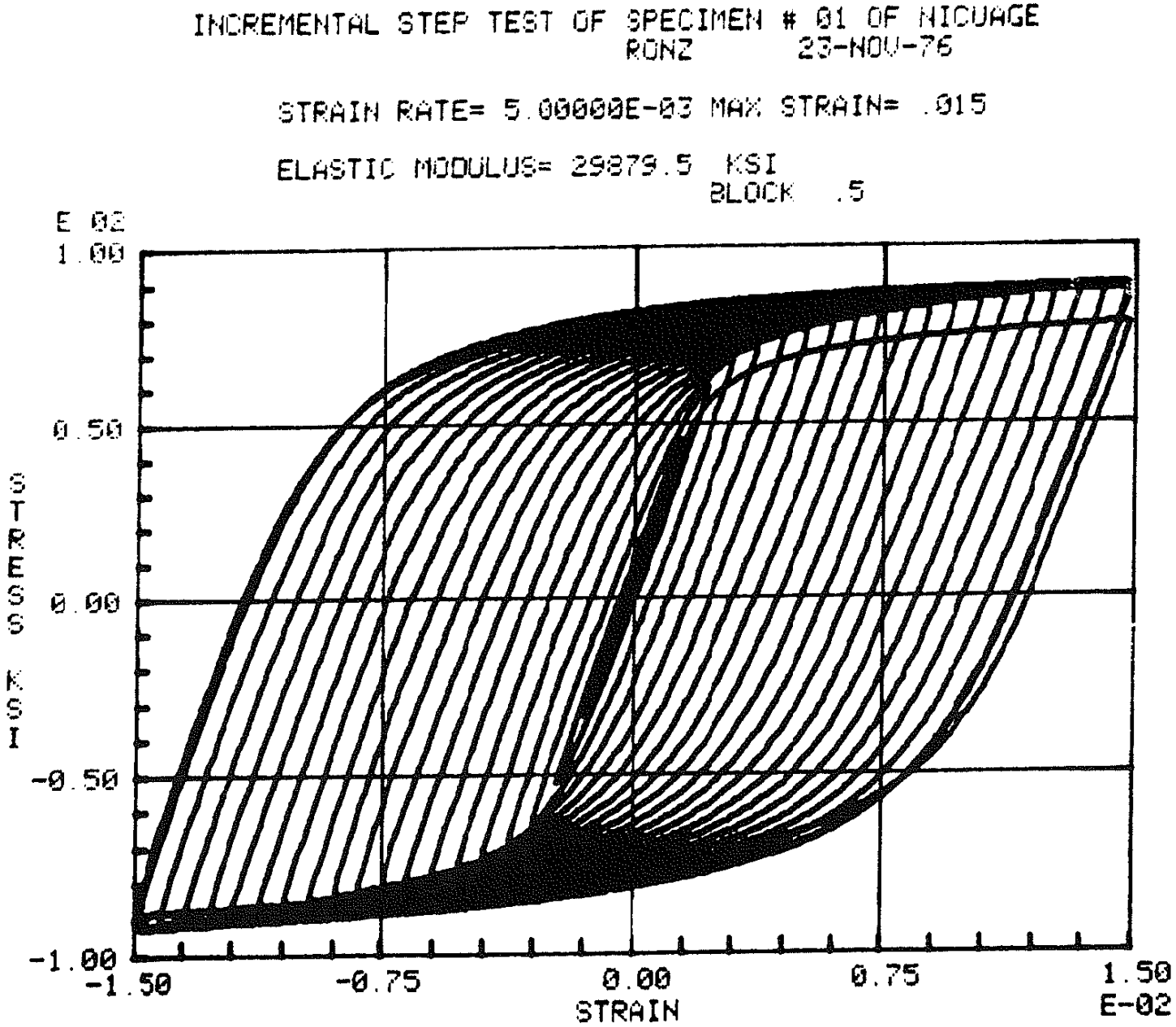
| | | | |
|---|---|---|---|
| ELASTIC MODULUS | = | 30072.5 | KSI |
| 0.002 YIELD STRESS | = | 66.3124 | KSI |
| @ STRAIN | = | 4.11334E-03 | |
| ULTIMATE STRENGTH | = | 90.7909 | KSI |
| @ STRAIN | = | .126888 | |
| FRACTURE STRESS | = | 50.3371 | KSI |
| INITIAL SPECIMEN AREA | = | .0486955 | SQ IN |
| FINAL SPECIMEN AREA | = | 9.50332E-03 | SQ IN |
| % REDUCTION IN AREA | = | 80.4842 | % |
| TRUE FRACTURE STRAIN | = | 1.63395 | |
| TRUE FRACTURE STRENGTH | = | 257.93 | KSI |
| CORRECTED TO | = | 205.572 | KSI |
| STRAIN HARDENING EXPONENT | = | .140595 | |
| STRENGTH COEFFICIENT | = | 140.157 | KSI |

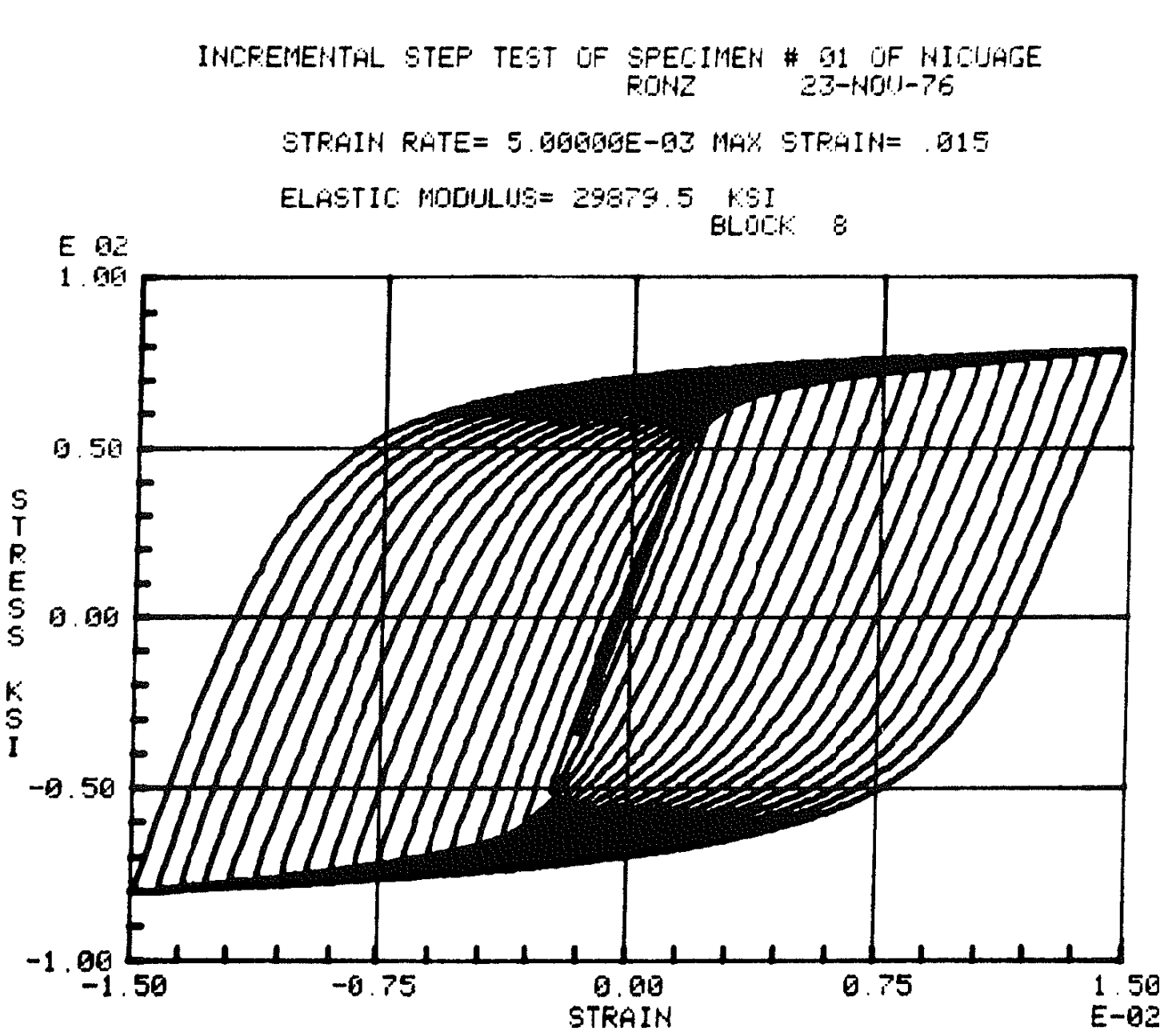
MONOTONIC TENSION TEST OF NICUAGE SPECIMEN # 15
STRAIN RATE = 5.00000E-04 16-NOV-76 RON2

SUMMARY OF MONOTONIC TENSION PROPERTIES

| | | | |
|---|---|---|---|
| ELASTIC MODULUS | = | 29452.3 | KSI |
| 0.002 YIELD STRESS | = | 65.0624 | KSI |
| @ STRAIN | = | 4.10357E-03 | |
| ULTIMATE STRENGTH | = | 89.5472 | KSI |
| @ STRAIN | = | .131104 | |
| FRACTURE STRESS | = | 50.3371 | KSI |
| INITIAL SPECIMEN AREA | = | .0494809 | SQ IN |
| FINAL SPECIMEN AREA | = | .0136848 | SQ IN |
| % REDUCTION IN AREA | = | 72.3433 | % |
| TRUE FRACTURE STRAIN | = | 1.2853 | |
| TRUE FRACTURE STRENGTH | = | 182.007 | KSI |
| CORRECTED TO | = | 150.169 | KSI |
| STRAIN HARDENING EXPONENT | = | .139322 | |
| STRENGTH COEFFICIENT | = | 137.154 | KSI |

# INCREMENTAL STEP-STRAIN TESTS


INCREMENTAL STEP TEST OF SPECIMEN # 01 OF NICUAGE
RONZ 23-NOV-76
STRAIN RATE= 5.00000E-03 MAX STRAIN= .015
ELASTIC MODULUS= 29879.5 KSI
BLOCK .5
E 02
1.00
0.50
0.00
-0.50
-1.00
STRESS KSI
-1.50
-0.75
0.00
0.75
1.50
E-02
STRAIN

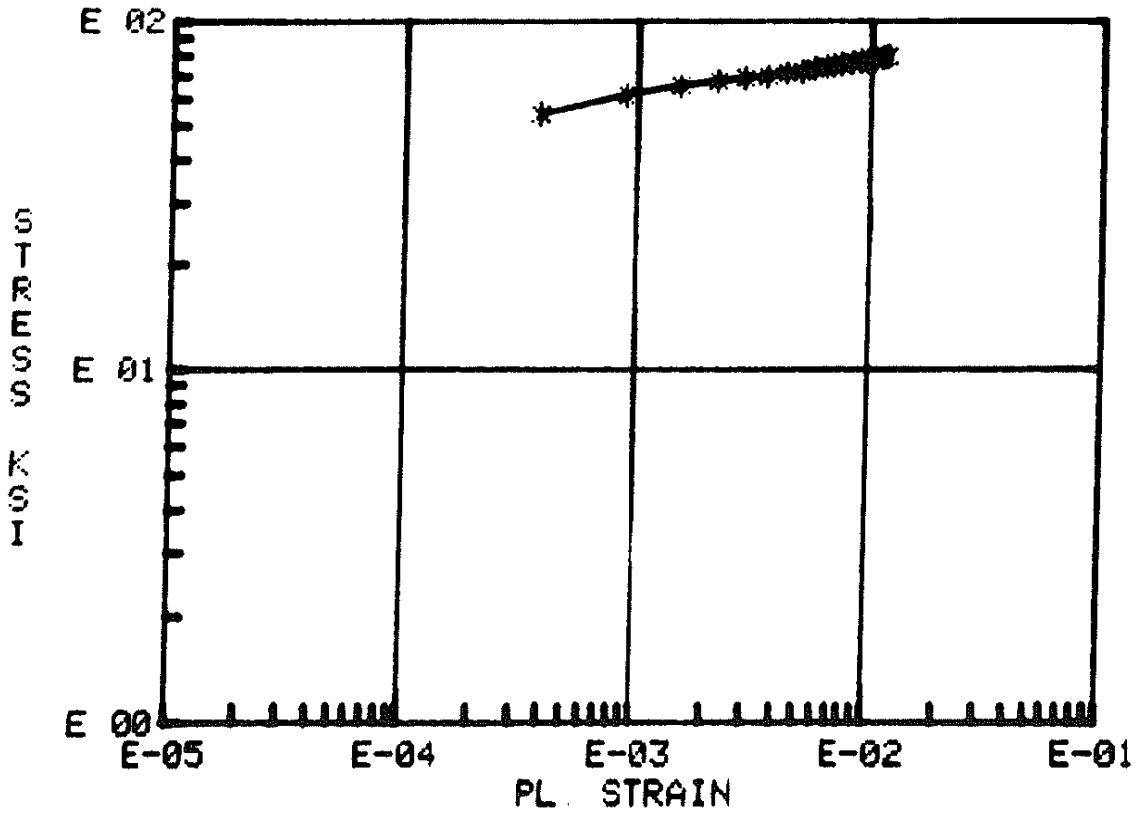

INCREMENTAL STEP TEST OF SPECIMEN # 01 OF NICUAGE
RONZ 23-NOV-76
STRAIN RATE= 5.00000E-03 MAX STRAIN= .015
ELASTIC MODULUS= 29879.5 KSI
BLOCK 8
E 02
1.00
0.50
0.00
-0.50
-1.00
STRESS KSI
-1.50
-0.75
0.00
0.75
1.50
STRAIN
E-02

INCREMENTAL STEP TEST OF SPECIMEN # 01 OF NICUAGE
RONZ 23-NOV-76

STRAIN RATE= 5.00000E-03 MAX STRAIN= .015

ELASTIC MODULUS= 29879.5 KSI
BLOCK 8

N'= .0996847
K'= 123.506 KSI



INCREMENTAL STEP TEST OF SPECIMEN # 01 OF NICUAGE
RONZ 23-NOV-76

STRAIN RATE= 5.00000E-03 MAX STRAIN= .015

ELASTIC MODULUS= 29879.5 KSI
BLOCK 8

***** STRESS IN KSI UNITS

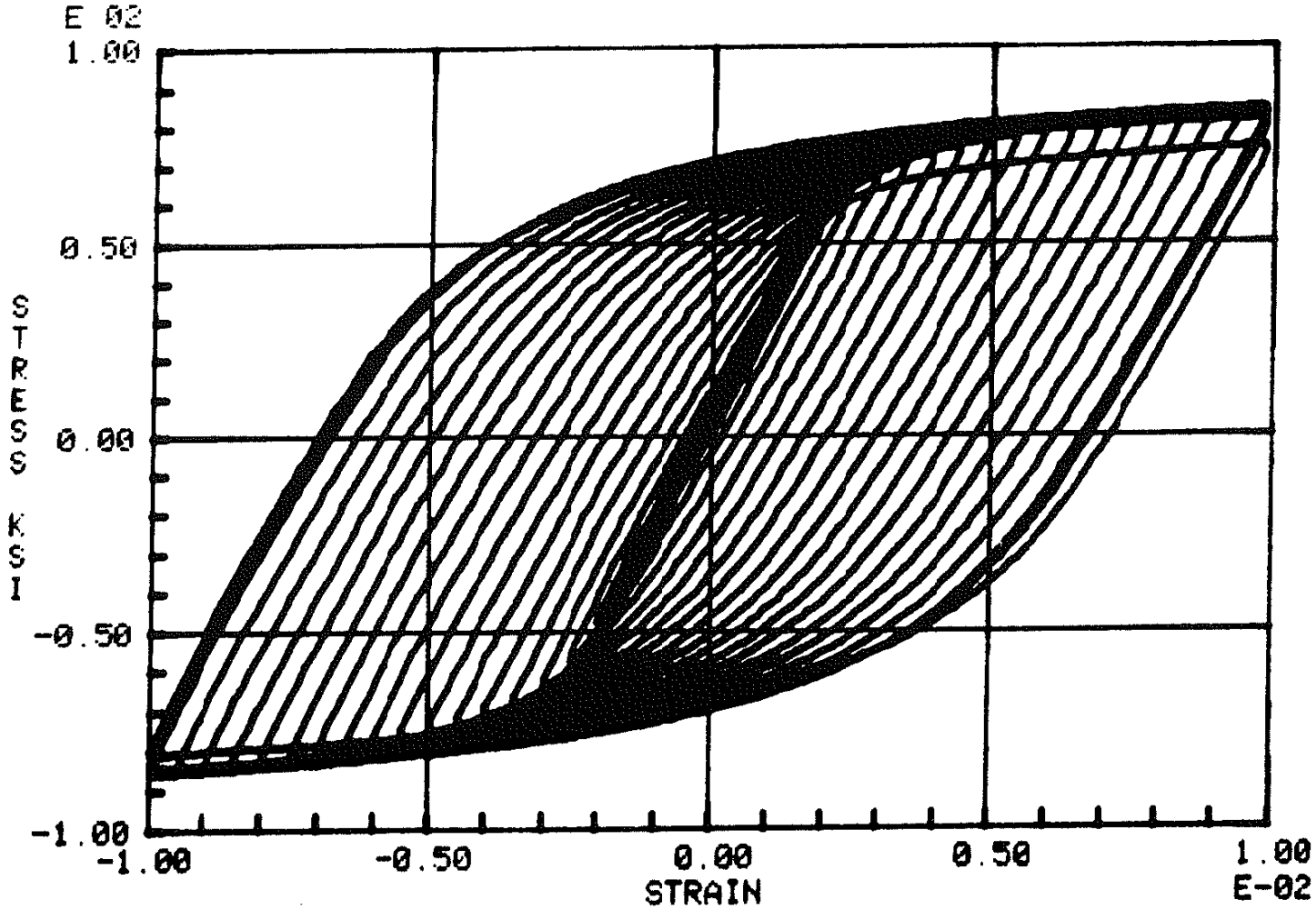
| ********** AMPLITUDES ********** | | | -- ******** MEANS ******** | | |
|---|---|---|---|---|---|
| CYC | STRAIN | STRESS | PL. STRAIN | STRAIN | STRESS |
| 1 | 6.15535E-04 | 17.6566 | 2.46096E-05 | 1.95407E-05 | 8.32668 |
| 2 | 1.45579E-03 | 39.4263 | 1.36279E-04 | -3.90816E-05 | 5.81864 |
| 3 | 2.20811E-03 | 54.4745 | 3.84970E-04 | -2.93112E-05 | 3.41093 |
| 4 | 2.96043E-03 | 61.9986 | 8.85476E-04 | -3.90814E-05 | 1.90611 |
| 5 | 3.70787E-03 | 65.5039 | 1.51540E-03 | -2.44259E-05 | 1.20385 |
| 6 | 4.44553E-03 | 67.6166 | 2.18255E-03 | -3.90816E-05 | .702251 |
| 7 | 5.17831E-03 | 69.1215 | 2.86497E-03 | -6.83928E-05 | .401287 |
| 8 | 5.90132E-03 | 70.3253 | 3.54769E-03 | -4.88518E-05 | .200642 |
| 9 | 6.66341E-03 | 71.4288 | 4.27285E-03 | -2.93113E-05 | .100323 |
| 10 | 7.36688E-03 | 72.3819 | 4.94442E-03 | -8.79334E-05 | -.0501595 |
| 11 | 8.05081E-03 | 73.3349 | 5.59645E-03 | -1.27016E-04 | -.200645 |
| 12 | 8.86175E-03 | 74.2378 | 6.37718E-03 | -7.81631E-05 | -.300964 |
| 13 | 9.53591E-03 | 75.0404 | 7.02447E-03 | 6.83926E-05 | -.300964 |
| 14 | .0100733 | 75.7427 | 7.53834E-03 | -5.86221E-05 | -.401283 |
| 15 | .0108891 | 76.5452 | 8.32731E-03 | -1.80752E-04 | -.601925 |
| 16 | .0117831 | 77.3478 | 9.19444E-03 | -6.83931E-05 | -.601929 |
| 17 | .0123107 | 77.9497 | 9.70190E-03 | 6.83931E-05 | -.601929 |
| 18 | .0130777 | 78.652 | .0104454 | 1.41671E-04 | -.702251 |
| 19 | .0139863 | 79.3542 | .0113305 | -1.12359E-04 | -.80257 |
| 20 | .0146654 | 79.9562 | .0119894 | 1.17245E-04 | -.80257 |

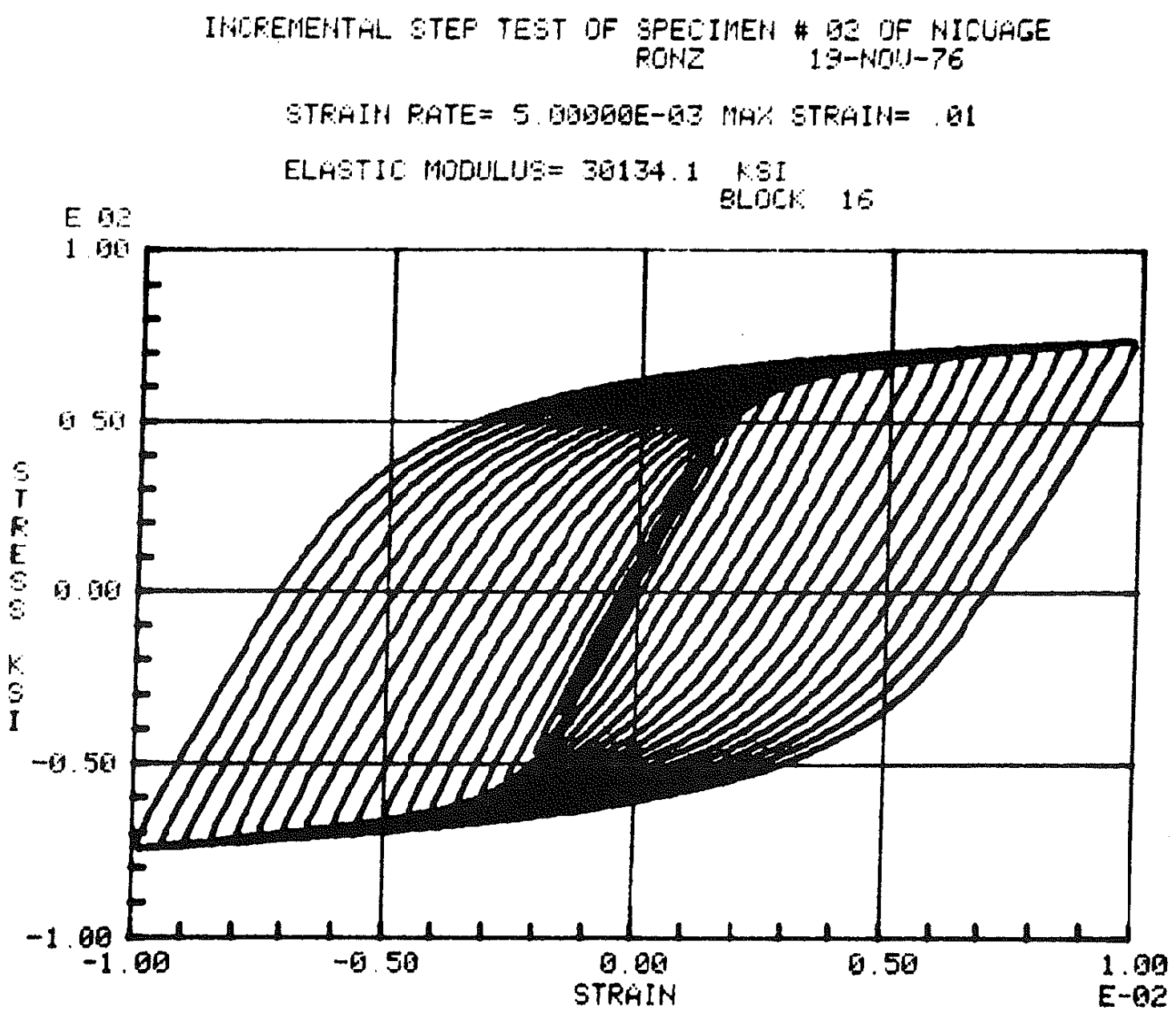
PRECYCLED TENSION TEST

INCREMENTAL STEP TEST OF SPECIMEN # 02 OF NICUAGE
RONZ 19-NOV-76

STRAIN RATE= 5.00000E-03 MAX STRAIN= .01

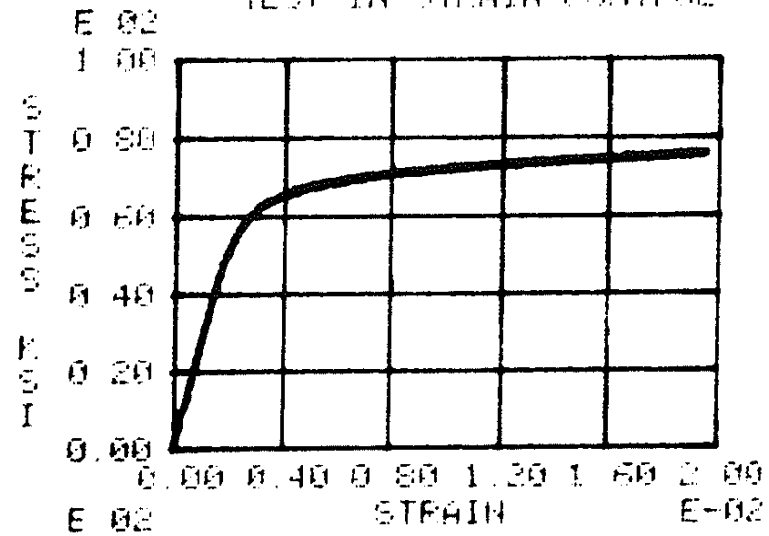
ELASTIC MODULUS= 30134.1 KSI
BLOCK .5




INCREMENTAL STEP TEST OF SPECIMEN # 02 OF NICUAGE
RONZ 19-NOV-76
STRAIN RATE= 5.00000E-03 MAX STRAIN= .01
ELASTIC MODULUS= 30134.1 KSI
BLOCK 16
E 02
1.00
0.50
0.00
-0.50
-1.00
STRESS
KSI
-1.00
-0.50
0.00
0.50
1.00
STRAIN
E-02

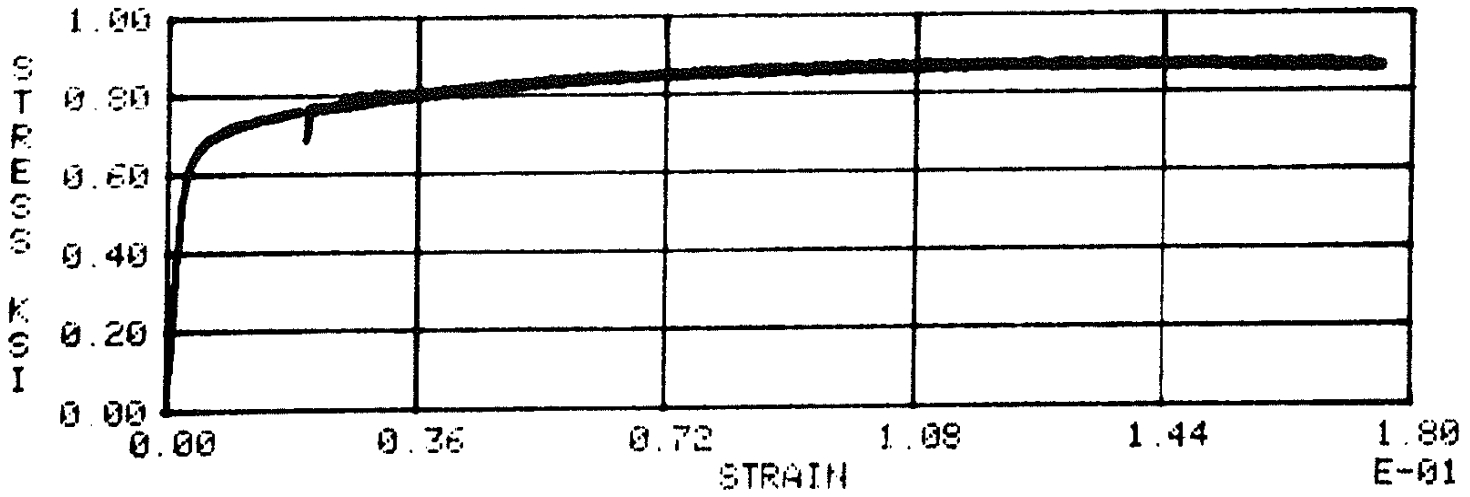
MONOTONIC TENSION TEST OF PRE-CYCLED NICUNGE SPECIMEN # 02
STRAIN RATE = 5.00000E-04 13-NOV-78 PONZ

TEST IN STRAIN CONTROL



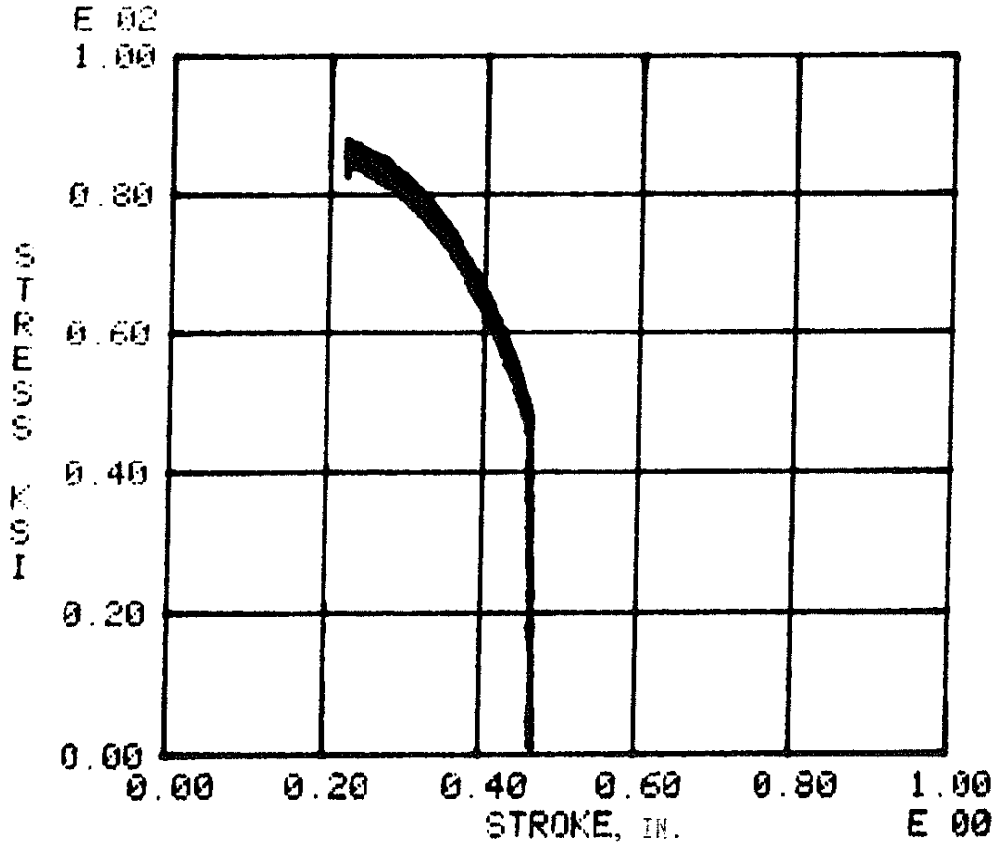

NOTE : COMPUTER MALFUNCTION AFTER BLOCK 16 - SPECIMEN PULLED IN TENSION AFTER PRECYCLING

SWITCH?



MONOTONIC TENSION TEST OF PRE-CYCLED NICUAGE SPECIMEN # 02
STRAIN RATE = 5.000000E-04 19-NOV-76 RON2

TEST IN STROKE CONTROL



MONOTONIC TENSION TEST OF PRE-CYCLED NICUAGE SPECIMEN # 02
STRAIN RATE = 5.000000E-04 19-NOV-76 RONZ

SUMMARY OF MONOTONIC TENSION PROPERTIES

| | | | |
|---|---|---|---|
| ELASTIC MODULUS | = | 27958.8 | KSI |
| 0.002 YIELD STRESS | = | 66.4126 | KSI |
| @ STRAIN | = | 4.31851E-03 | |
| ULTIMATE STRENGTH | = | 87.1791 | KSI |
| @ STRAIN | = | .139725 | |
| FRACTURE STRESS | = | 50.1124 | KSI |
| INITIAL SPECIMEN AREA | = | .0486956 | SQ IN |
| FINAL SPECIMEN AREA | = | .0132733 | SQ IN |
| % REDUCTION IN AREA | = | 72 7424 | % |
| TRUE FRACTURE STRAIN | = | 1.29984 | |
| TRUE FRACTURE STRENGTH | = | 183.847 | KSI |
| CORRECTED TO | = | 151.449 | KSI |
| STRAIN HARDENING EXPONENT | = | .12838 | |
| STRENGTH COEFFICIENT | = | 128.862 | KSI |

# STRESS-STRAIN HYSTERESIS LOOPS STRESS-LIFE RESPONSE AND PLASTIC STRAIN-LIFE RESPONSE FROM CONTROLLED STRAIN FATIGUE TESTS

IN-787

| Specimen No. | Strain Amplitude $\frac{\Delta\varepsilon}{2}$ | Reversals to Failure $2N_f$ | | Plastic Strain Amplitude $\frac{\Delta\varepsilon_p}{2}$ | Stabilized* Stress Amplitude $\frac{\Delta\sigma}{2}$, ksi |
|---|---|---|---|---|---|
| 15 | | 1 | | | |
| 4 | | 1 | | | |
| 08 | 0.01 | 2,080 | | | |
| 09 | 0.01 | 2,364 | 2,090 | 0.0071 | 85.0 |
| 13 | 0.01 | 1,830 | | | |
| 07 | 0.005 | 11,676 | | | |
| 05 | 0.005 | 9,630 | 10,287 | 0.0025 | 74.0 |
| 10 | 0.005 | 9,554 | | | |
| 12 | 0.003 | 78,790 | | | |
| 14 | 0.003 | 70,590 | 77,179 | 0.00075 | 68.0 |
| 17 | 0.003 | 82,158 | | | |
| 16 | 0.0018 | $>10^7$ | | | |
| 18 | 0.0018 | $>10^7$ | runouts | 0.00013 | 50.0 |
| 23 | 0.0018 | $>10^7$ | | | |
| 21** | 0.0018 | 800,500 | | | |
| 24** | 0.0018 | 1,000,000 | 894,535 | 0.00013 | 50.0 |
| 22** | 0.0018 | 883,104 | | | |

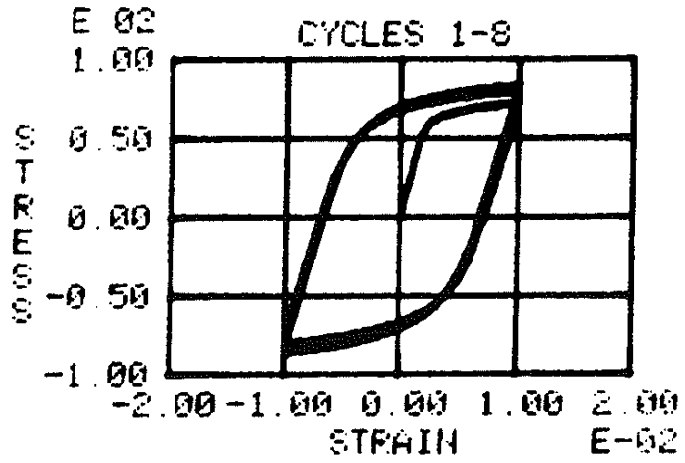
*Measured at 50% of life to failure.

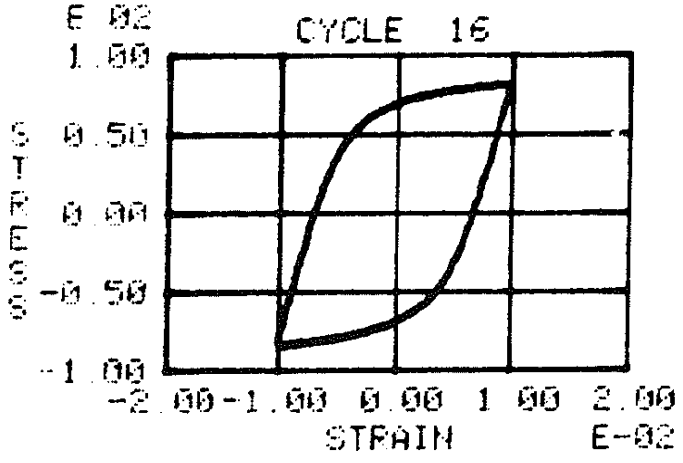
**Specimens overstrained every $10^5$ reversals to a strain of $\pm 1\%$ which was incrementally decreased to 0-0 in 40 reversals.

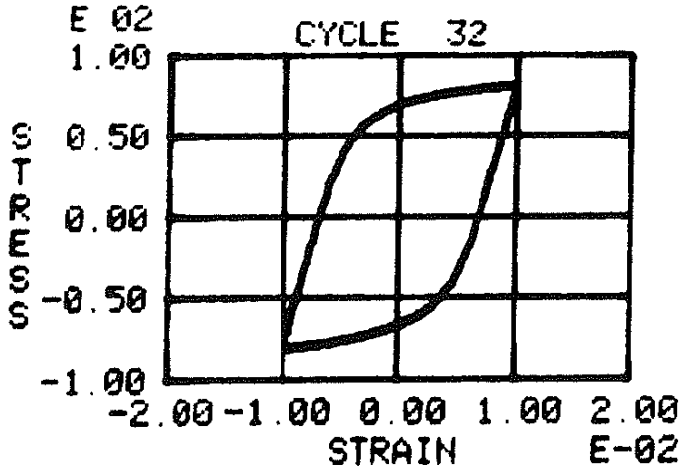
FATIGUE TEST OF SPECIMEN #08 OF NICUAGE
RONZ 6-DEC-76

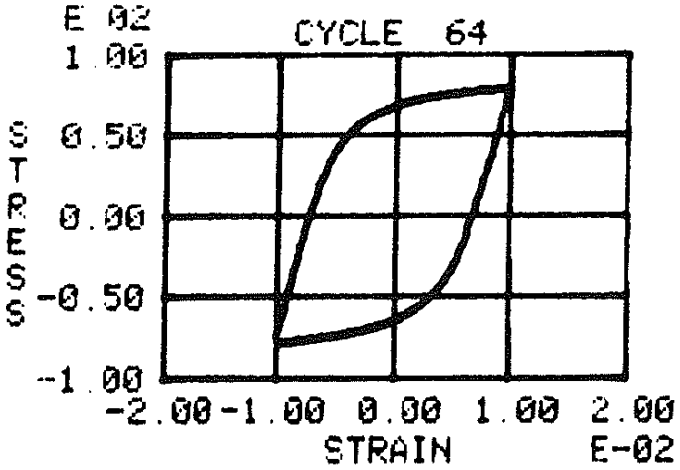
STRAIN RATE = .02 STRAIN LIMIT = .01

***** STRESS IN KSI UNITS
***** LOOPS RECORDED @ 0.1 HZ



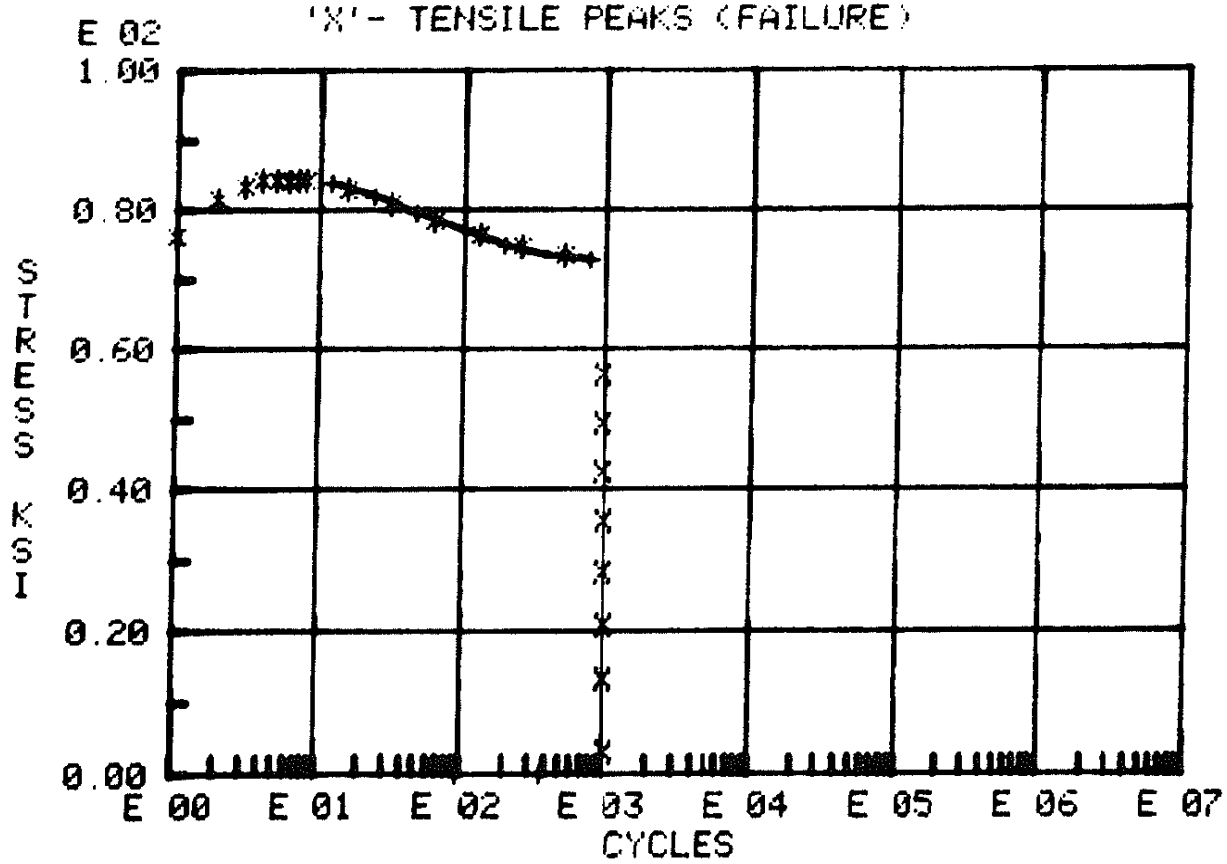



FATIGUE TEST OF SPECIMEN #08 OF NICUAGE
RONZ 6-DEC-76

STRAIN RATE = .02 STRAIN LIMIT = .01
ELASTIC MODULUS = 29523.4 KSI
***** STRESS IN KSI UNITS

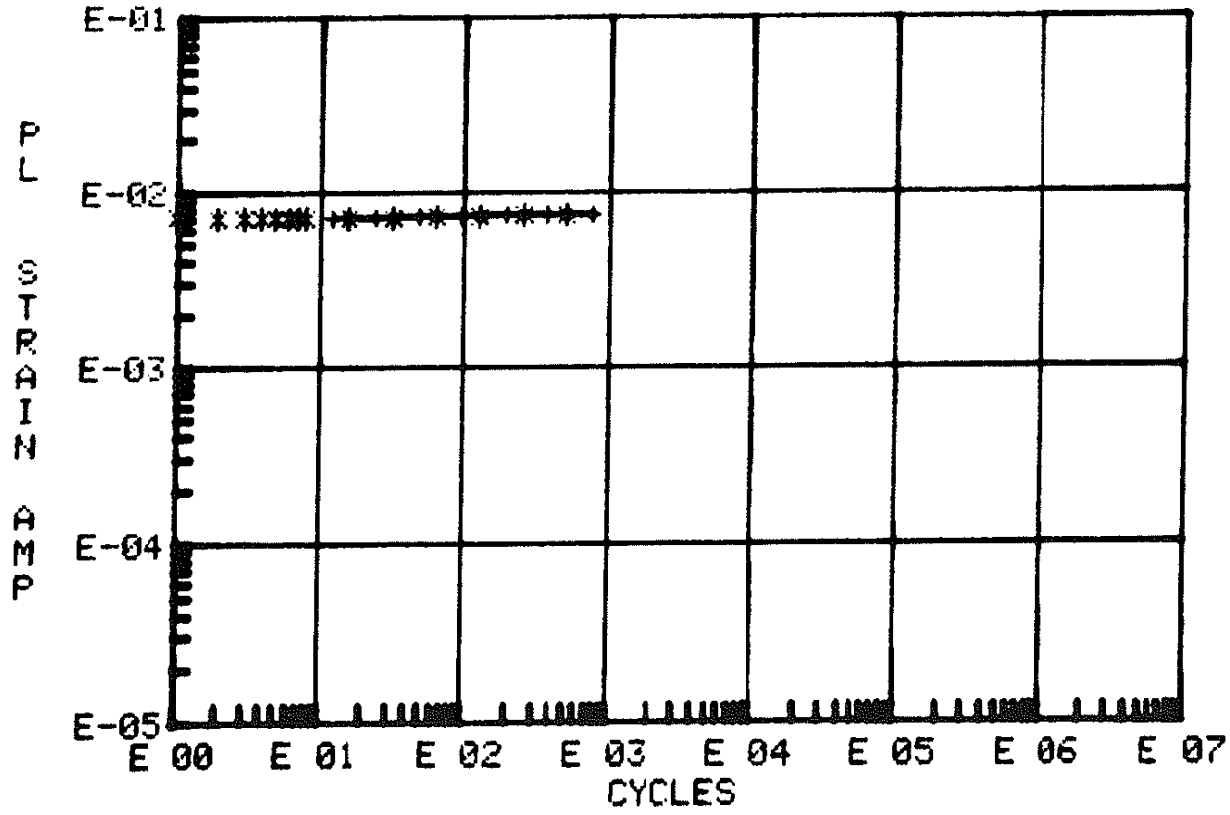
'*'- AMPLITUDES @ 0.1 HZ (LOOPS)
'+'- AMPLITUDES @ THE SPECIFIED STRAIN RATE
'X'- TENSILE PEAKS (FAILURE)



FATIGUE TEST OF SPECIMEN #08 OF NICUAGE
RUN2 6-DEC-76

STRAIN RATE = .02 STRAIN LIMIT = .01
ELASTIC MODULUS = 29523.4 KSI
***** STRESS IN KSI UNITS

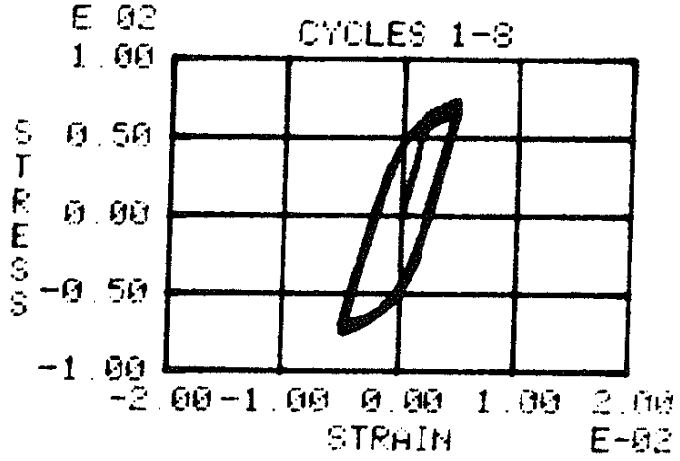
'*'- AMPLITUDES @ 0.1 HZ (LOOPS)
'+'- AMPLITUDES @ SPECIFIED STRAIN RATE

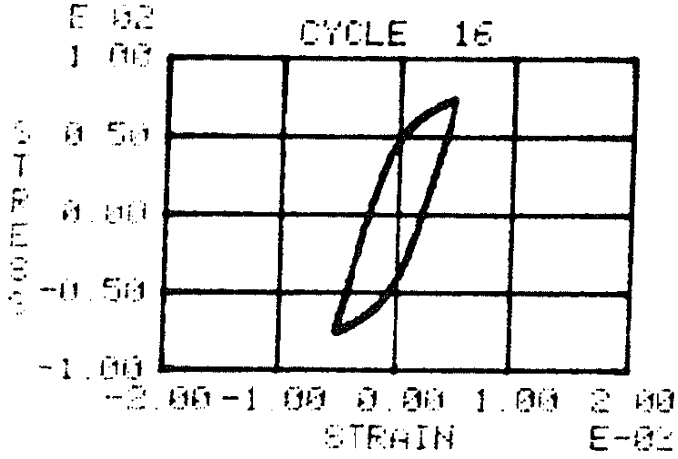


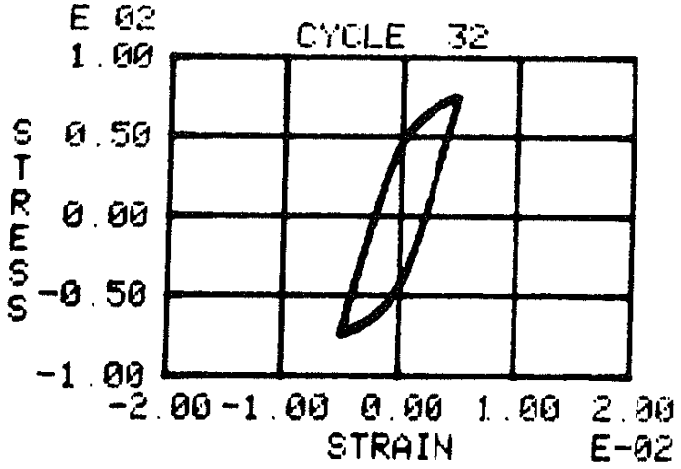
FATIGUE TEST OF SPECIMEN #07 OF NICUAGE
RUN2 07-DEC-76

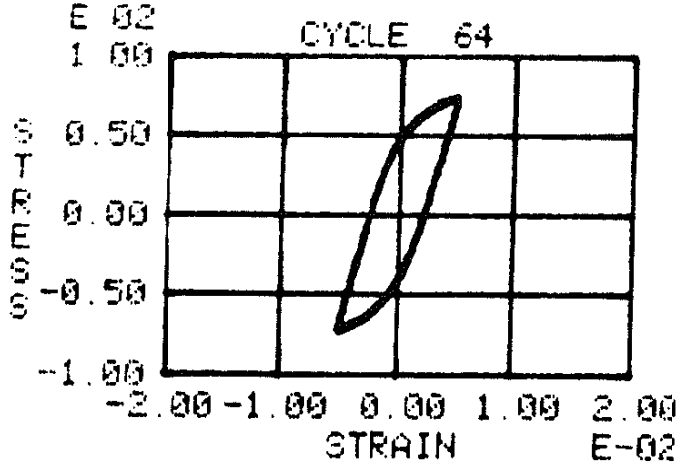
STRAIN RATE = .02 STRAIN LIMIT = 5.000000E-03

***** STRESS IN KSI UNITS
***** LOOPS RECORDED @ 0.1 HZ



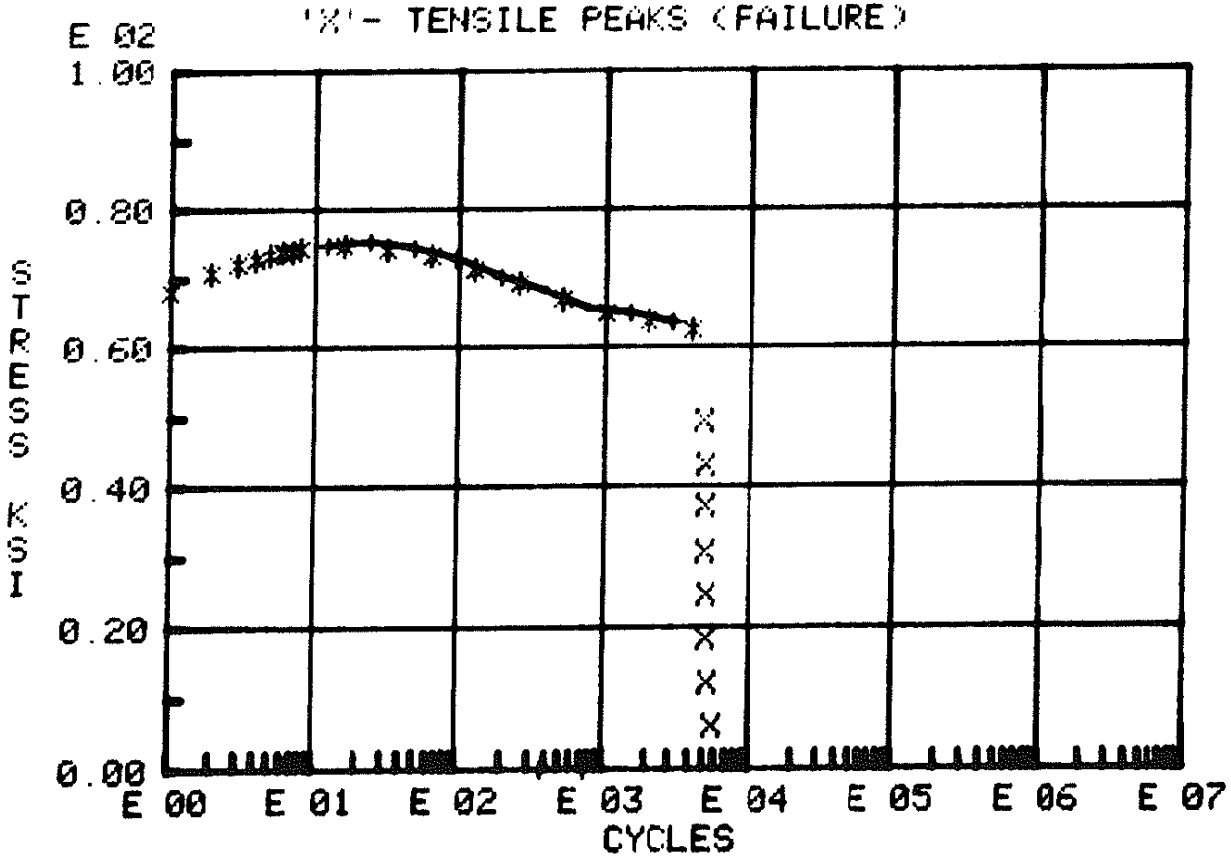



FATIGUE TEST OF SPECIMEN #07 OF NICUAGE
RONZ 07-DEC-76

STRAIN RATE = .02 STRAIN LIMIT = 5.00000E-03
ELASTIC MODULUS = 30297.7 KSI
***** STRESS IN KSI UNITS

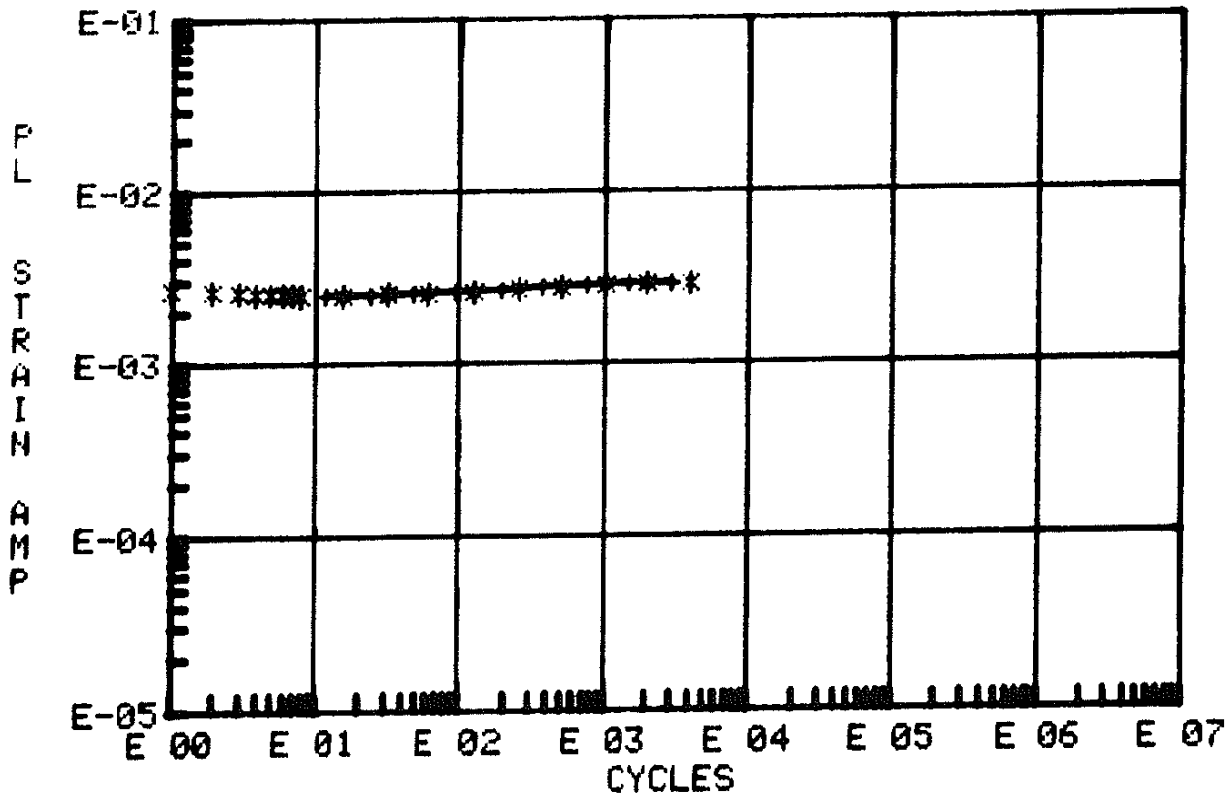
'*'- AMPLITUDES @ 0.1 HZ (LOOPS)
'+'- AMPLITUDES @ THE SPECIFIED STRAIN RATE
'X'- TENSILE PEAKS (FAILURE)



FATIGUE TEST OF SPECIMEN #07 OF NICUAGE
RONZ 07-DEC-76

STRAIN RATE = 02 STRAIN LIMIT = 5.00000E-03
ELASTIC MODULUS = 30297.7 KSI
***** STRESS IN KSI UNITS

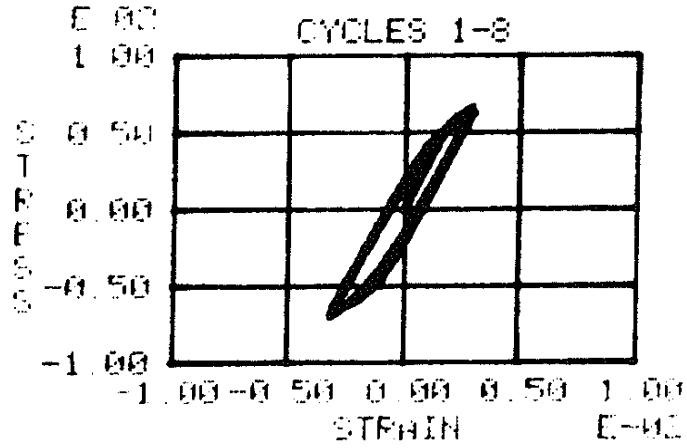
'*'- AMPLITUDES @ 0.1 HZ (LOOPS)
'+'- AMPLITUDES @ SPECIFIED STRAIN RATE

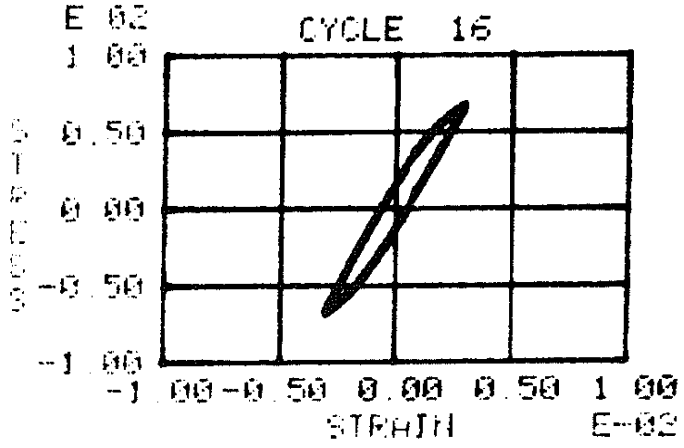


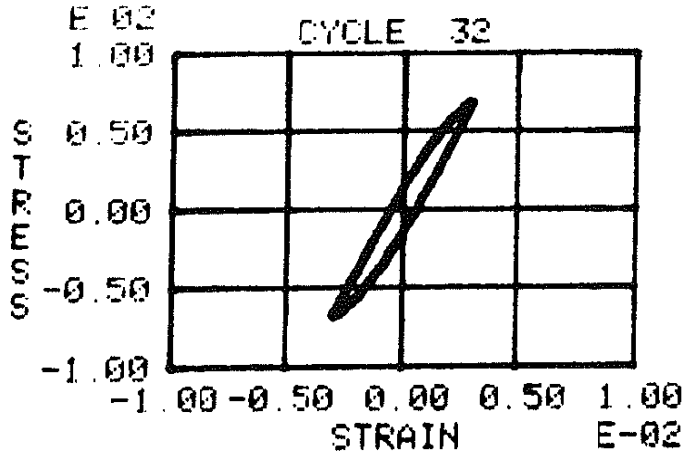
FATIGUE TEST OF SPECIMEN #12 OF NICUAGE
RONZ 18-JAN-77

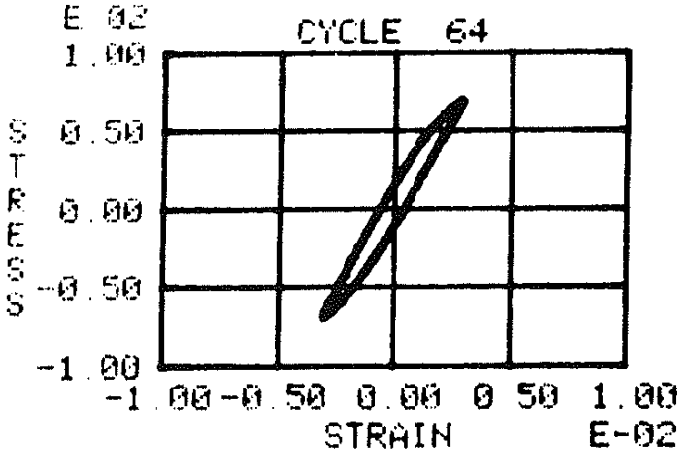
STRAIN RATE = .05 STRAIN LIMIT = 3.000000E-03

***** STRESS IN KSI UNITS
***** LOOPS RECORDED @ 0.1 HZ



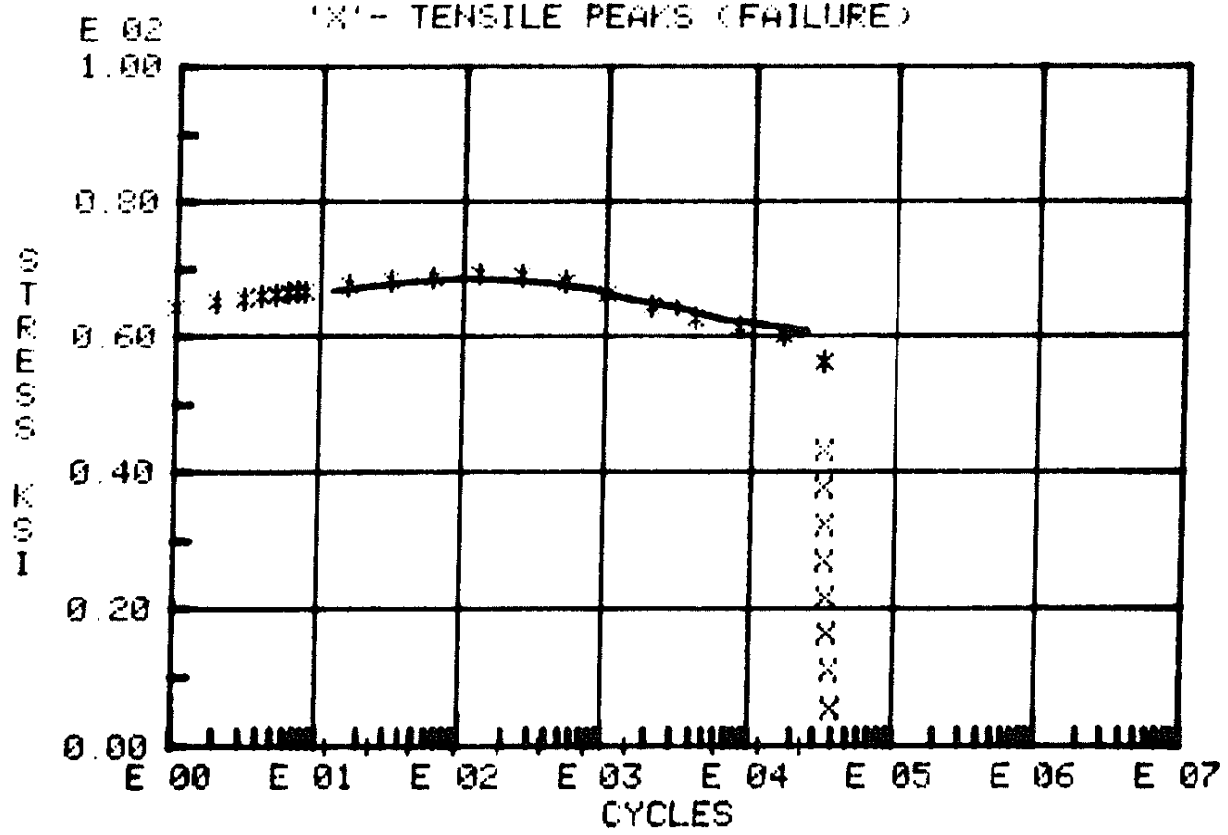



FATIGUE TEST OF SPECIMEN #12 OF NICUAGE
RUN2 18-JAN-77

STRAIN RATE = .05 STRAIN LIMIT = 3.00000E-03
ELASTIC MODULUS = 29772.8 KSI
***** STRESS IN KSI UNITS

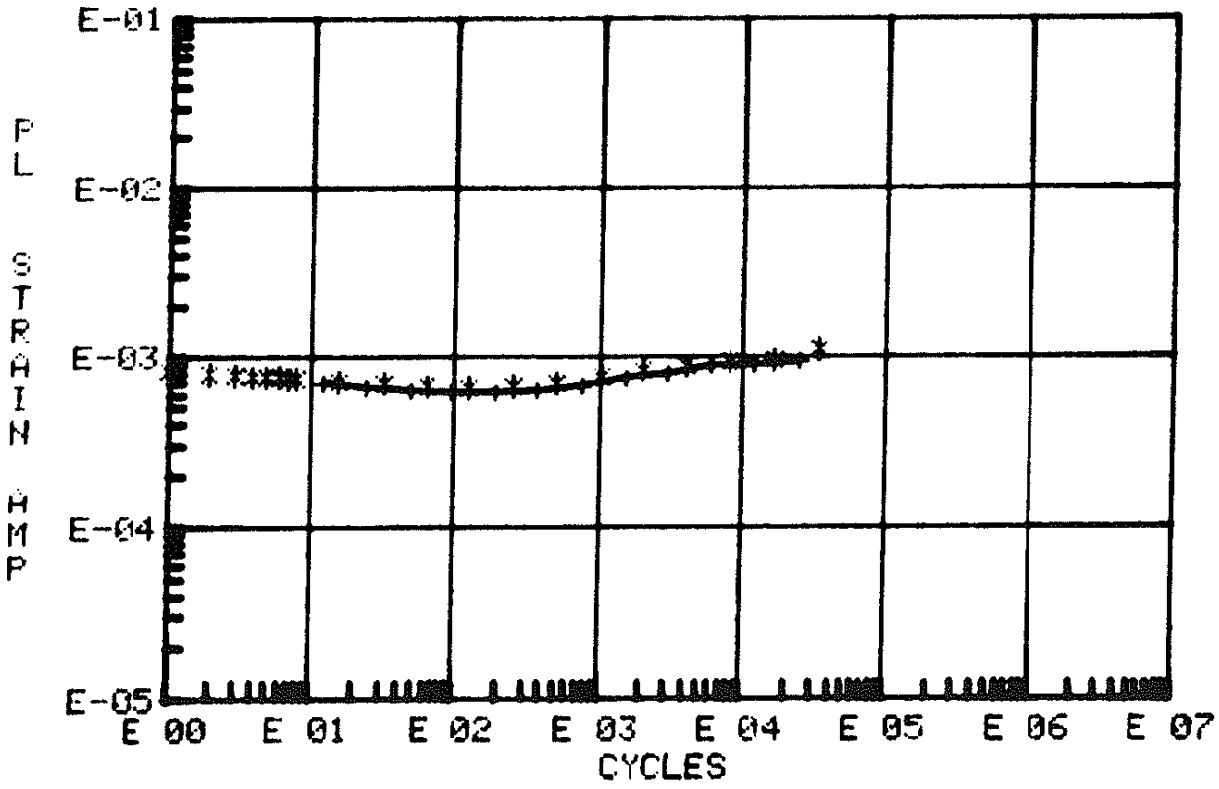
'*'- AMPLITUDES @ 0.1 HZ (LOOPS)
'+'- AMPLITUDES @ THE SPECIFIED STRAIN RATE
'X'- TENSILE PEAKS (FAILURE)



FATIGUE TEST OF SPECIMEN #12 OF NICUAGE
RONZ 18-JAN-77

STRAIN RATE = .05 STRAIN LIMIT = 3.00000E-03
ELASTIC MODULUS = 29772.0 KSI
***** STRESS IN KSI UNITS

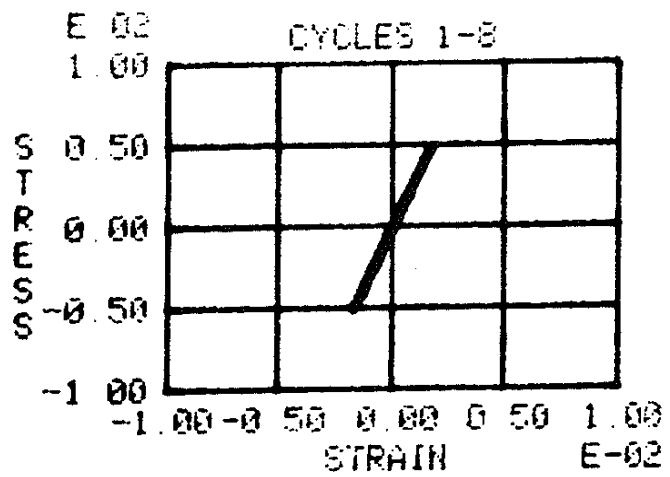
'*'- AMPLITUDES @ 0.1 HZ (LOOPS)
'+'- AMPLITUDES @ SPECIFIED STRAIN RATE

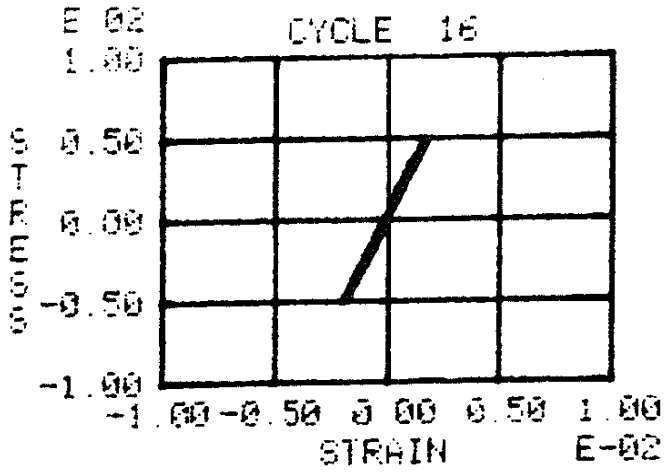


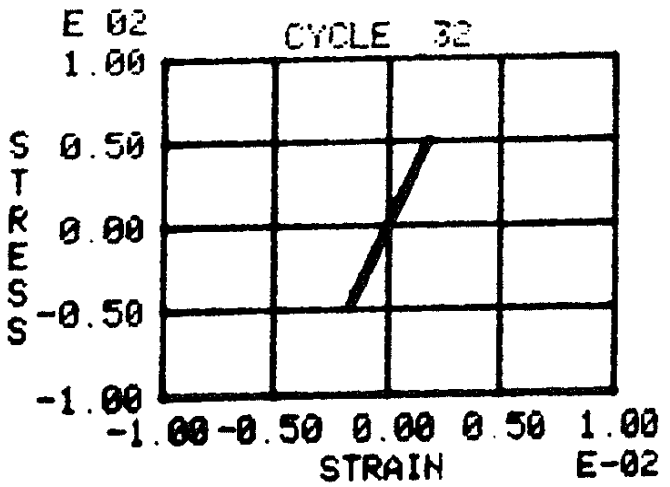
FATIGUE TEST OF SPECIMEN #23 OF NICUAGE
RONZ 19-MAR-77

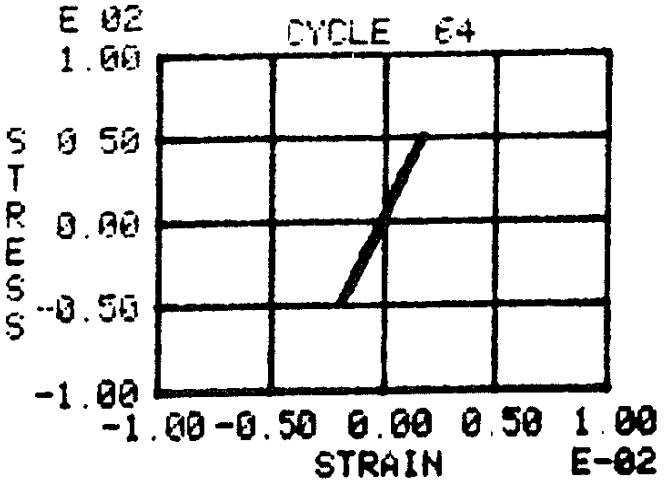
STRAIN RATE = 7.20000E-03 STRAIN LIMIT = 1.60000E-03

***** STRESS IN KSI UNITS
***** LOOPS RECORDED @ 0.1 HZ



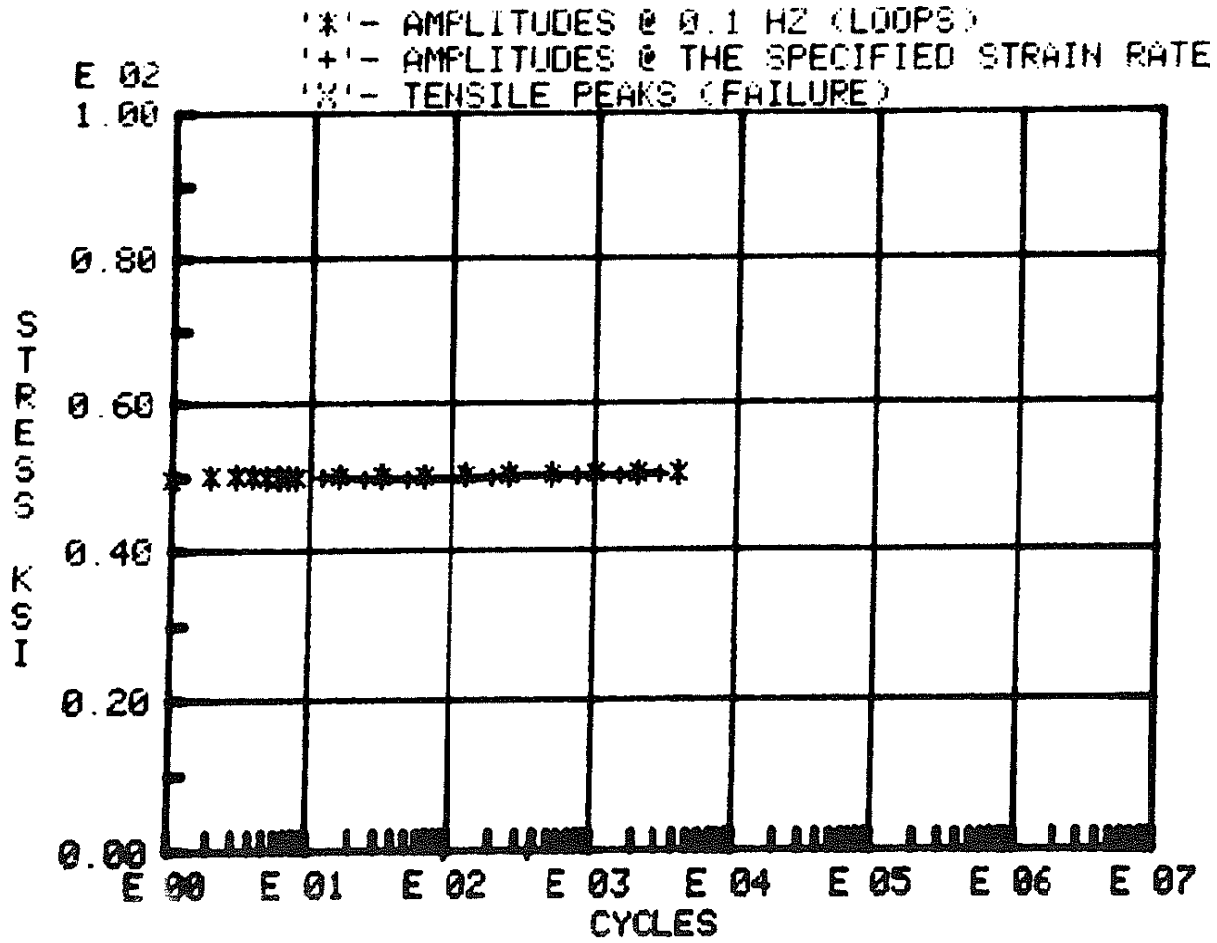



FATIGUE TEST OF SPECIMEN #23 OF NICUAGE
RONZ 19-MAR-77

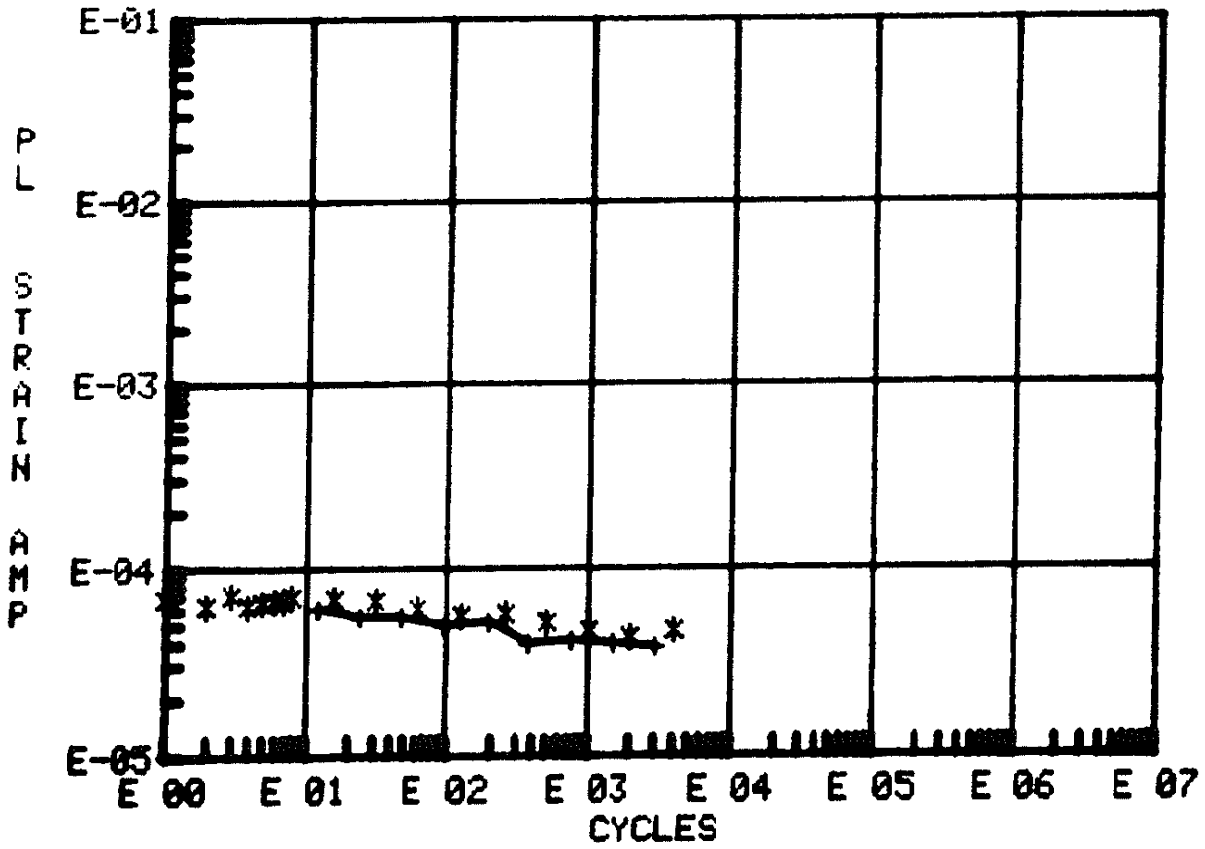
STRAIN RATE = 7.20000E-03 STRAIN LIMIT = 1.80000E-03
ELASTIC MODULUS = 29098.2 KSI
***** STRESS IN KSI UNITS
***** LOOPS RECORDED @ 0.1 HZ

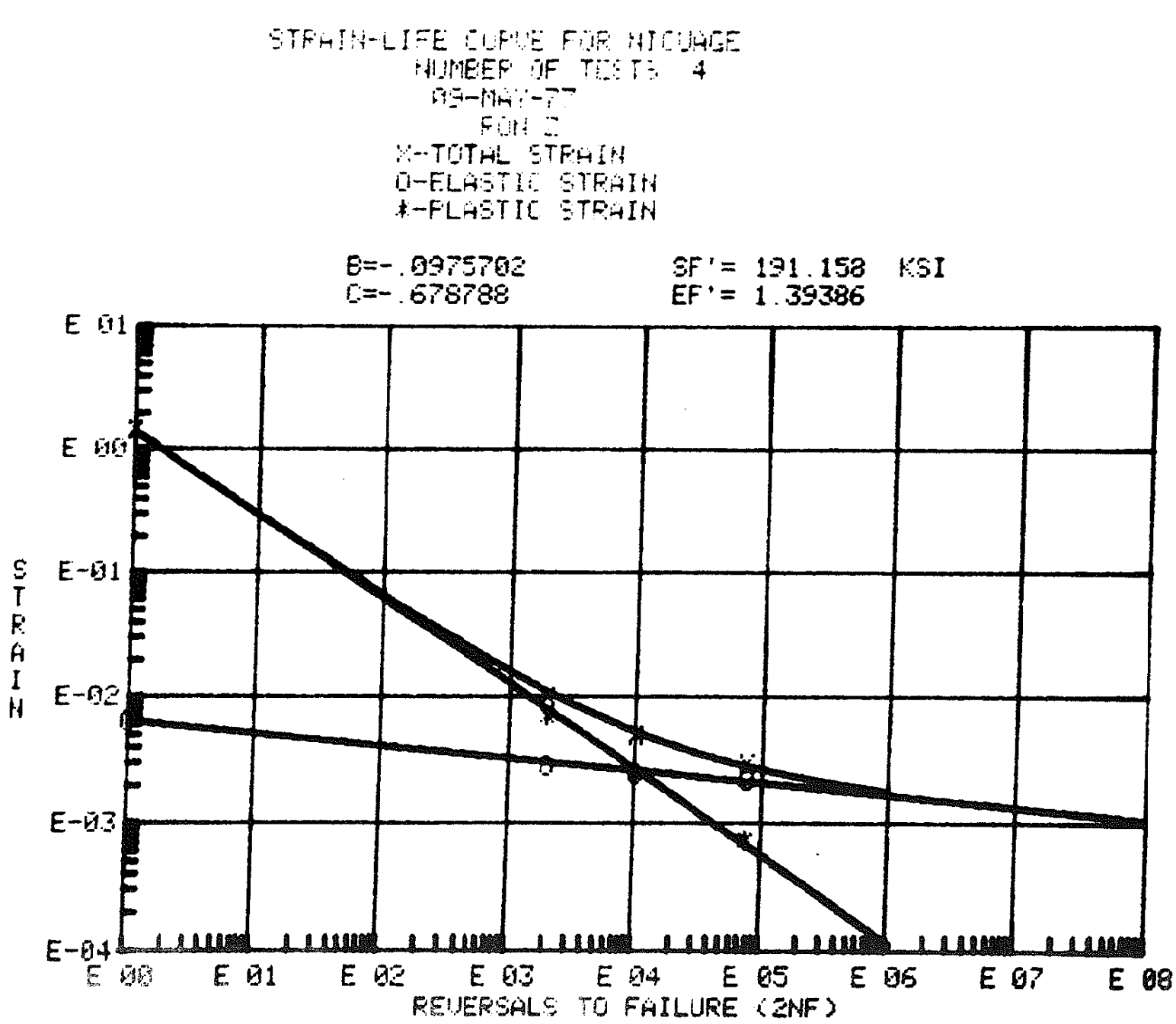


FATIGUE TEST OF SPECIMEN #23 OF NICUAGE
RONZ 19-MAR-77

STRAIN RATE = 7.20000E-03 STRAIN LIMIT = 1.80000E-03
ELASTIC MODULUS = 29098.2 KSI
***** STRESS IN KSI UNITS
***** LOOPS RECORDED @ 0.1 HZ

'*'- AMPLITUDES @ 0.1 HZ (LOOPS)
'+'- AMPLITUDES @ SPECIFIED STRAIN RATE




STRAIN-LIFE CURVE FOR NICUAGE
NUMBER OF TESTS 4
09-MAY-77
FOR 2
X-TOTAL STRAIN
O-ELASTIC STRAIN
*-PLASTIC STRAIN
B=-.0975702
C=-.678788
SF'= 191.158 KSI
EF'= 1.39386
E 01
E 00
E-01
E-02
E-03
E-04
STRAIN
E 00
E 01
E 02
E 03
E 04
E 05
E 06
E 07
E 08
REVERSALS TO FAILURE (2NF)