FCP Report No. 18

MATERIAL CHARACTERIZATION OF A NORMALIZED AND TEMPERED, 0.2 w/o C CAST STEEL

by

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ABSTRACT

Monotonic and cyclic stress-strain behavior and strain-life resistance of a 0.2 w/o C cast steel of 160 BHN are reported. This cast steel exhibits a monotonic 0.2% yield strength of 49 ksi and a minimum cyclic 0.2% yield strength of 47 ksi. The upper yield point is 58.5 ksi. However, due to cyclic softening, the cyclic flow stress is reduced to approximately 25 ksi. Engineering ultimate strength and ductility are comparable to a similar wrought steel of equal hardness.

As with other cast metals in which internal microdiscontinuities are present, the strain-life fatigue resistance is comparable to but slightly inferior to that of a wrought steel of equal hardness. Recently developed predictive techniques, which employ measurements of the size and distribution of the largest microdiscontinuities and matrix hardness measurement, produce an accurate description of the fatigue resistance of this cast steel.

A Report of the
FRACTURE CONTROL PROGRAM

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ACKNOWLEDGMENTS

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FOREWORD

This is the third in a series of the fatigue evaluation of steels of interest to sponsors of the Fracture Control Program (see FCP Nos. 12 on T-1 Steel and 13 on Cast 8630 Steel). General Motors Corporation, Electromotive Division supplied a cast, 0.2 w/o C steel at 160 BHN, in normalized and tempered condition for evaluation in this report. As in previous reports of this nature, the format includes reduced material characterization sheets as well as original laboratory records.

PROCEDURE

Specimens of the design shown in Fig. 1 were removed from cast keel blocks which were received in a normalized (1700° F) and tempered (1200° F) condition with a Brinell hardness of 160. All testing was accomplished using a ± 20 kip closed-loop test system.

RESULTS

Stress-Strain Behavior

On the Data Sheet for Material Characterization are listed the results from the monotonic stress-strain tests. Since these cast samples are of moderately low hardness with approximately a 75% ferritic, 25% pearlitic matrix and the internal microdiscontinuities are not significantly large, as shown in Fig. 2, the observed monotonic strength and ductility are comparable to a wrought steel of equal hardness.

As shown in Fig. 3, which is an enlargement of the stress-strain curves on the data sheets, the cast steel cyclically softens at strains less than ± 0.0046* and cyclically hardens at larger strains. Note also that there is a significant decrease

*From companion specimen cyclic stress-strain curve.

in the initial monotonic and cyclic "flow" strength (i.e., 59 ksi upper yield strength compared to 25 ksi). Consequently, in the stress-based design of a component to a maximum stress of 50 ksi (i.e., the lower yield strength) an "elastic" strain of approximately 0.0017 would be produced on the first application of load. Due to cyclic softening, however, a significant amount of plastic strain ($\epsilon_p \cong 0.0005$) would eventually result, since the material response follows the cyclic stress-strain curve. This would eventually cause a fatigue failure in about 10^5 reversals.* Secondly, the cyclic curve shown in the figure is essentially for a "bulk" or nominal stress-strain response of the cast steel. Since there are casting microdiscontinuities present, the local stresses and strains at these concentrations would be even greater than shown.

As demonstrated in FCP Report No. 13 on cast 8630 steel, employing the monotonic and cyclic properties to predict the strain-life response of cast metals can lead to serious errors in lives. It is somewhat erroneous to even list cyclic material properties for cast metals, since local stresses and strains at casting microdiscontinuities govern behavior. These properties are included on the data sheet for convenience only and should be used with caution!

Strain-Life Resistance

Figure 4 illustrates the constant amplitude, strain-life curves for single samples which received an initial precycle of 5 cycles at ± 0.013 with an incremental decrease of amplitude to zero stress and strain in 20 cycles. These results are listed at the back of the report.

Superimposed in Fig. 5 is a strain-life curve predicted from hardness results (see Appendix A) and considering the cast steel to be wrought. As shown, such attempts may result in non-conservative predictions by orders of magnitude in life,

*See Fig. 5. At a strain of 0.0017, $2N_f \cong 10^5$ reversals.

because the effect of microdiscontinuities is not taken into account. Figure 6 shows micrographs of the fracture surface of the fatigue specimens. Note that all failures initiated from gas bubbles at or in the proximity of surfaces.

Predicted Strain-Life Curve for Cast Steel

It has been suggested in previous FCP reports (14 and 15) that the size, shape and distribution of microdiscontinuities must be included in life predictions for cast irons.

Since the largest discontinuities, particularly those at or in proximity to the surface of a sample, control fatigue behavior, they are the most important.* Table 1 lists results of microdiscontinuity diameter measurements made on four specimens whose gage length (i.e., the stressed volume) was divided into eight sectors. Only the largest discontinuity visible at 7X in each sector is listed. If no "large discontinuity" is observed, a dash is recorded but these "no show" observations are included in the subsequent ranking of these data which is shown in Table 2. These results, plotted as log-normal and Weibull distributions, are shown in Figs. 7 and 8.

To determine a fatigue notch factor, K_f, for the microdiscontinuities, the recently proposed procedure outlined in FCP No. 15 was employed. Using an average diameter ($d \cong 0.016$ in) of largest microdiscontinuities from the four samples (i.e., 0.02047, 0.01968, 0.01181 and 0.00984), a value for the fatigue notch factor, K_f, was determined by

$$K_f = 1 + \frac{K_t - 1}{1 + a/r}$$

Shape { K_t = theoretical stress concentration factor for hemispherical shaped surface discontinuity ($\cong 2.5$)

*This, of course, presumes a uniform, random distribution of largest flaws or "weakest links."

$$a = \left(\frac{300}{0.5\ \mathrm{BHN}}\right)^{1.8} \times 10^{-3}\ \mathrm{in} = 0.011\ \mathrm{in}$$

$$\text{Size} \begin{cases} r = \frac{0.016}{2} = 0.008\ \mathrm{in} \end{cases}$$

$$\therefore\ K_f = 1.6$$

Incorporating results of the wrought steel prediction shown in Fig. 5, values for the Neuber parameter, $(\Delta\sigma\ \Delta\epsilon\ E_s)^{\frac{1}{2}}$, were obtained. This particular parameter would describe the fatigue resistance of the equivalent wrought steel. The quotient $(\Delta\sigma\ \Delta\epsilon\ E_s)/K_f = (\Delta S\ \Delta e\ E_c)^{\frac{1}{2}}$ is plotted in Fig. 9 in comparison to the Neuber parameter from the cast steel test results. Since the average diameter of the largest microdiscontinuities was used to determine K_f, this curve is for median behavior. Therefore, employing the size and shape of the average largest surface microdiscontinuity to determine a fatigue notch factor and appropriately modifying the Neuber parameter for the matrix steel provides a predicted cast steel curve. As shown, the agreement is quite good.

In the predictive technique outlined above, there have been several assumptions, namely that initiation of a fatigue crack occurs at surface imperfections. The rationale of this assumption is the increase in value of the theoretical stress concentration factor, K_t, as a microdiscontinuities position in a sample varies from center to surface. The value of K_t approaches 2.0 for a centerline spherical discontinuity and increases as the imperfection approaches the sample surface. Secondly, surface residual stresses are not, as yet, taken into account. If, for example, a sizable compressive residual stress exists, there is the possibility of sub-surface initiation as in the case of shot-peened or case hardened components. Thirdly, only a relatively small sample volume was scanned in order to ascertain the average "largest" microdiscontinuities. In order that this analysis be extended to larger volumes, a function describing the distribution of microdiscontinuities must be employed.

An approximate measure of the volume scanned during these observations, shown in Fig. 10, is given by

$$V_o = \pi [r_o^2 - (r_o - D)^2] \, \ell \cdot n$$

where; r_o = radius of gage section of specimen (0.1375 in)

D = average diameter of largest surface microdiscontinuities ($D = \overline{X} = 0.011$ in)

ℓ = gage length of specimen (0.75 in)

n = number of specimens (4)

$\therefore \; V_o \doteq 0.019 \text{ in}^3$

In fatigue, the ratio V/V_o may be treated as the number of "links" in a chain. If the probability of survival (one minus the probability of failure) is $1 - p_o$ when the sample size is V_o, then the probability of survival for a volume V, will be

$$(1 - p) = (1 - p_o)^{V/V_o}$$

As an example, assume the population of microdiscontinuities is described by the log-normal distribution shown in Fig. 7. The median flaw diameter (at $p_o = 0.5$) is 0.0036 in. For purposes of illustration, assume that a component with 100 times the volume of highly stressed material is to be considered. This corresponds to the $p = 0.999$ level for the smaller sample. The microdiscontinuity diameter at that level is 0.07 in. For a surface imperfection of this size, the value of K_f is approximately 2.2, which was used in the construction of the "lower bound" fatigue curve shown in Fig. 9. In such an extrapolation it is presumed that the foundry practice and cooling rate of the larger castings is equivalent to those of the keel blocks from which the specimens were removed.

Summary of Predictive Technique for Fatigue Behavior of Cast Irons

From surface observations of four specimens, the average largest microdiscontinuity was determined. Using a matrix hardness measurement, the average largest microdiscontinuity size, and a theoretical stress concentration factor a value of the fatigue notch factor was determined. The "average" fatigue resistance for this cast steel was then predicted. The good agreement between predicted and actual results appears to be excellent, indicating that further research merits attention. In order to extrapolate to the maximum size microdiscontinuities expected in a larger volume of material, a distribution function was introduced.

Conclusions

Monotonic stress-strain results of cast 0.2 w/o C steel at 160 BHN are consistent with a similar wrought steel. Cyclic stress-strain results indicate significant softening at small strains. Methods which employ matrix hardness and the size and shape of microdiscontinuities adequately predict fatigue resistance. A lower bound curve of fatigue resistance in larger volumes of material may be established by introducing a distribution function for the largest microdiscontinuities observed in the sample volume.

TABLE 1

LARGEST SURFACE DISCONTINUITY OBSERVED AT 7X, (INCHES)*

	Sector No.							
Sample No.	A1	A2	A3	A4	B1	B2	B3	B4
J3-12	0.00984	0.00669	-	-	-	0.00708	-	-
J3-9	0.02047	-	-	-	-	-	-	-
J3-3	-	-	-	0.01968	-	-	-	-
J3-6	0.00393	-	0.01181	0.01023	0.00787	-	0.01181	-

Average diameter $\overline{X}$ = 0.011 inches.

*Converted from millimeters.

- Indicates "no show" observation of discontinuity at 7X.

TABLE 2

MEDIAN RANKING OF 32 OBSERVATIONS

Order	Dia. (inches)	Rank
23	0.00393	0.7006
24	0.00669	0.7315
25	0.00708	0.7623
26	0.00787	0.7932
27	0.00984	0.8240
28	0.01023	0.8549
29	0.01181	0.8858
30	0.01181	0.9166
31	0.01968	0.9474
32	0.02047	0.9783

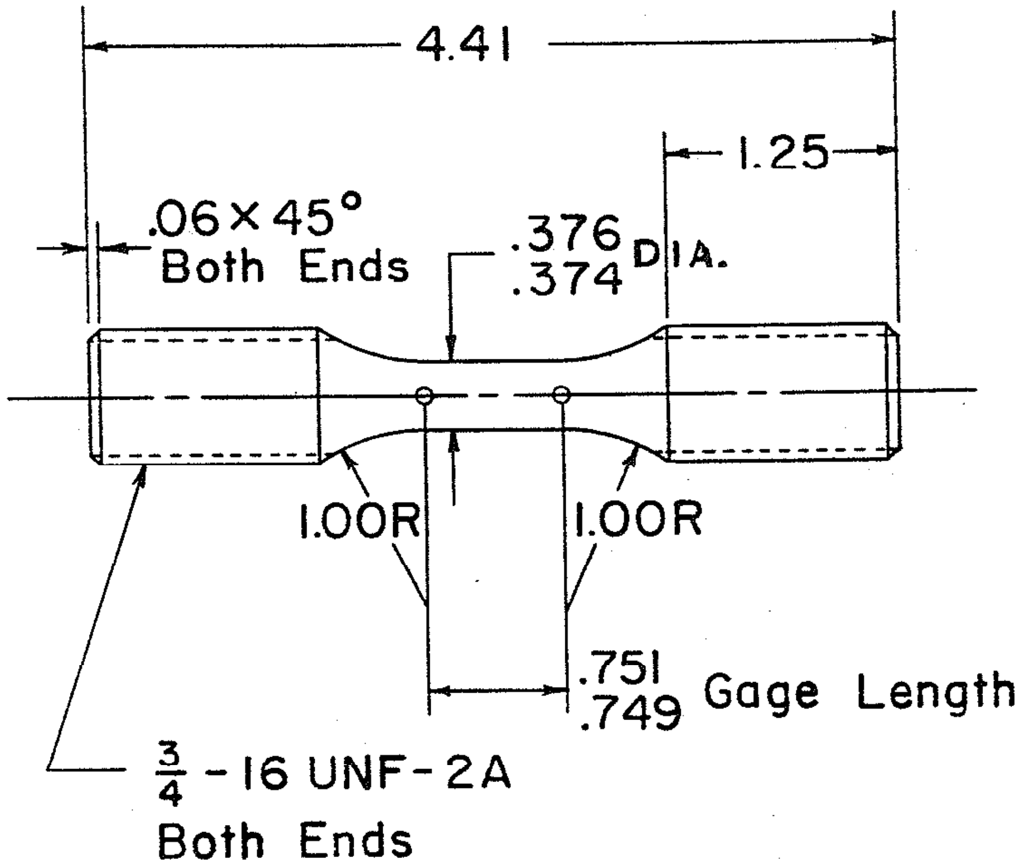
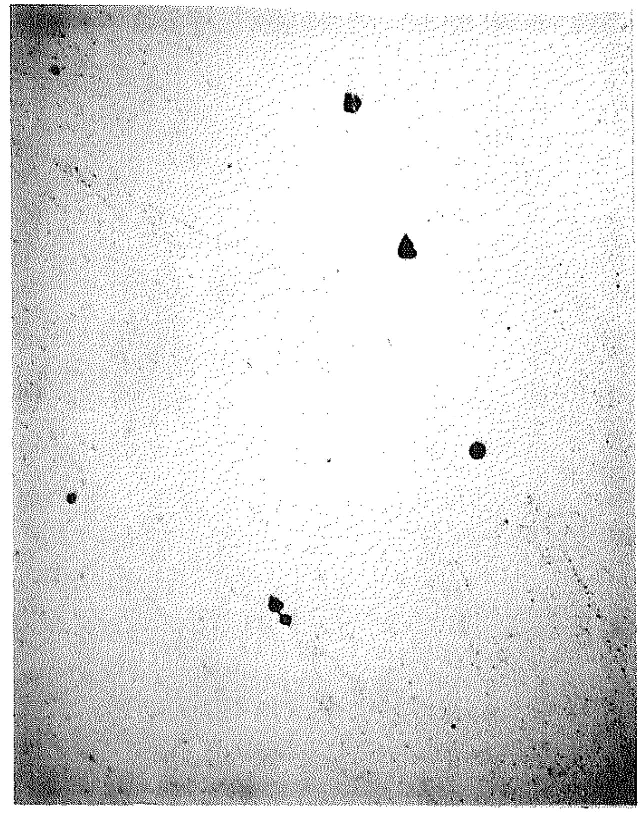


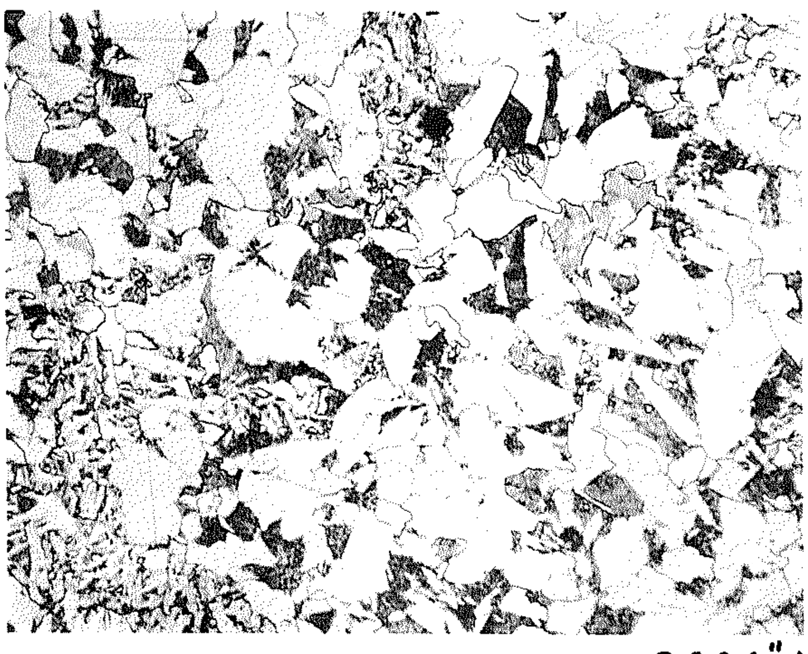
FIG. 1 - SPECIMEN DESIGN

0.006"



0.006"

TYPICAL MICRODISCONTINUITIES - UNETCHED



0.004"

FERRITIC-PEARLITIC MATRIX - 2% NITAL

FIGURE 2 - MACROGRAPHS SHOWING TYPE I INCLUSIONS & GAS BUBBLES AND MICROGRAPH OF 0.2 w/o C CAST STEEL

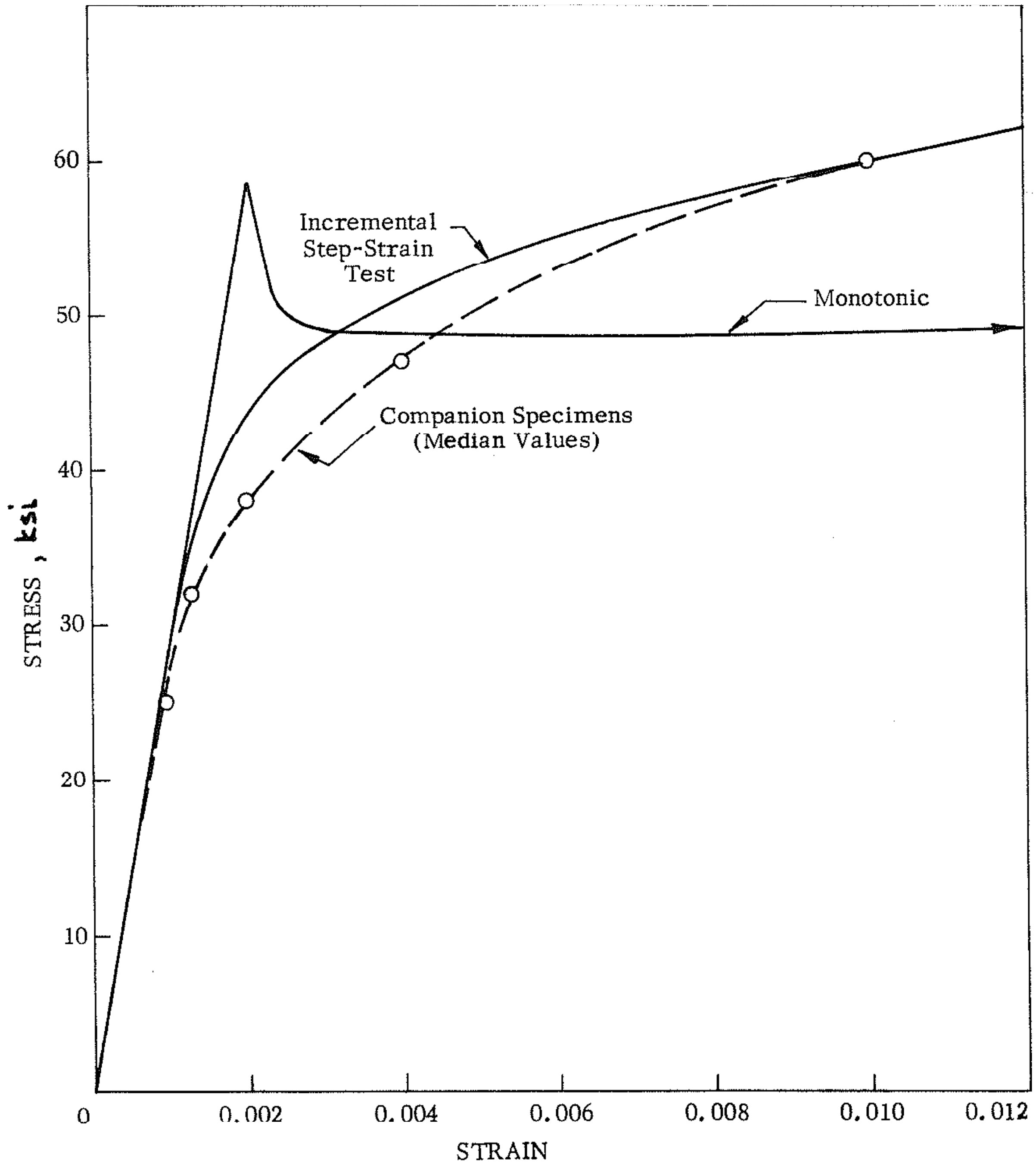


FIGURE 3 - MONOTONIC & CYCLIC STRESS - STRAIN CURVES FOR 0.2% C CAST STEEL @ 160 BHN

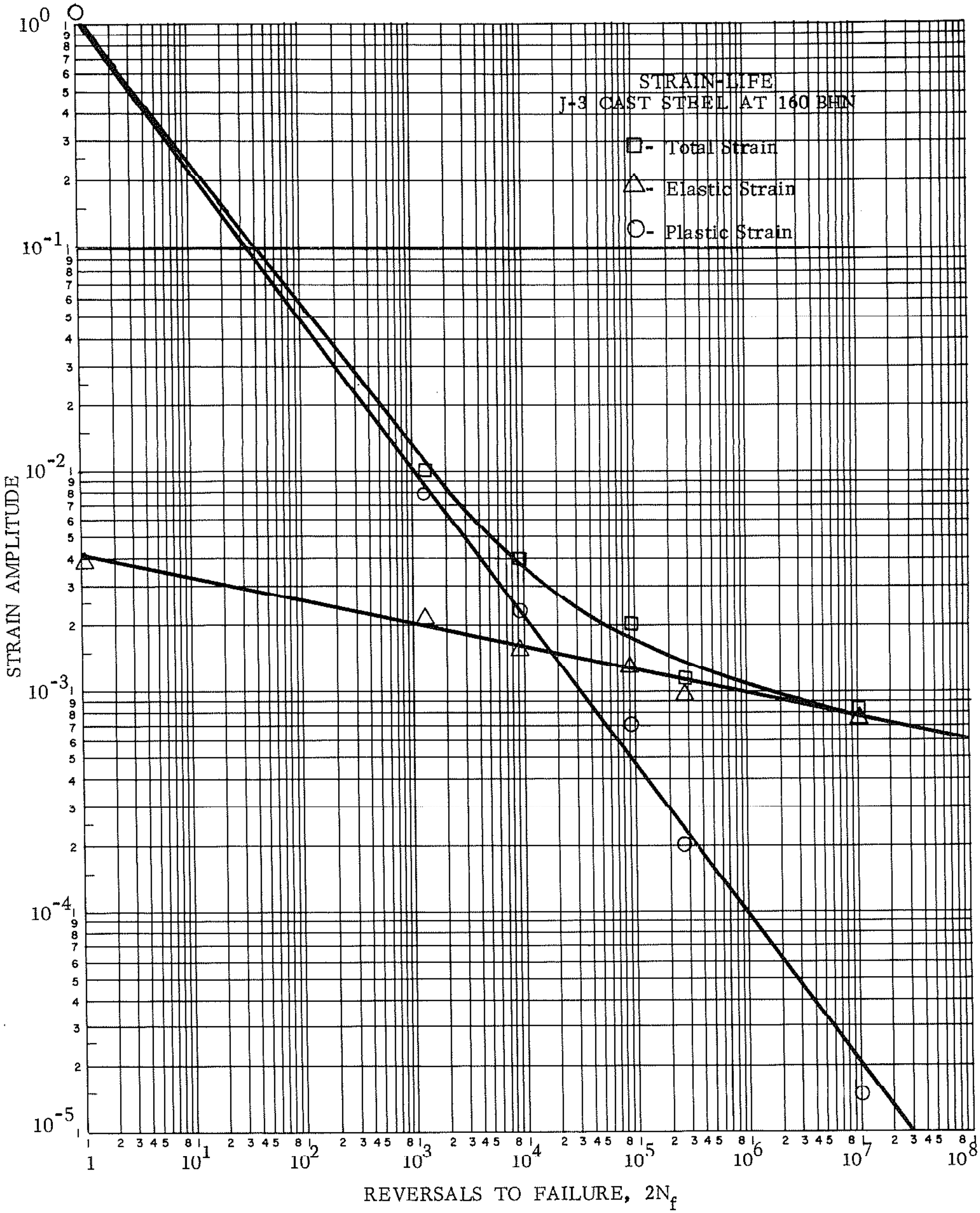


FIGURE 4 - STRAIN-LIFE CURVE FOR CAST 0.2 w/o C STEEL @ 160 BHN

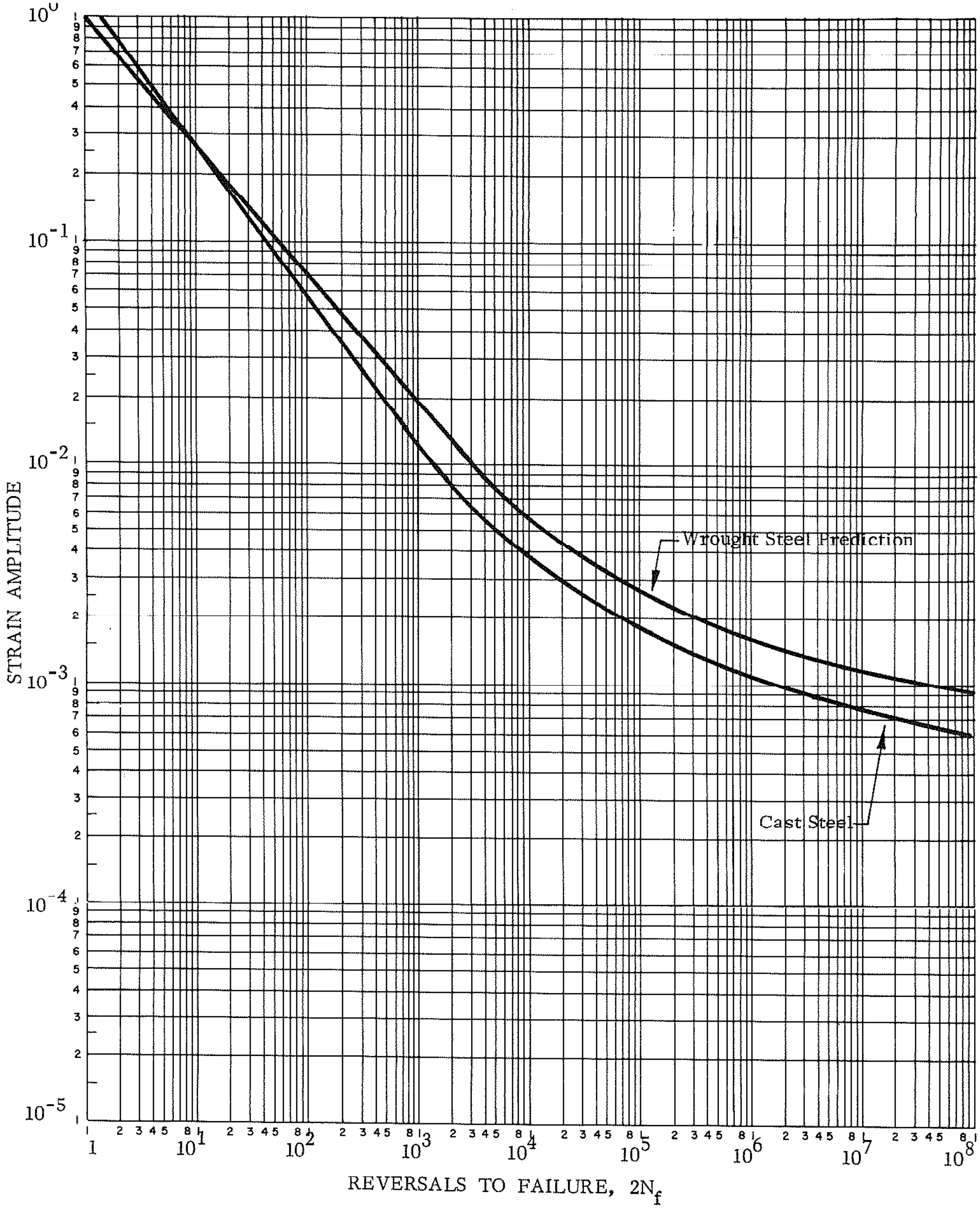


FIGURE 5 - STRAIN-LIFE FOR CAST 0.2w% C STEEL IN COMPARISON TO AN EQUAL HARDNESS WROUGHT STEEL (160BHN).

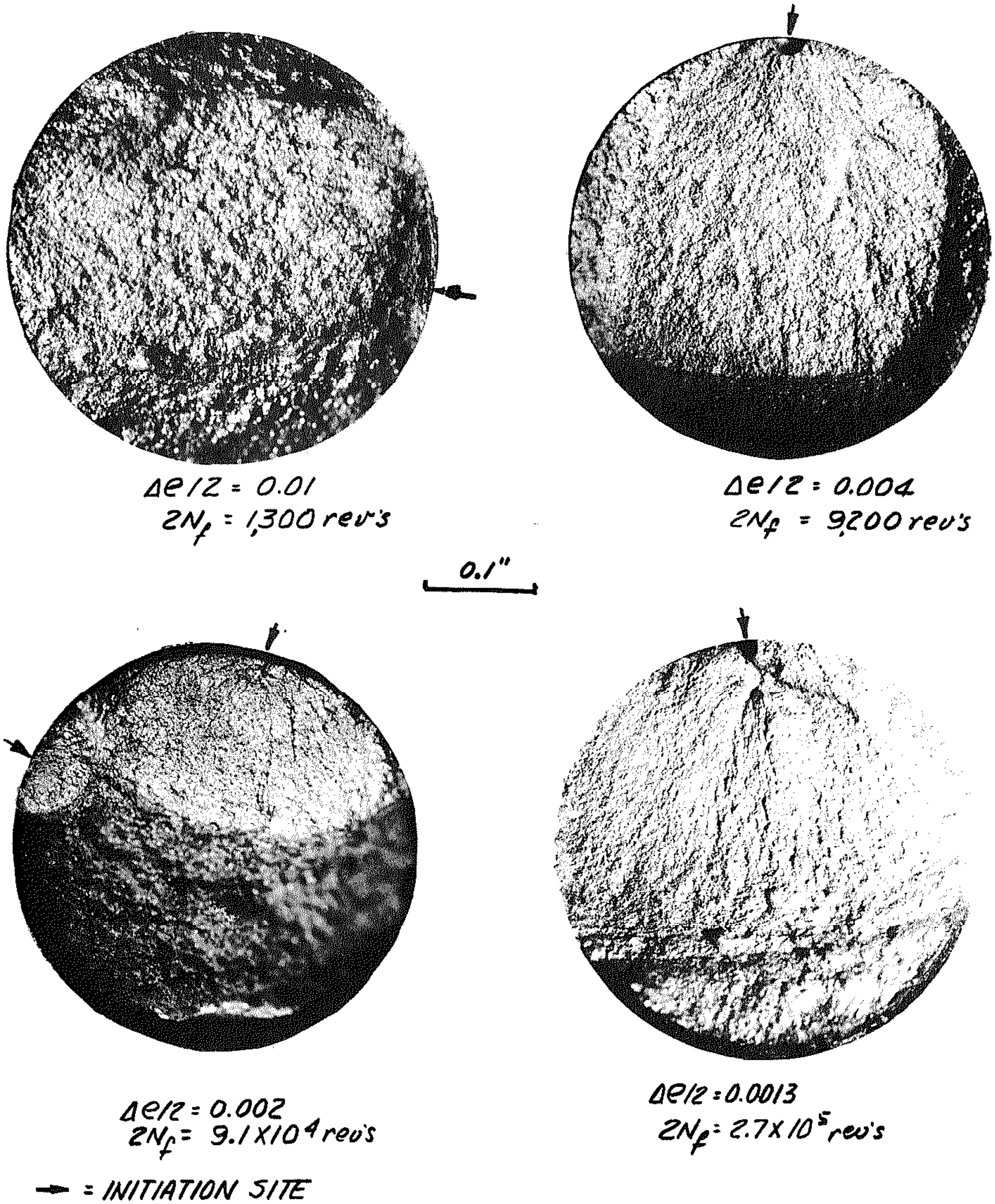


FIGURE 6 – MACROGRAPHS OF FRACTURE SURFACES OF FATIGUE SPECIMENS.

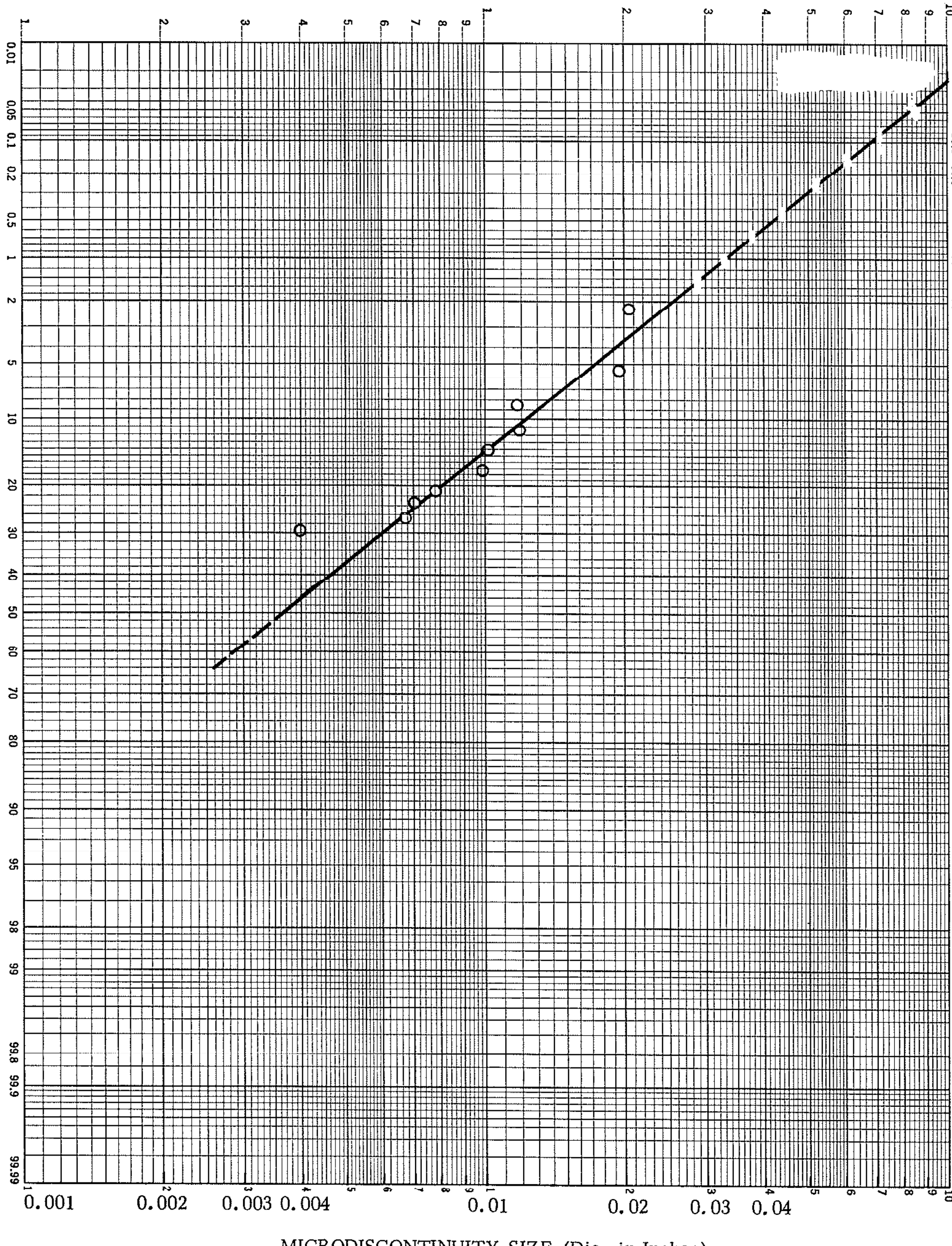


FIGURE 7- LOG-NORMAL PLOT OF LARGEST MICRODISCONTINUITIES

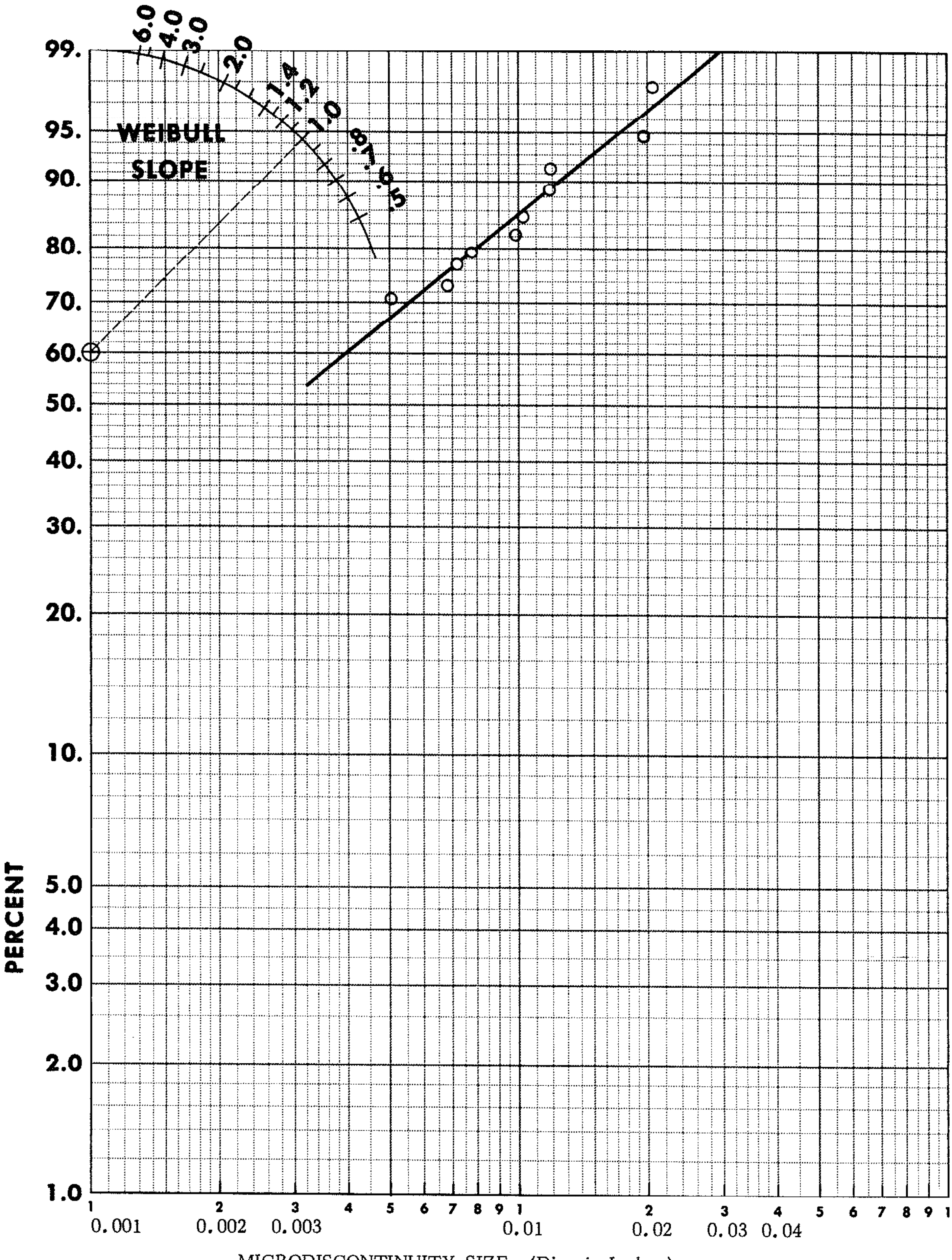


FIGURE 8 - WEIBULL PLOT OF LARGEST MICRODISCONTINUITIES

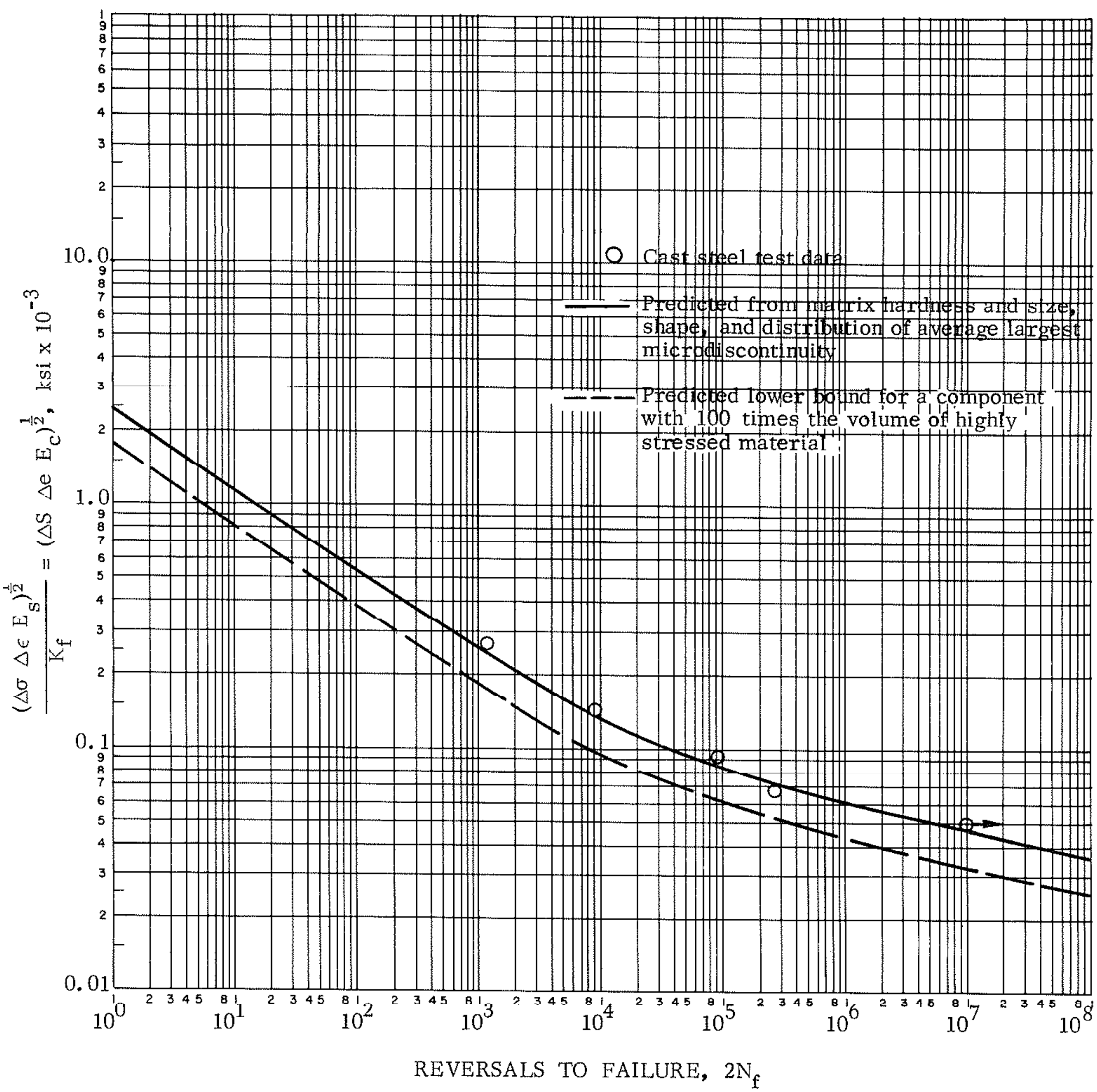


FIGURE 9 - PREDICTED STRAIN-LIFE CURVES FOR CAST 0.2%C STEEL @160 BHN.

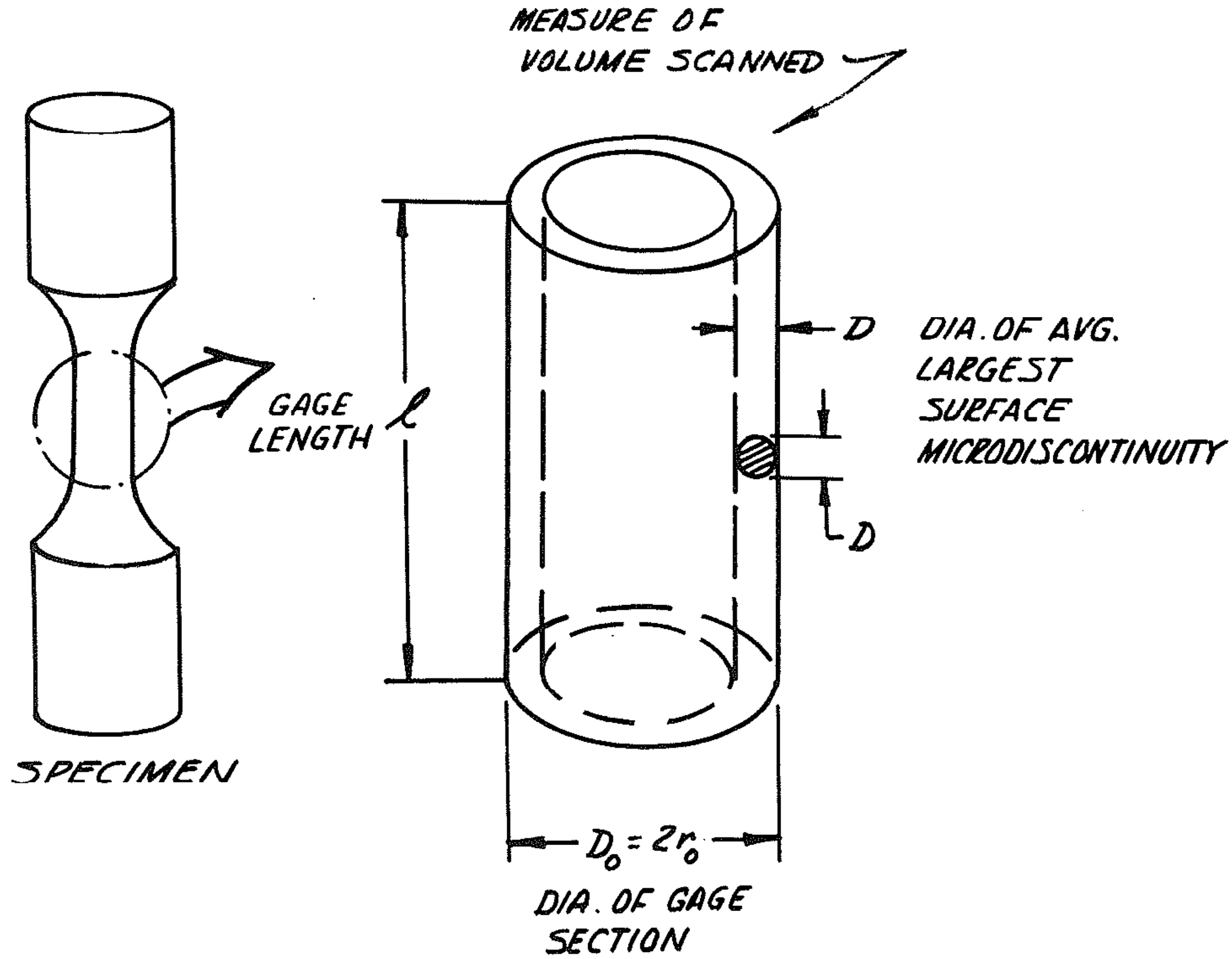


FIGURE 10 - SCHEMATIC OF VOLUME SCANNED DURING MACROGRAPHIC OBSERVATIONS.

APPENDIX A

STRAIN-LIFE FATIGUE PREDICTION FOR A WROUGHT STEEL OF COMPARABLE HARDNESS (BHN = 160)

$$S_{ult}\,(\text{ksi}) \cong 0.5\ \text{BHN} \cong 0.5\,(160) = 80\ \text{ksi}$$

$$\sigma_f' = \sigma_f \cong 50 + S_u\,(\text{ksi}) = 50 + 80 = 130\ \text{ksi}$$

$$E = 30 \times 10^3\ \text{ksi}$$

$$\therefore\ \frac{\sigma_f}{E} = \frac{130}{30 \times 10^3} = 0.00433$$

$$b \cong -\frac{1}{6}\log\frac{2\sigma_f}{S_{ult}} \cong -0.085$$

Let $\epsilon_f' = \epsilon_f \cong 1$ since steel is of "lower" hardness and let $c = -0.6$

MATERIAL CHARACTERIZATION SHEETS

DATA SHEET FOR MATERIAL CHARACTERIZATION

Material: J-3 Cast Steel

Condition: Normalized at 1700°F
Tempered at 1200°F

Matrix Hardness: 160 BHN

Converted from: R_B

Monotonic Properties:

Modulus of Elasticity, E	28.6×10^3 ksi
Yield Strength, 0.2% S_y	49.0 ksi
Ultimate Strength, S_u	75.0 ksi
Red. in Area, % RA	67.8%
True Fracture Strength, σ_f	134.0 ksi
σ_f	113.0 ksi (corrected)
True Fracture Ductility, ϵ_f	1.13
Strain Hardening Exponent, n	0.14
Strength Coefficient, K	110 ksi
True Toughness, U_p	112 ksi

Cyclic Properties:

Yield Strength, 0.2% S_y'	47.0* ksi
Strain Hardening Exponent, n'	0.12
Strength Coefficient, K'	107 ksi
Fatigue Strength Coefficient, σ_f'	--- ksi
Fatigue Ductility Coefficient, ϵ_f'	---
Fatigue Strength Exponent, b	-0.11
Fatigue Ductility Exponent, c	-0.68
Transition Fatigue Life, $2N_t$	19,000 rev

*From companion specimen test results

Composition:

w/o C	= 0.20	w/o Mo	= 0.19
w/o Si	= 0.44	w/o Cu	= 0.16
w/o P	= 0.015	w/o Ni	= 0.14
w/o S	= 0.010	w/o Va	= ---
w/o Mn	= 1.13	w/o Al	= 0.035
w/o Cr	= 0.13	w/o B	= 0.001

Grain Size:

Eutectic Cell Size (Cast irons):

Microstructure:

Magnification:

Comments:

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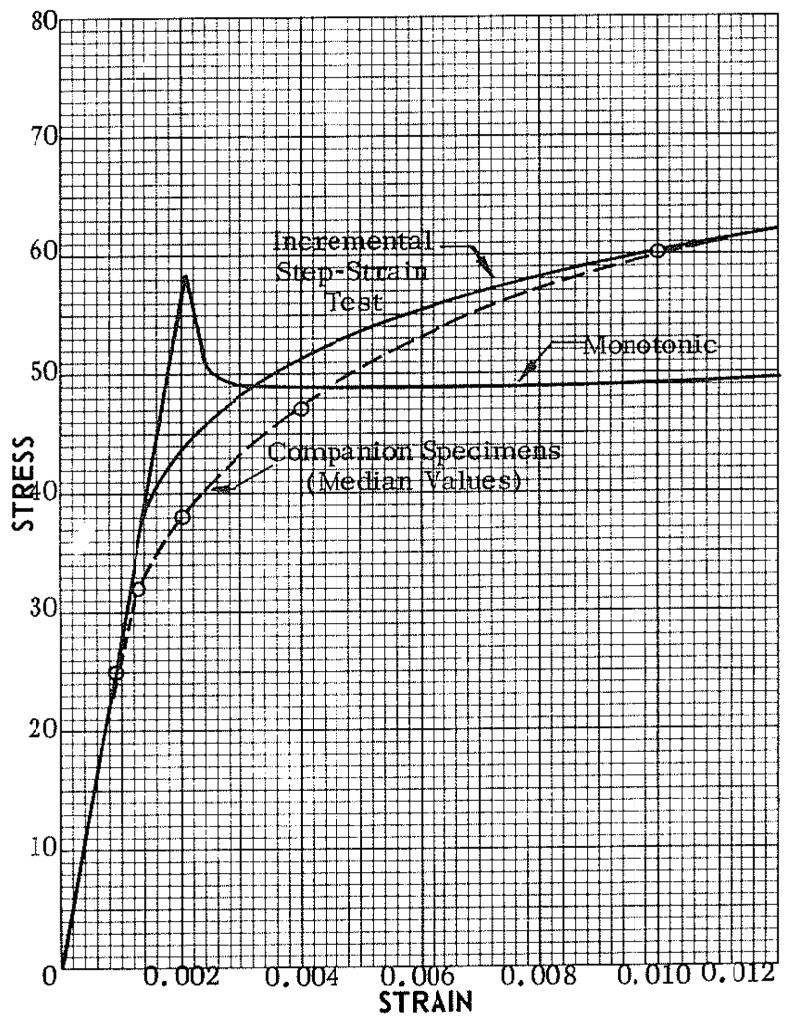
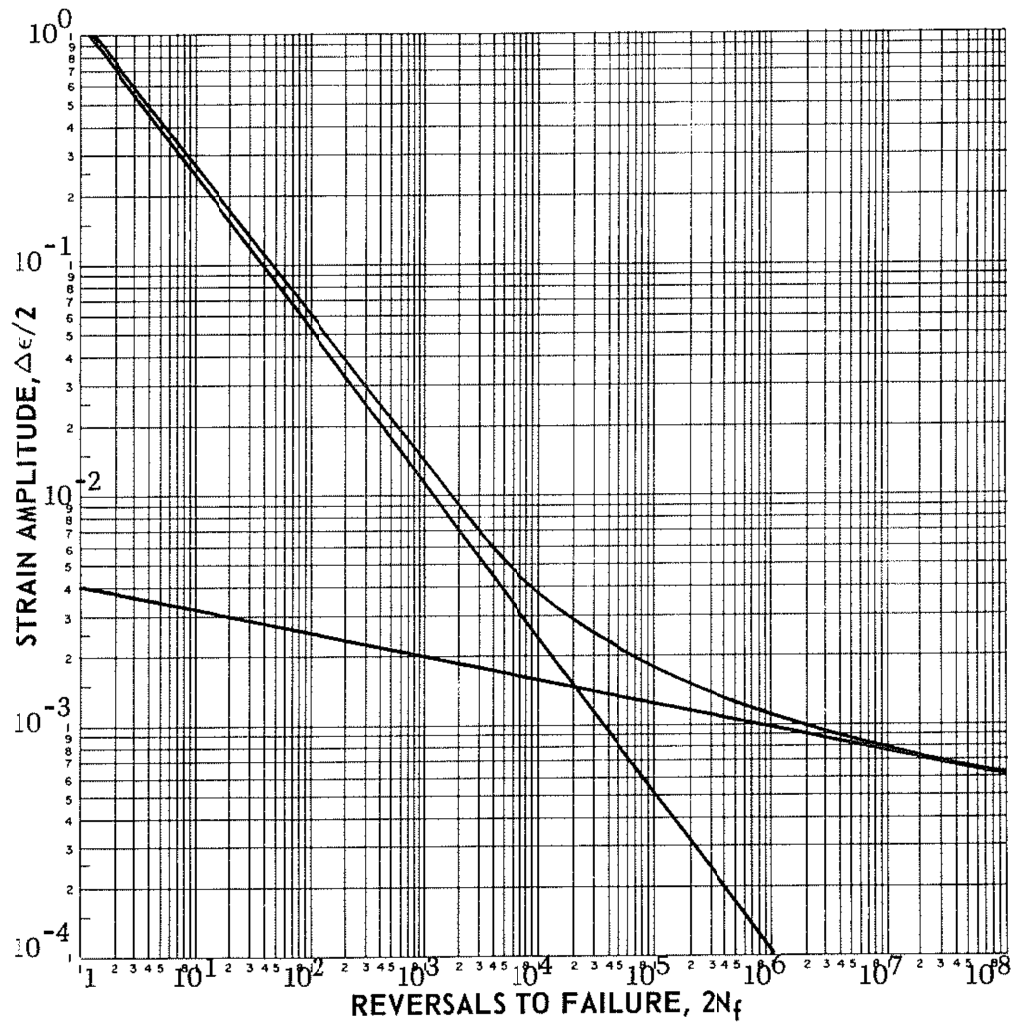
Material: J-3 CAST STEEL **Hardness:** 160 BHN

Condition: Normalized at 1700° F
Tempered at 1200° F





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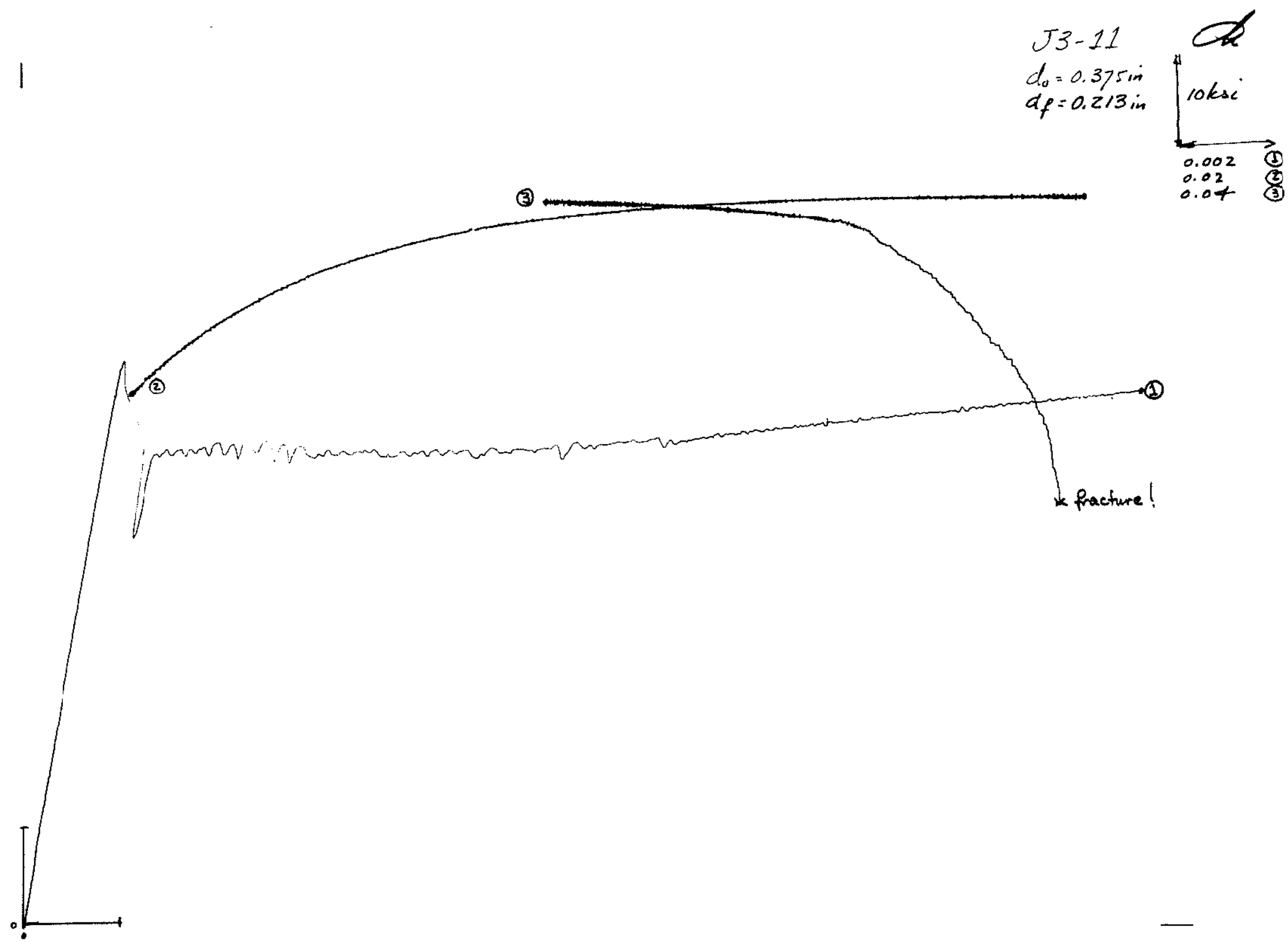
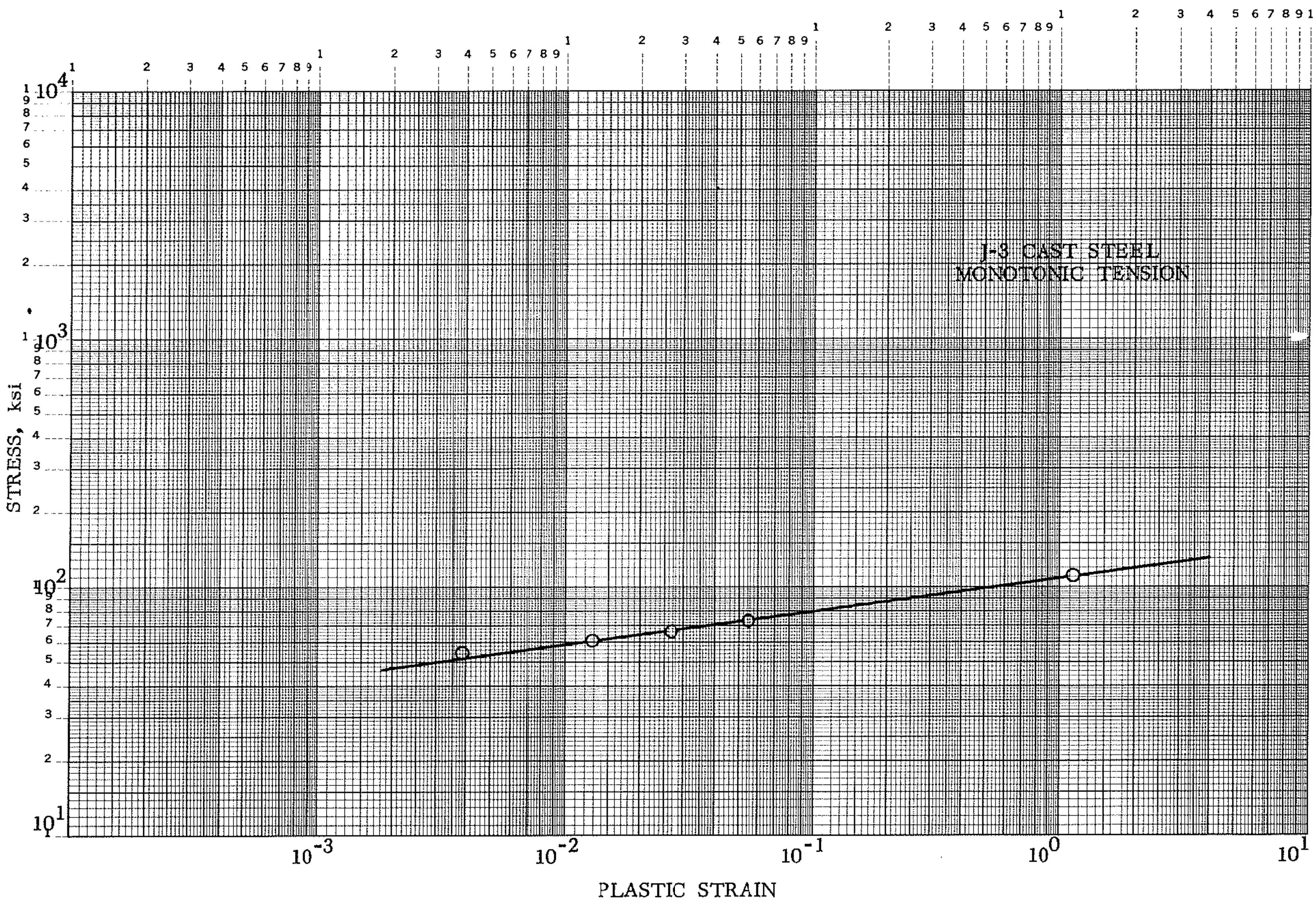
MONOTONIC STRESS-STRAIN RESULTS



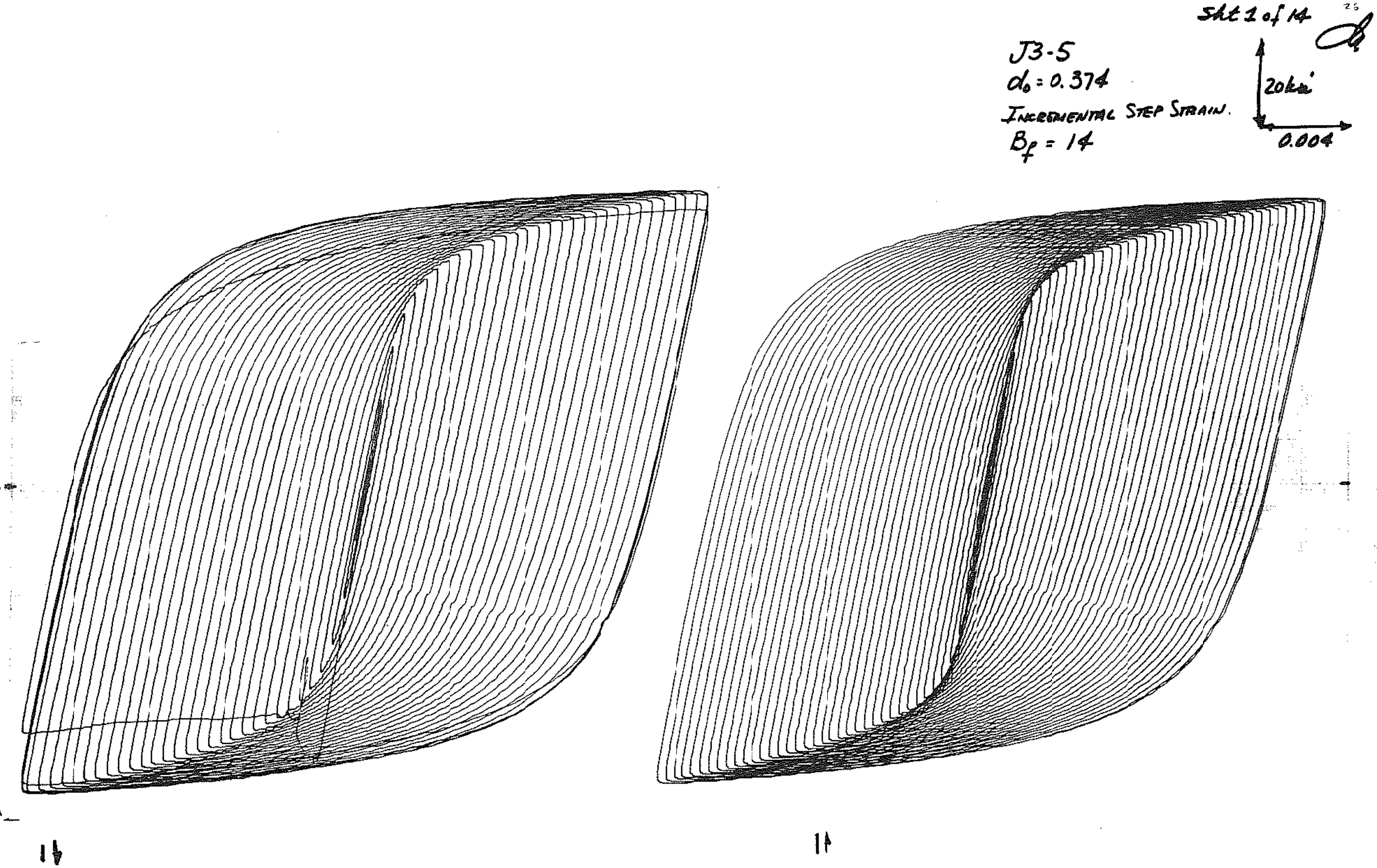
J3-11
$d_o = 0.375$ in
$d_f = 0.213$ in
10 ksi
0.002 ①
0.02 ②
0.04 ③
③
②
①
fracture!
0


J-3 CAST STEEL
MONOTONIC TENSION
STRESS, ksi
PLASTIC STRAIN
10^{4}
10^{3}
10^{2}
10^{1}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

CYCLIC STRESS-STRAIN RESULTS

Sht 1 of 14

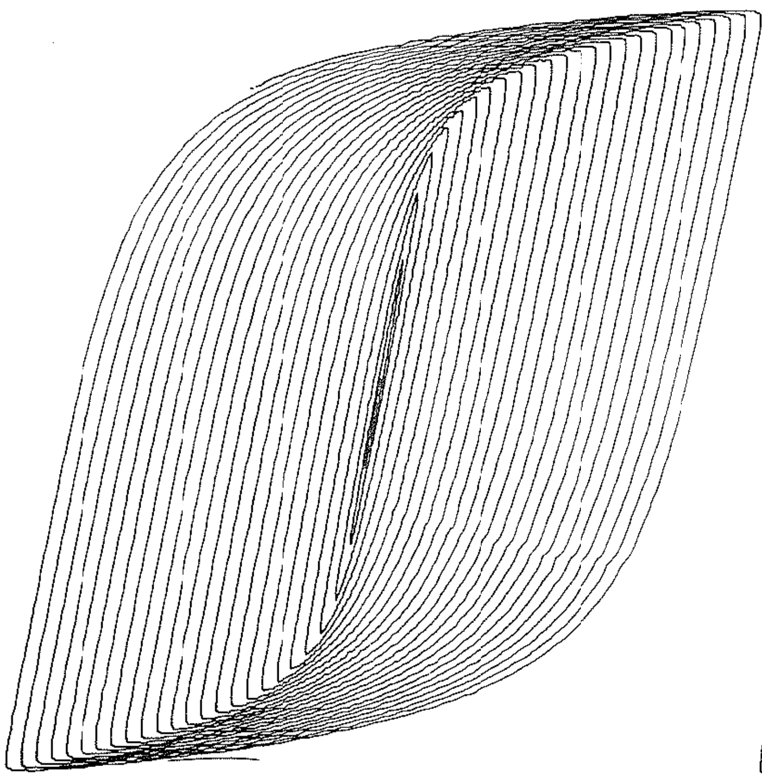
J3-5
$d_0 = 0.374$
INCREMENTAL STEP STRAIN.
$B_f = 14$



Skt 2 of 14

20ksi

0.004



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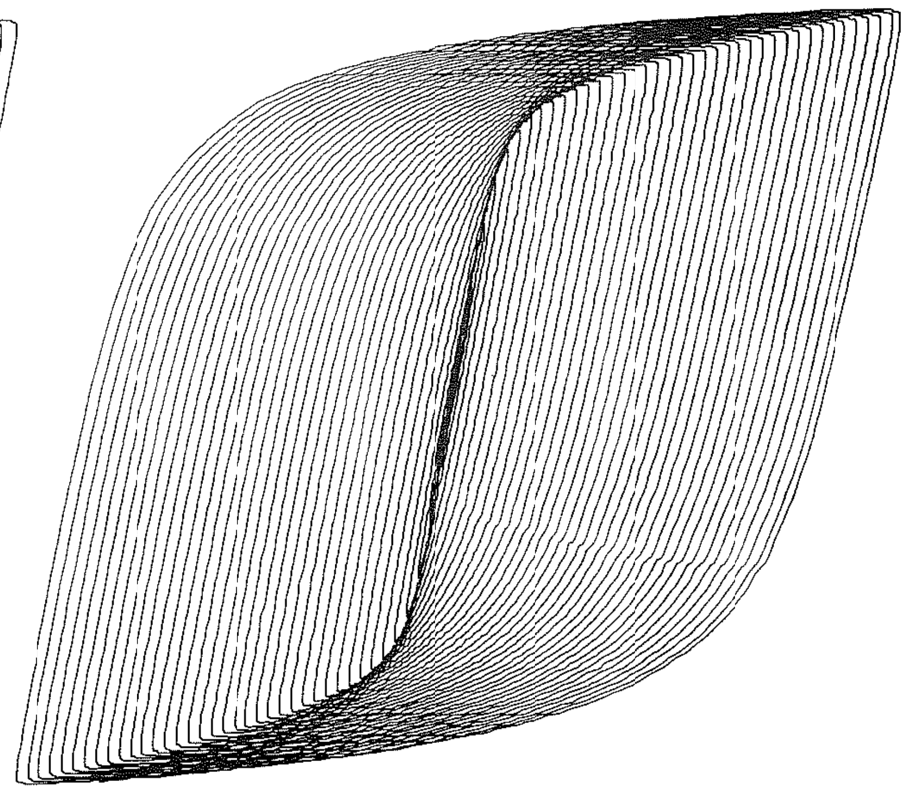

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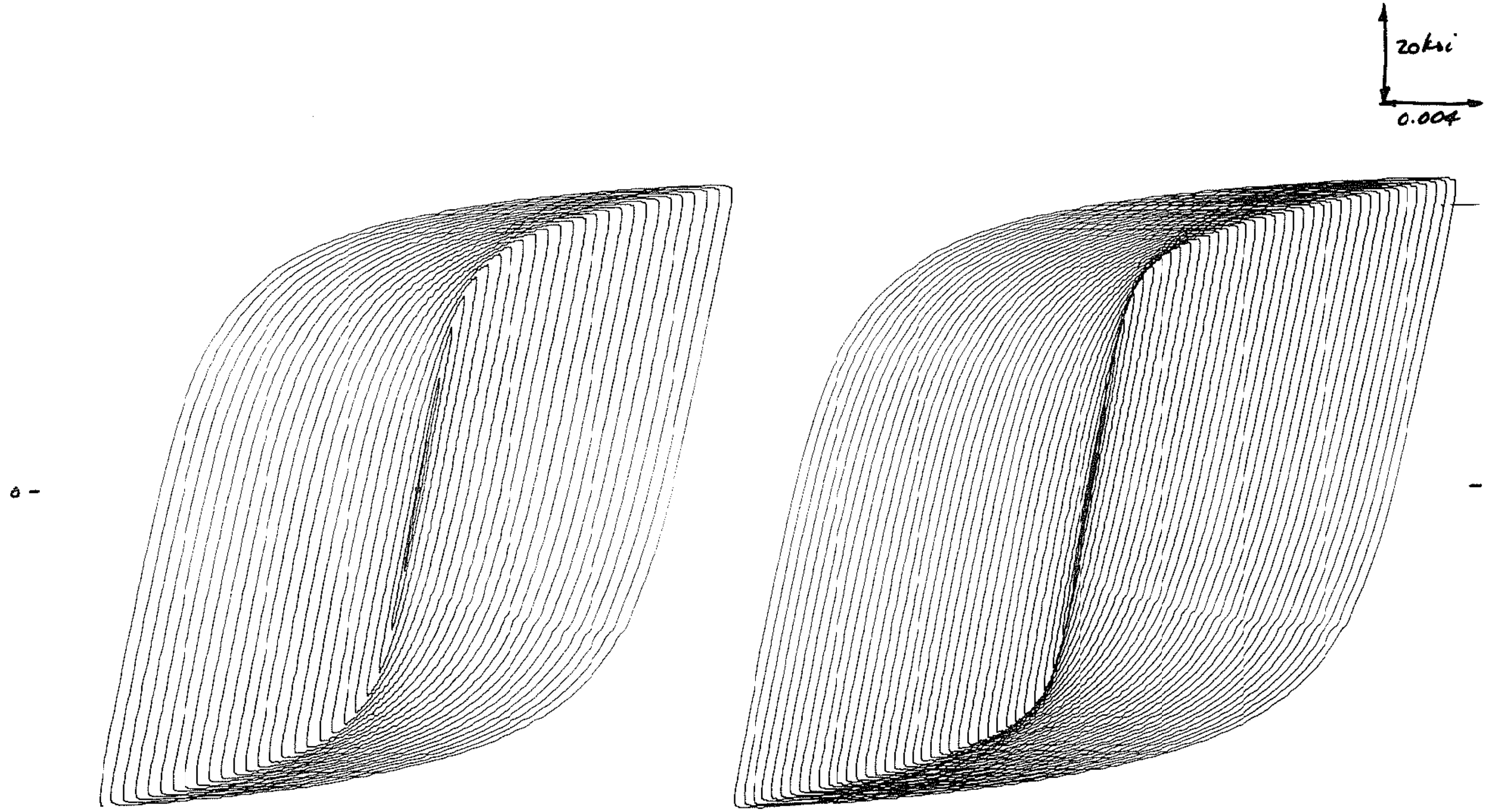
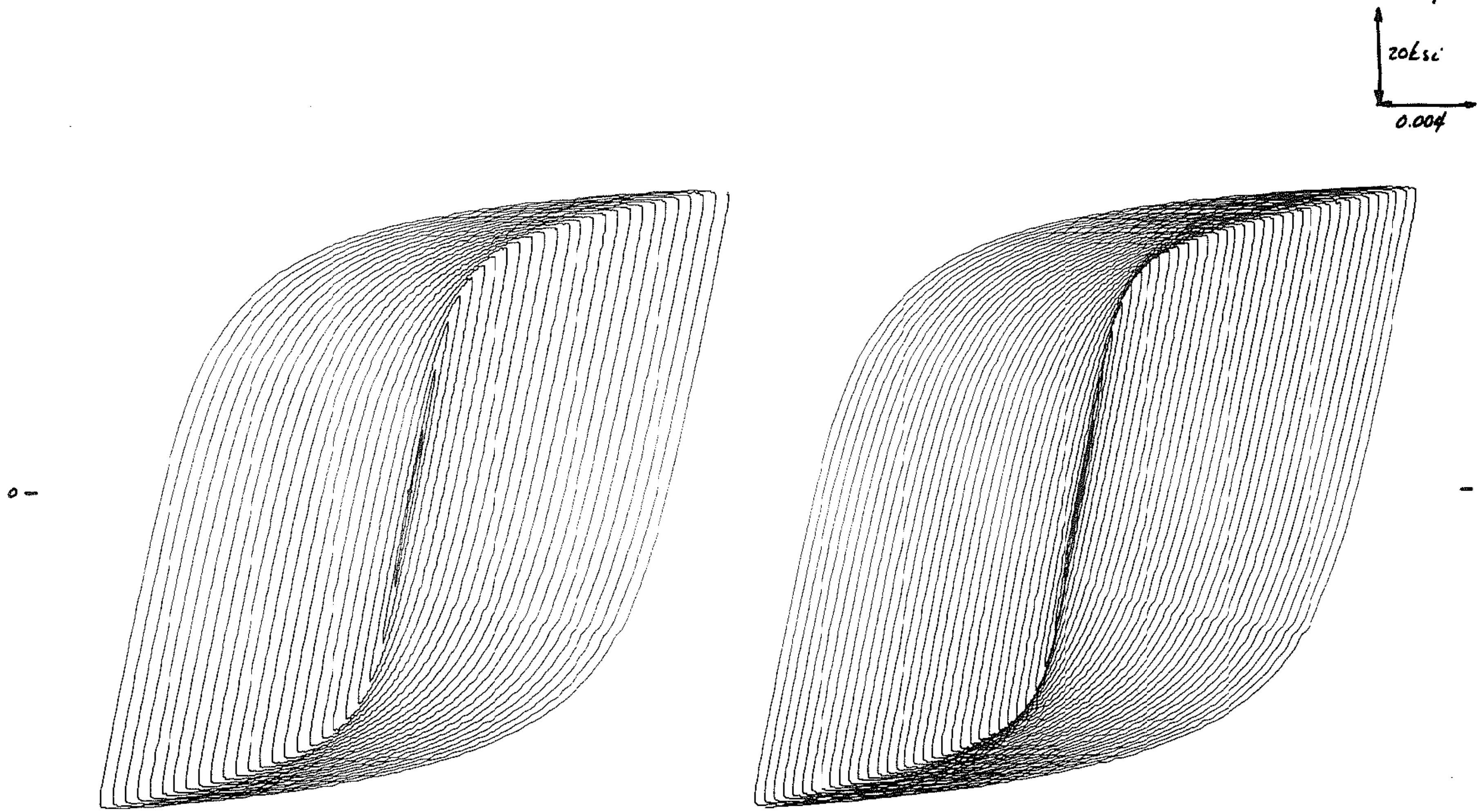
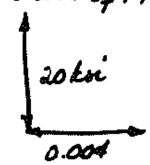


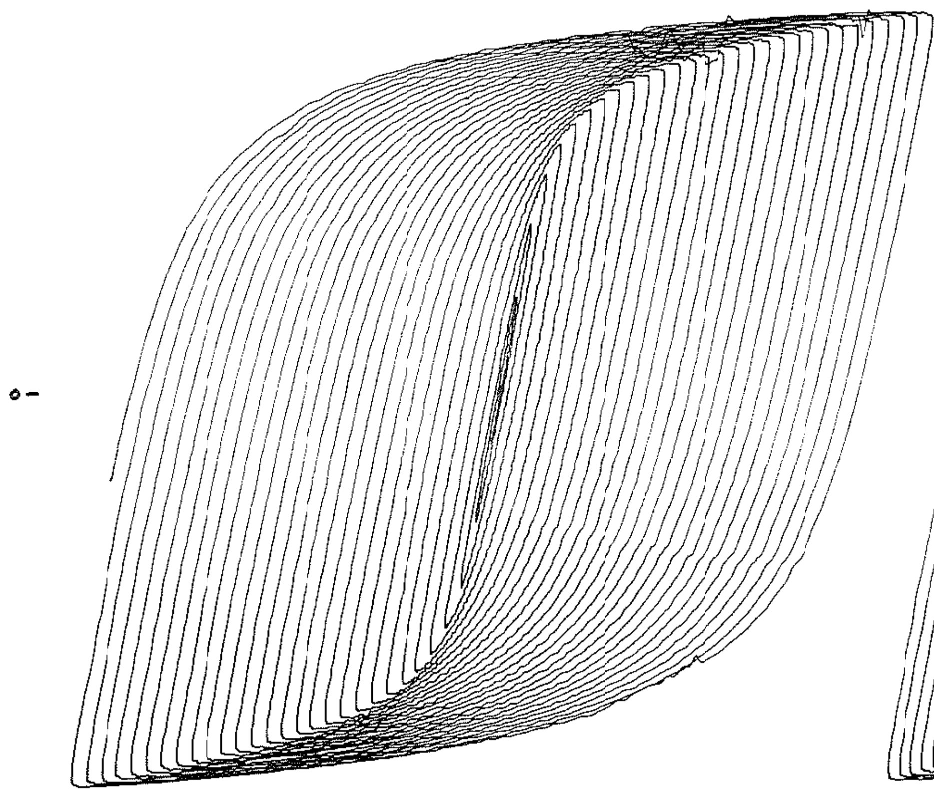
3↓ 3↑



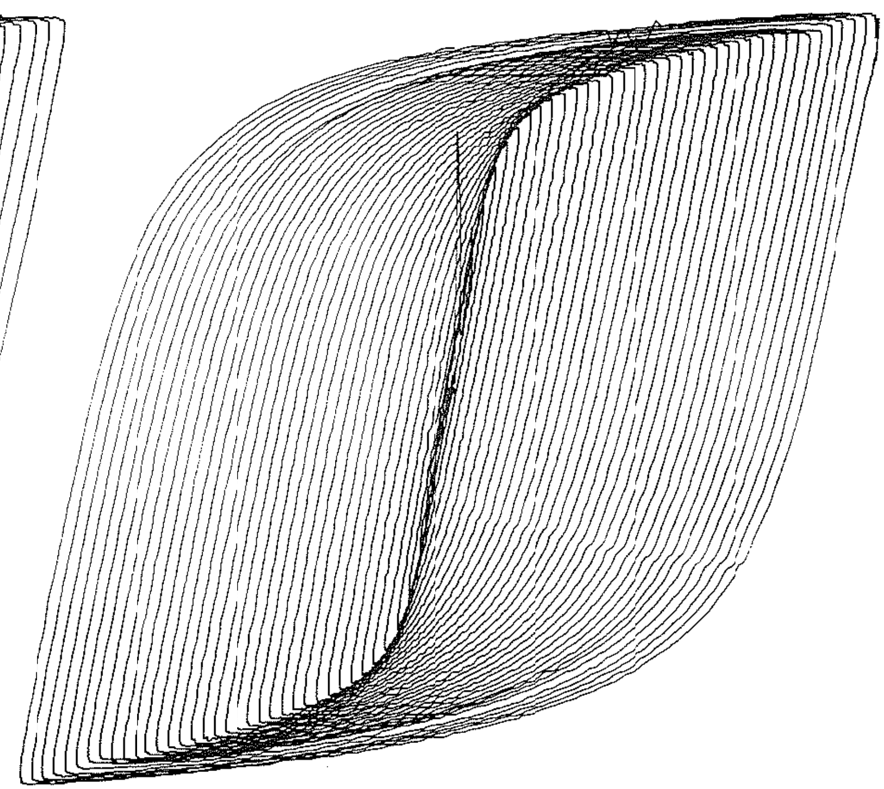
4↓

4↑





5↓



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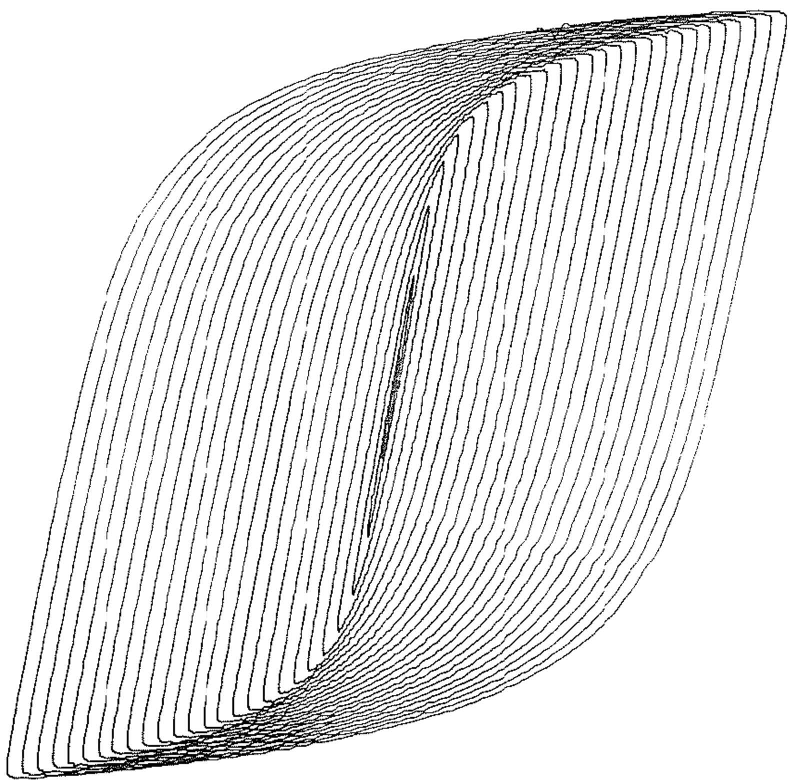
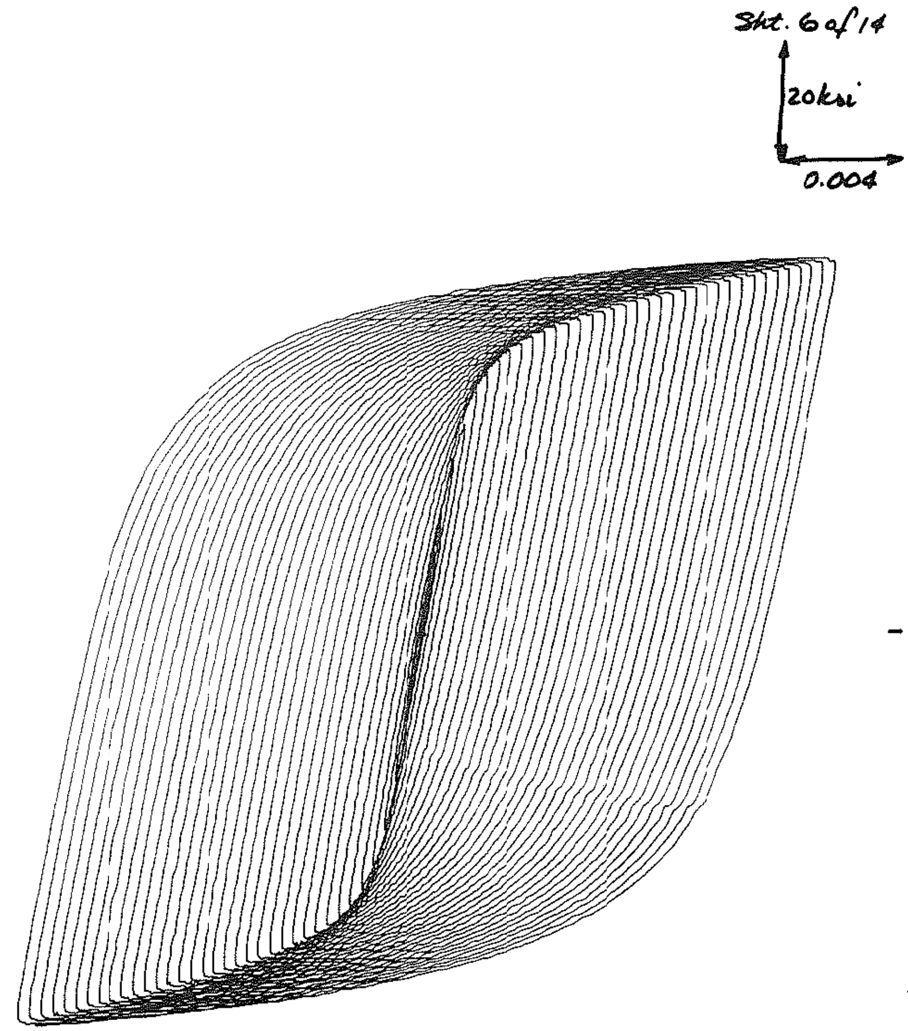


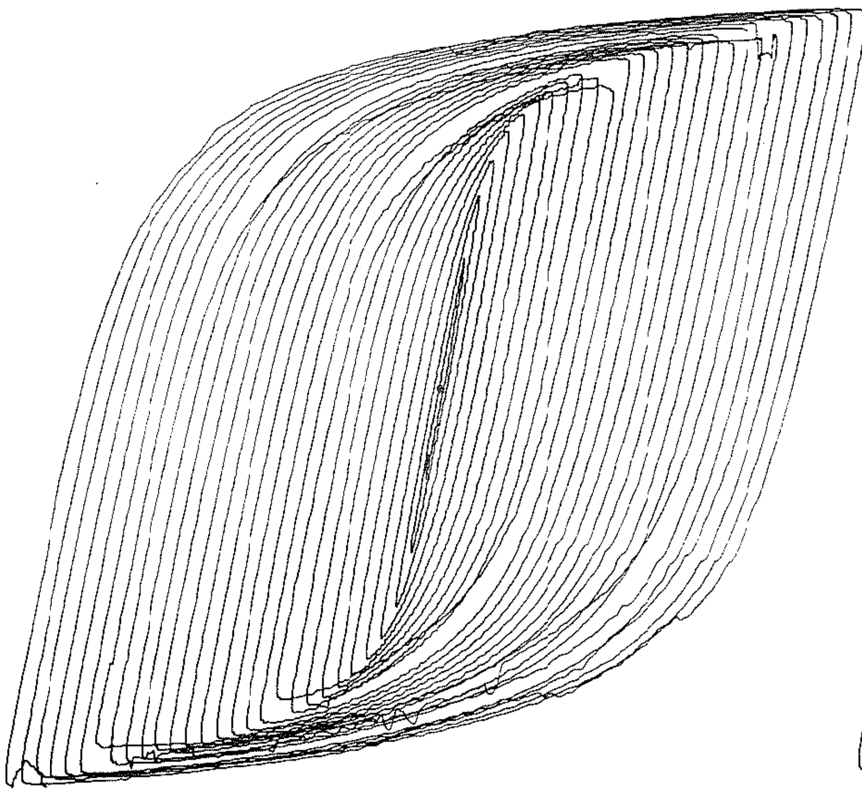
6F



6P

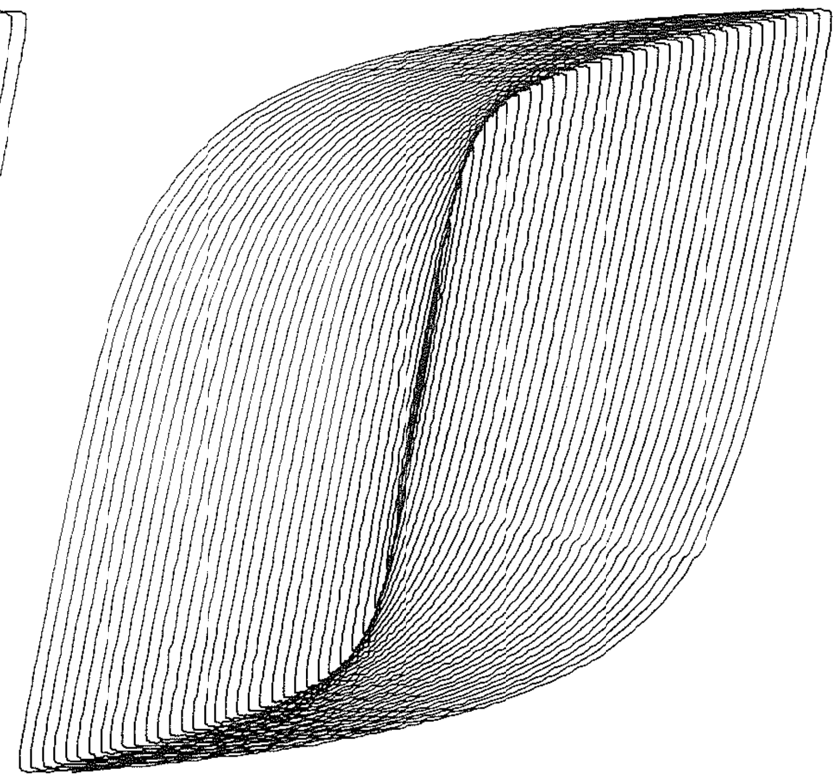
20ksi

0.004



↙recorder "noise" ... not specimen response! :(

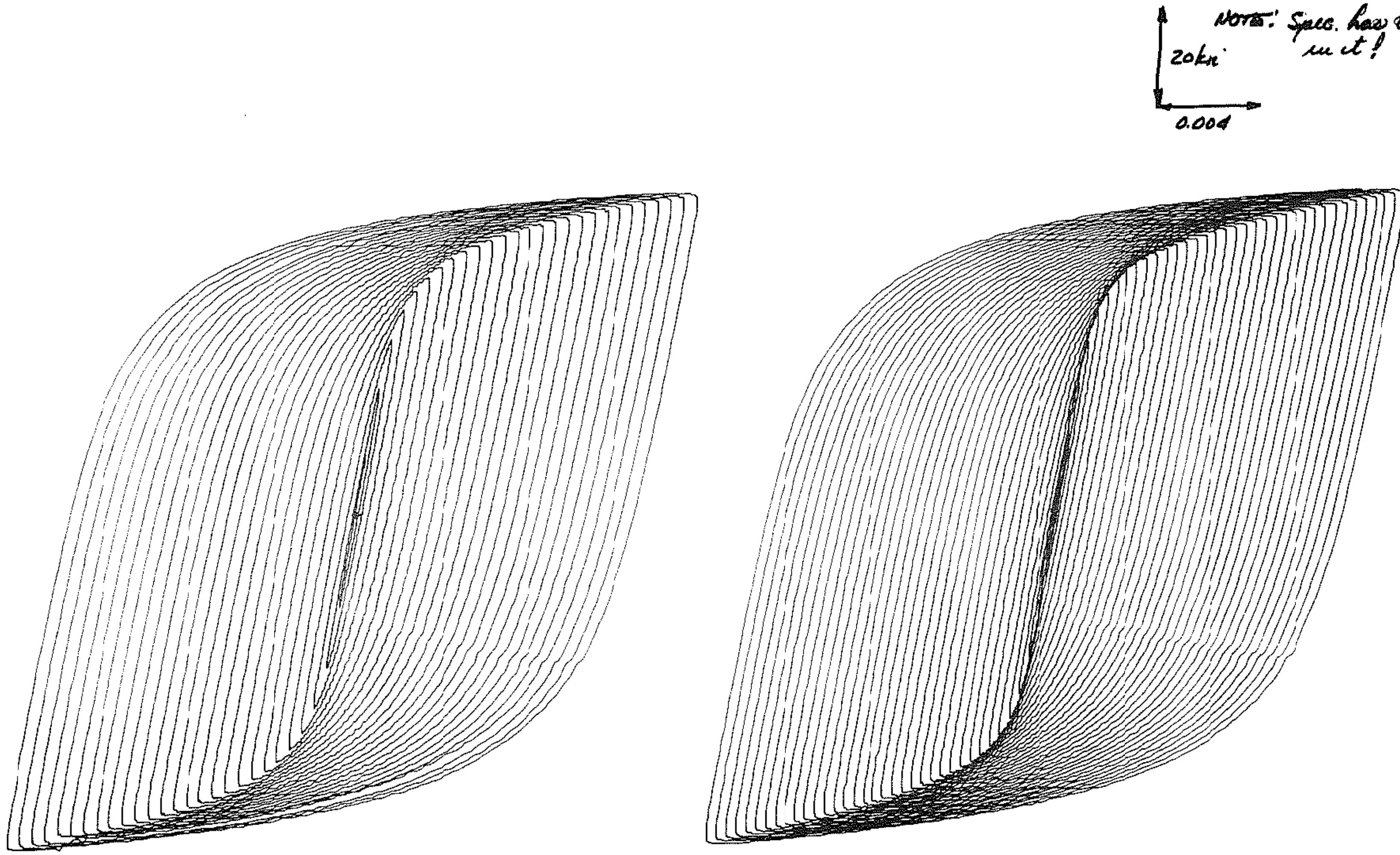
7B

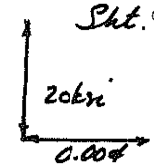


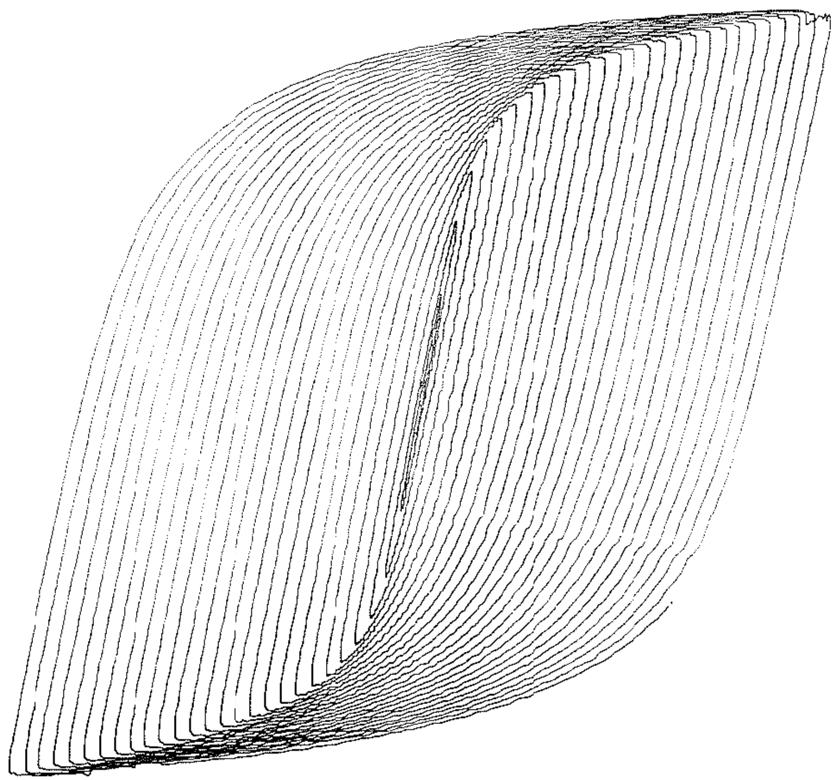
7A

The "un-loops"

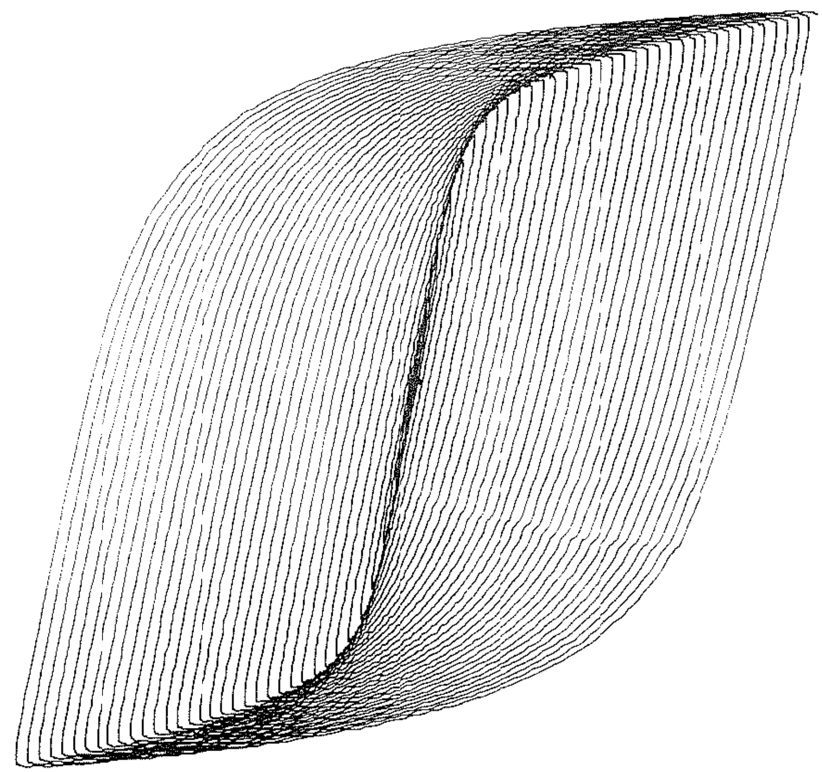
NOTE: Spec. has crack in it!







9b



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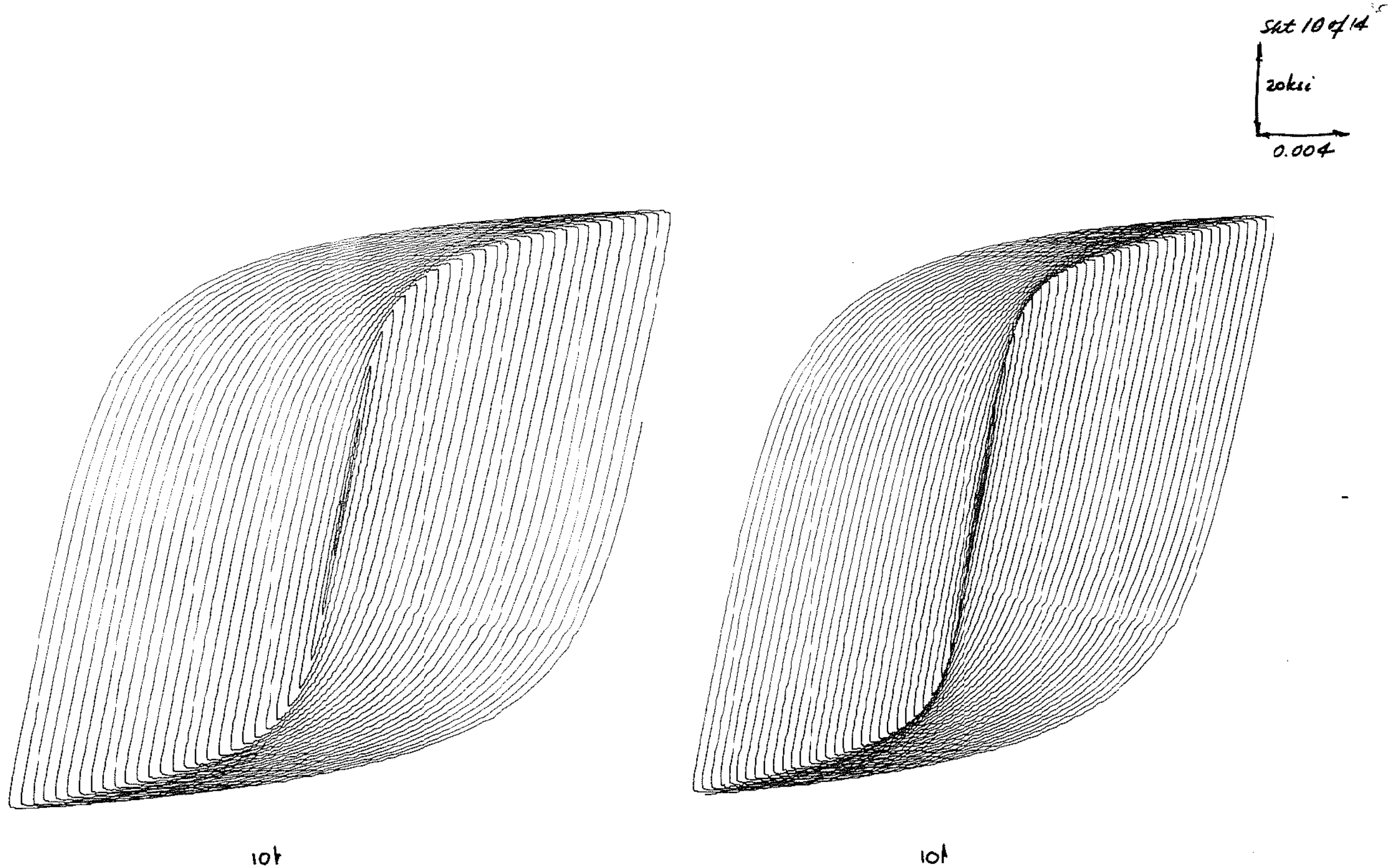
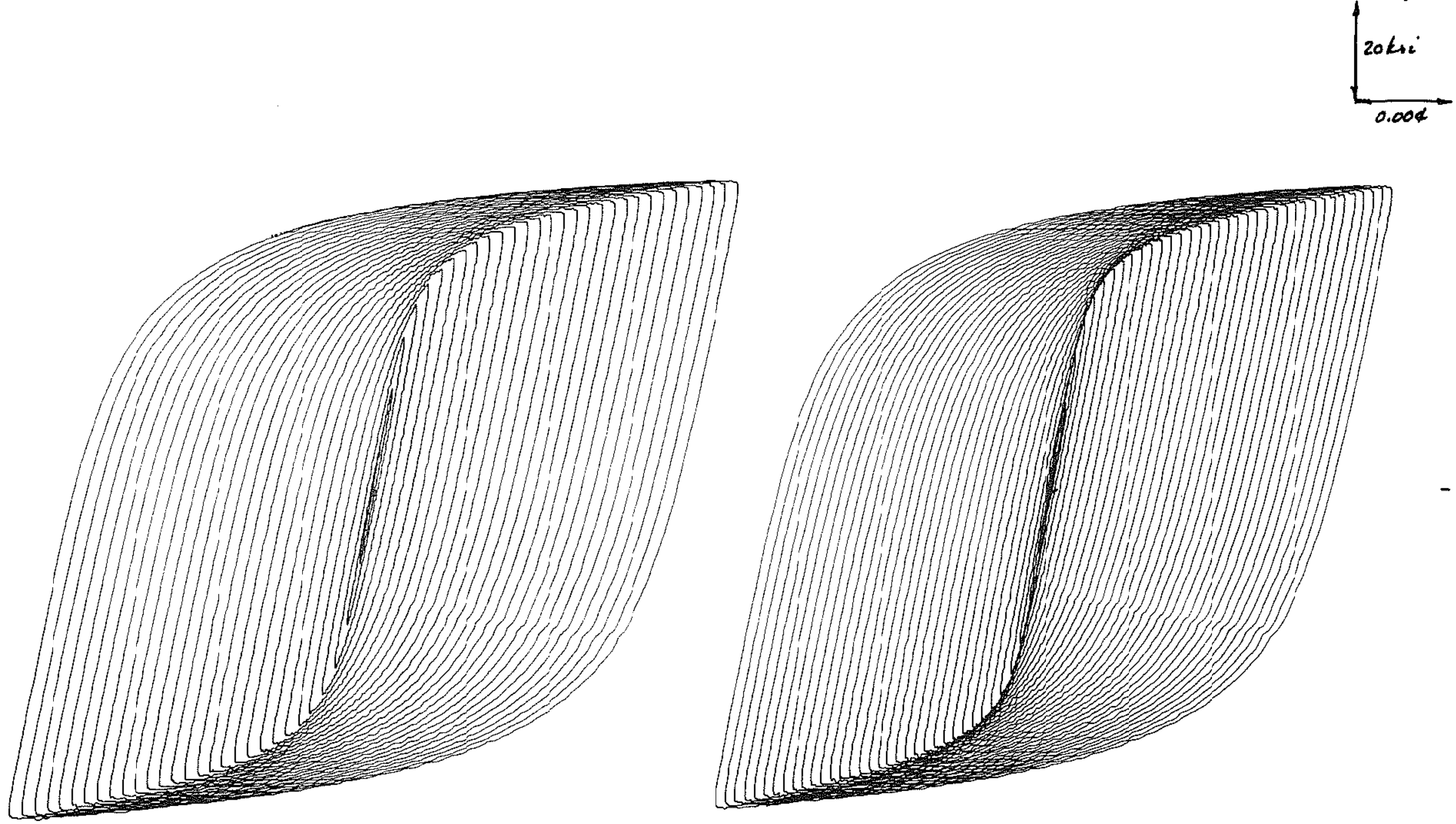
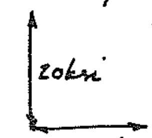

Skt 10 of 14
20ksi
0.004

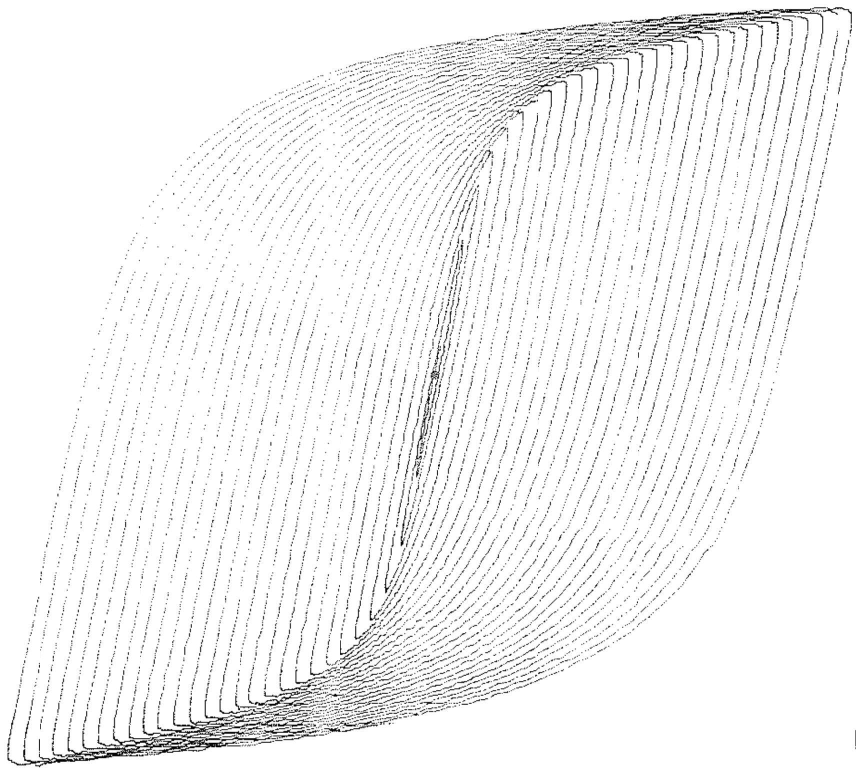
Sht 11 of 14



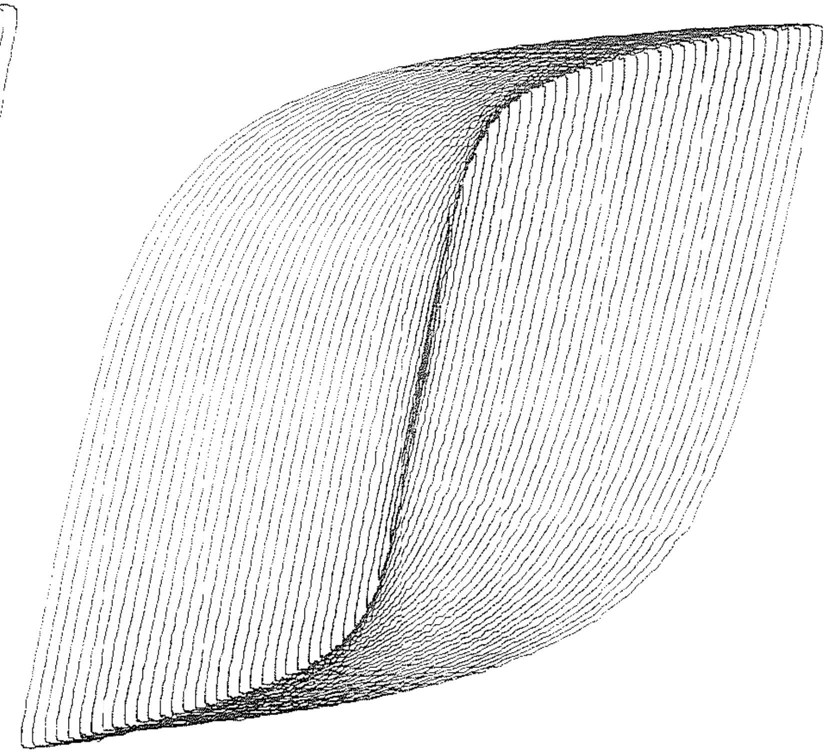
11b

11A



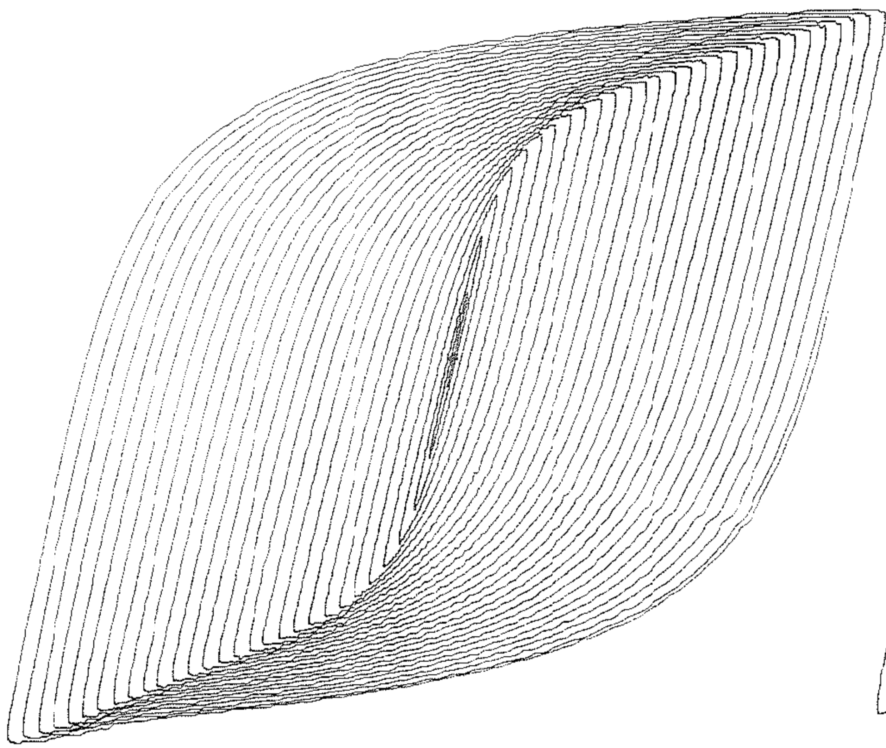


12B

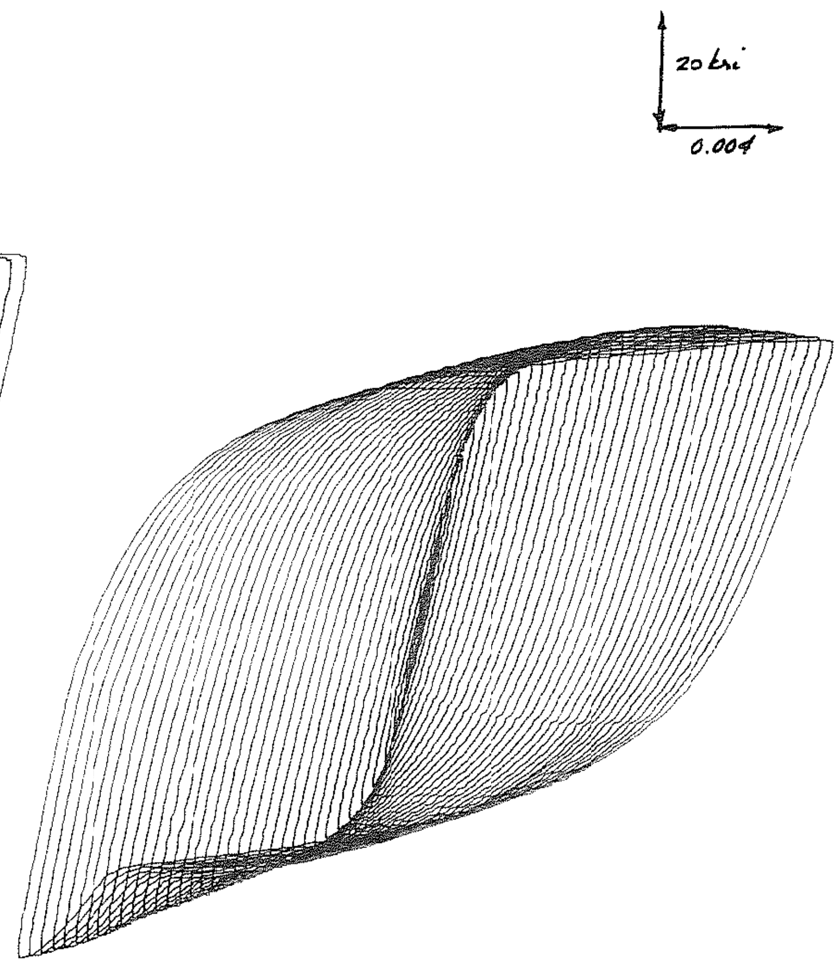


12A

Sht. 13 of 14

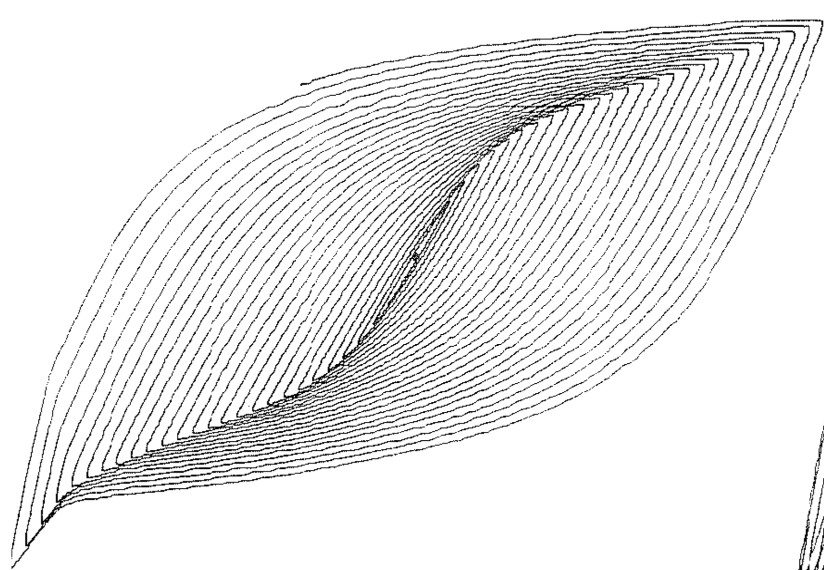


13E

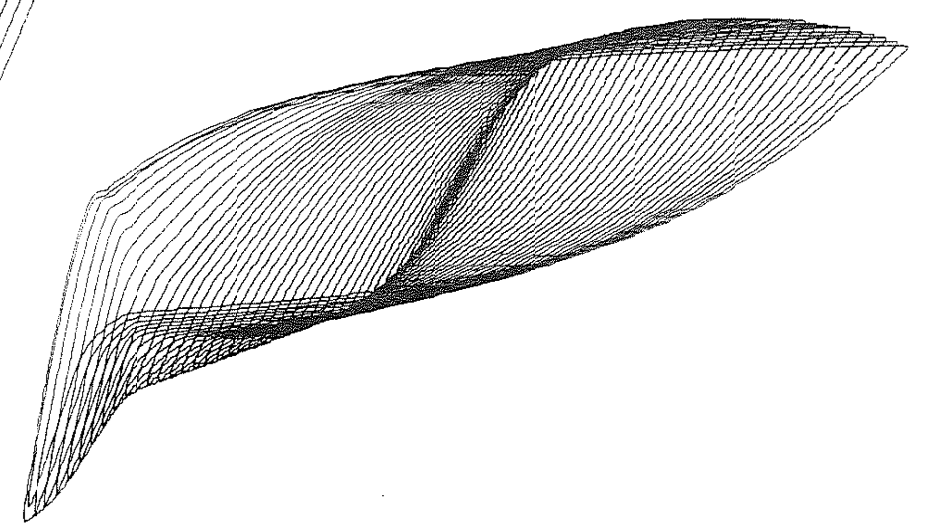


13F

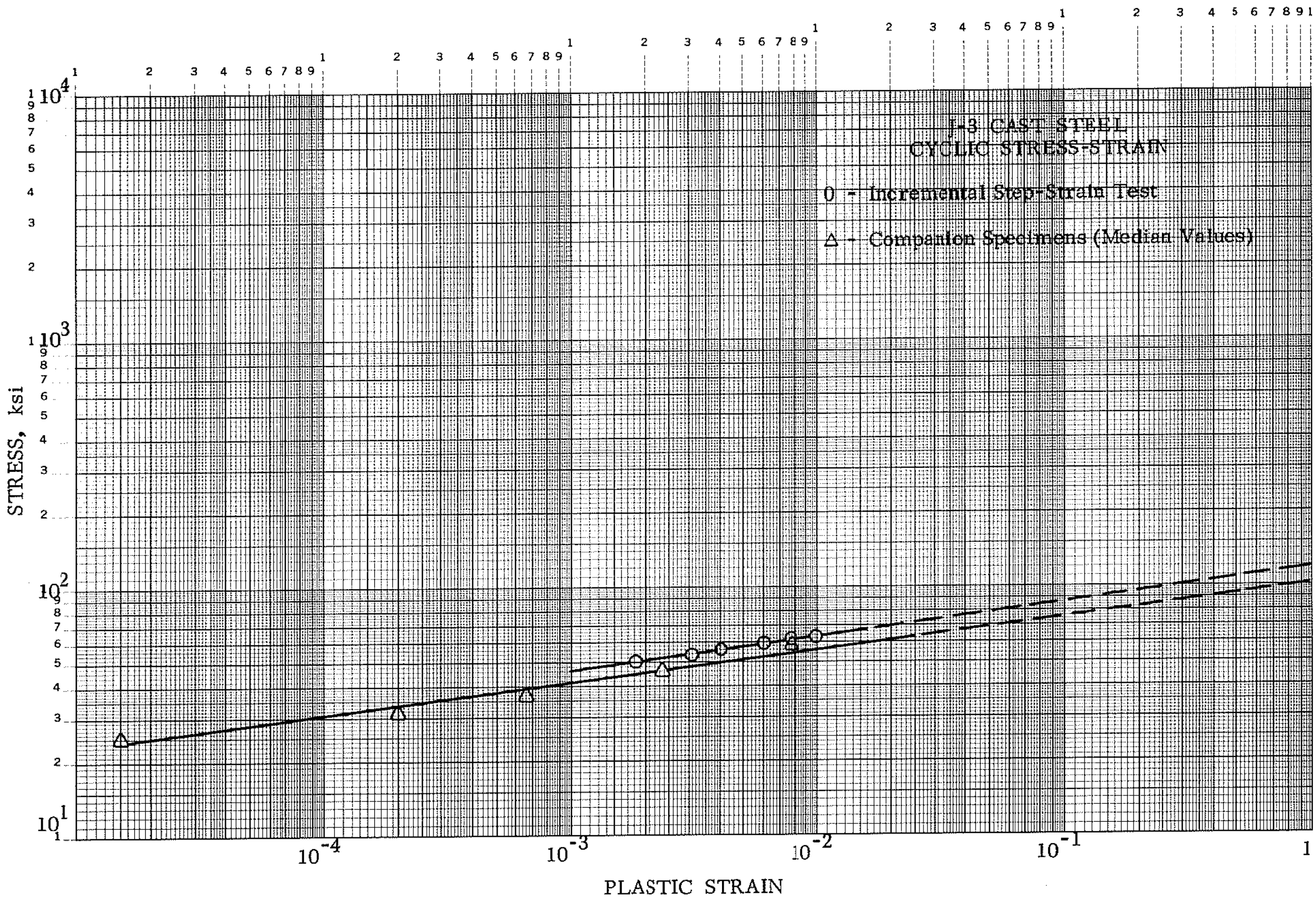
Sht 14 of 14



14b



14f

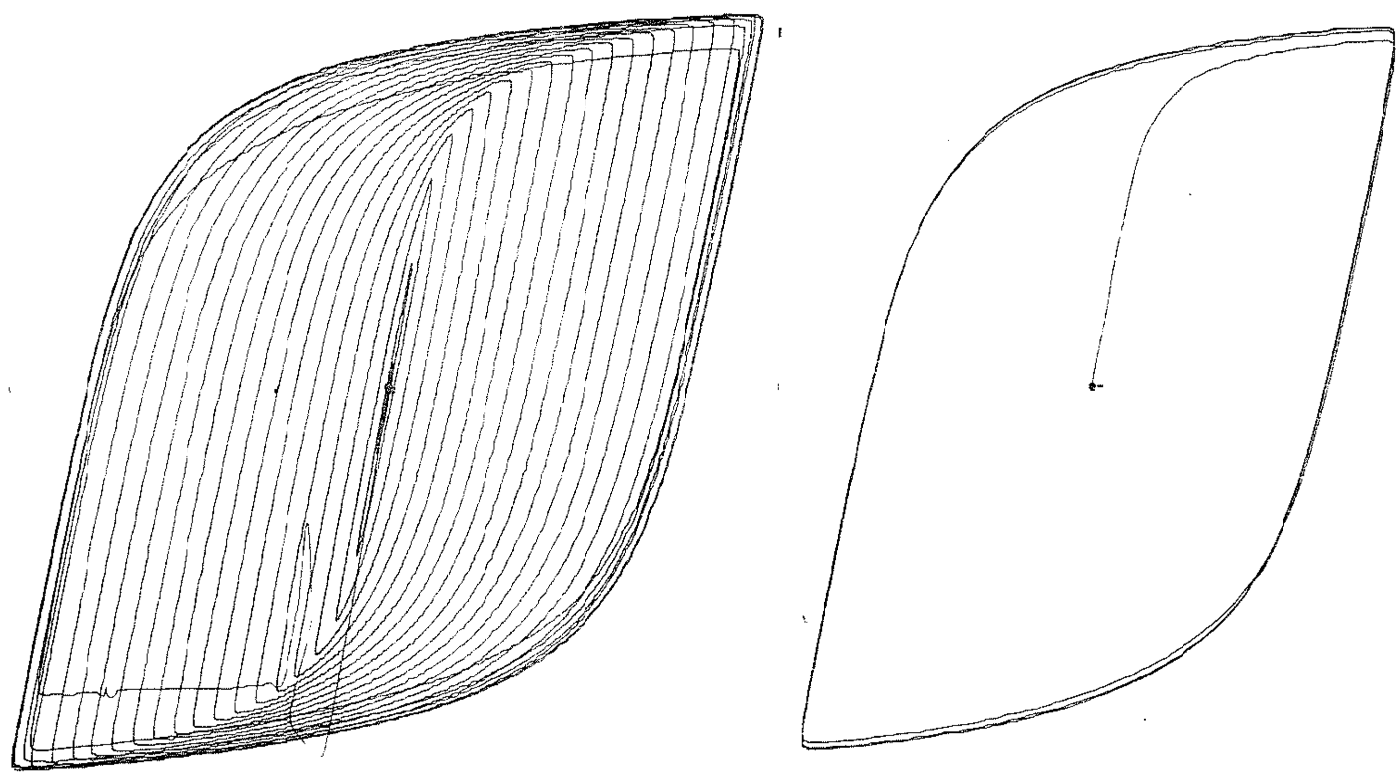

J-3 CAST STEEL
CYCLIC STRESS-STRAIN
0 - Incremental Step-Strain Test
Δ - Companion Specimens (Median Values)
STRESS, ksi
PLASTIC STRAIN
10^4
10^3
10^2
10^1
10^-4
10^-3
10^-2
10^-1
1

STRAIN-LIFE RESULTS

J3-8
$d_0 = 0.376.$

$\frac{\Delta e}{2} = \pm 0.01$
$N_f = 650 \sim$

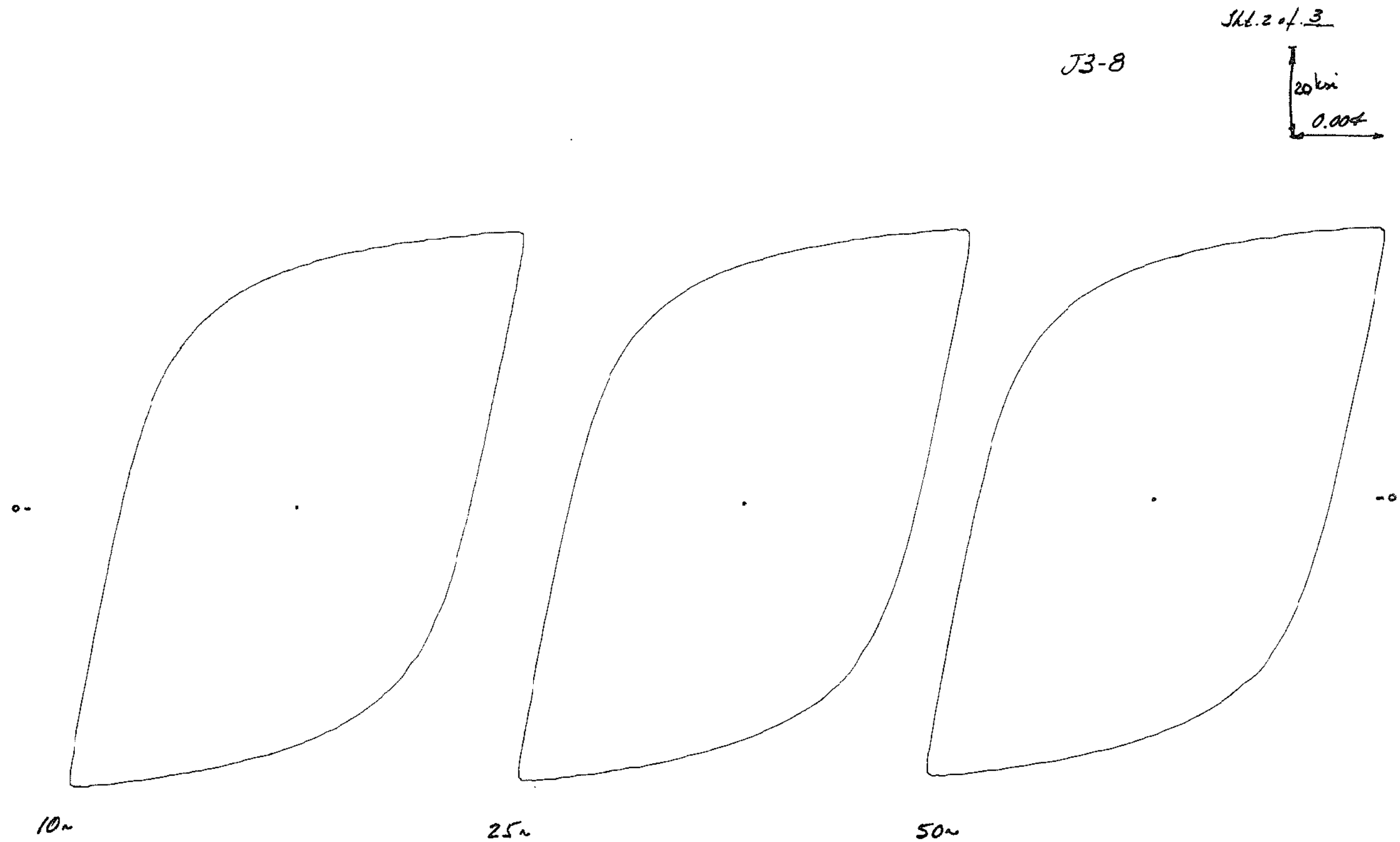
Sht 1 of 3



20ksi
0.004

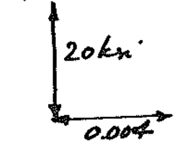
-46-

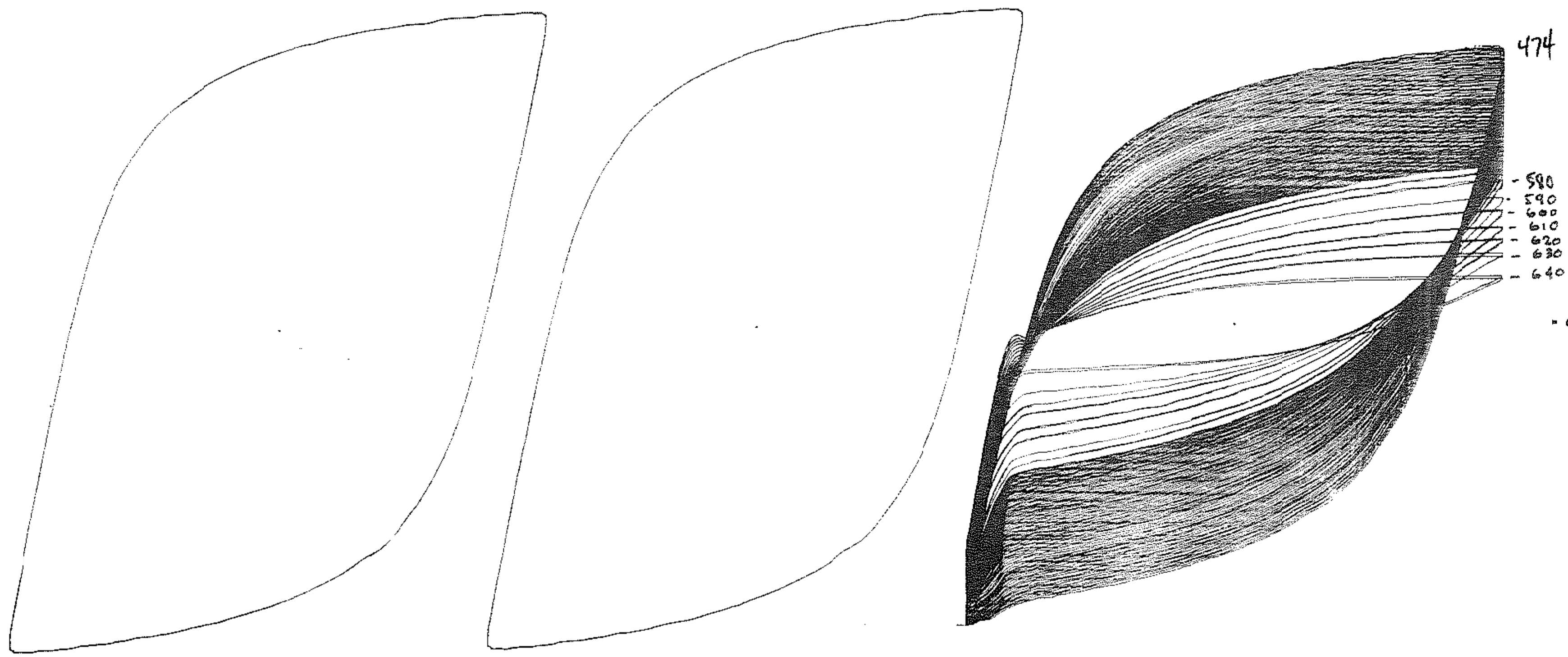
Precyck 5cyc @ ± 0.013
20cyc dec. to 0-0.


Sht. 2 of 3
J3-8
20 ksi
0.004
10~
25~
50~

Sht 3 of 3

J3-8



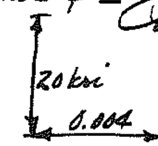


100~

250~

$N_f = 650$~

Sht 1 of 3

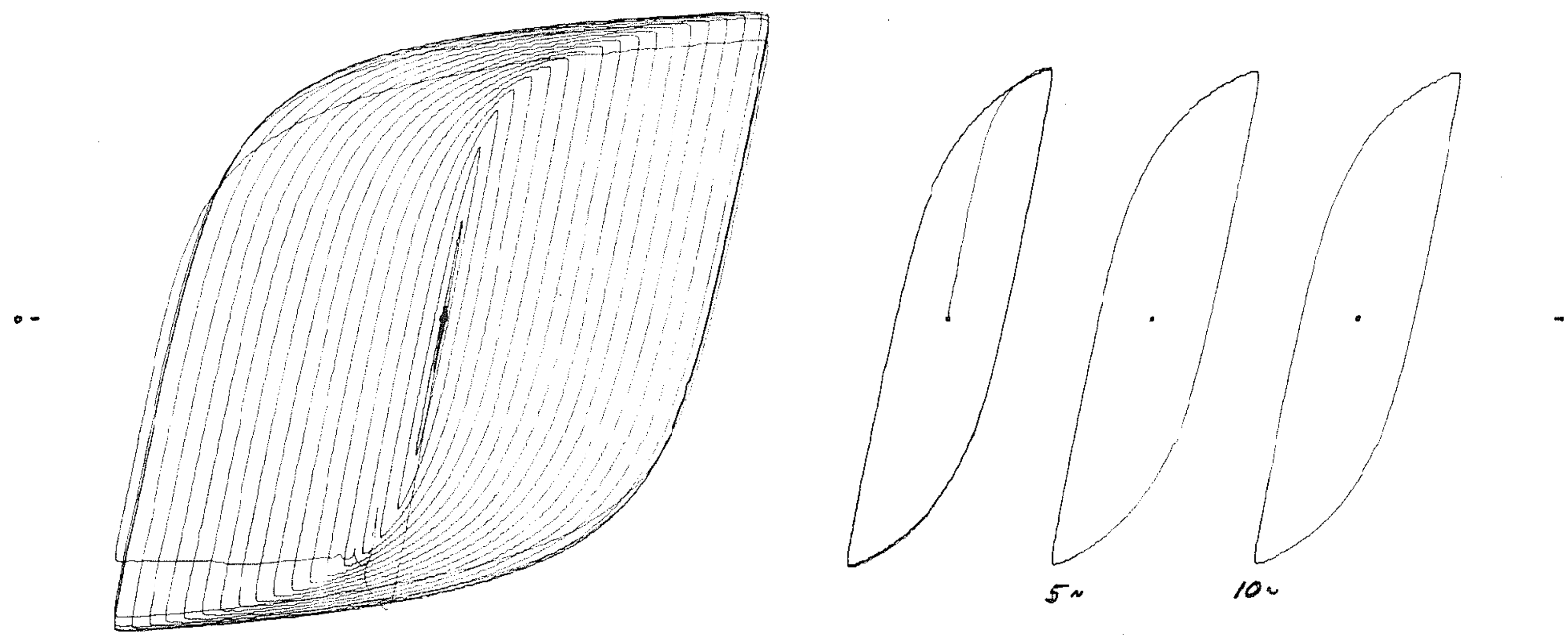


J3-7

$d_o = 0.376$

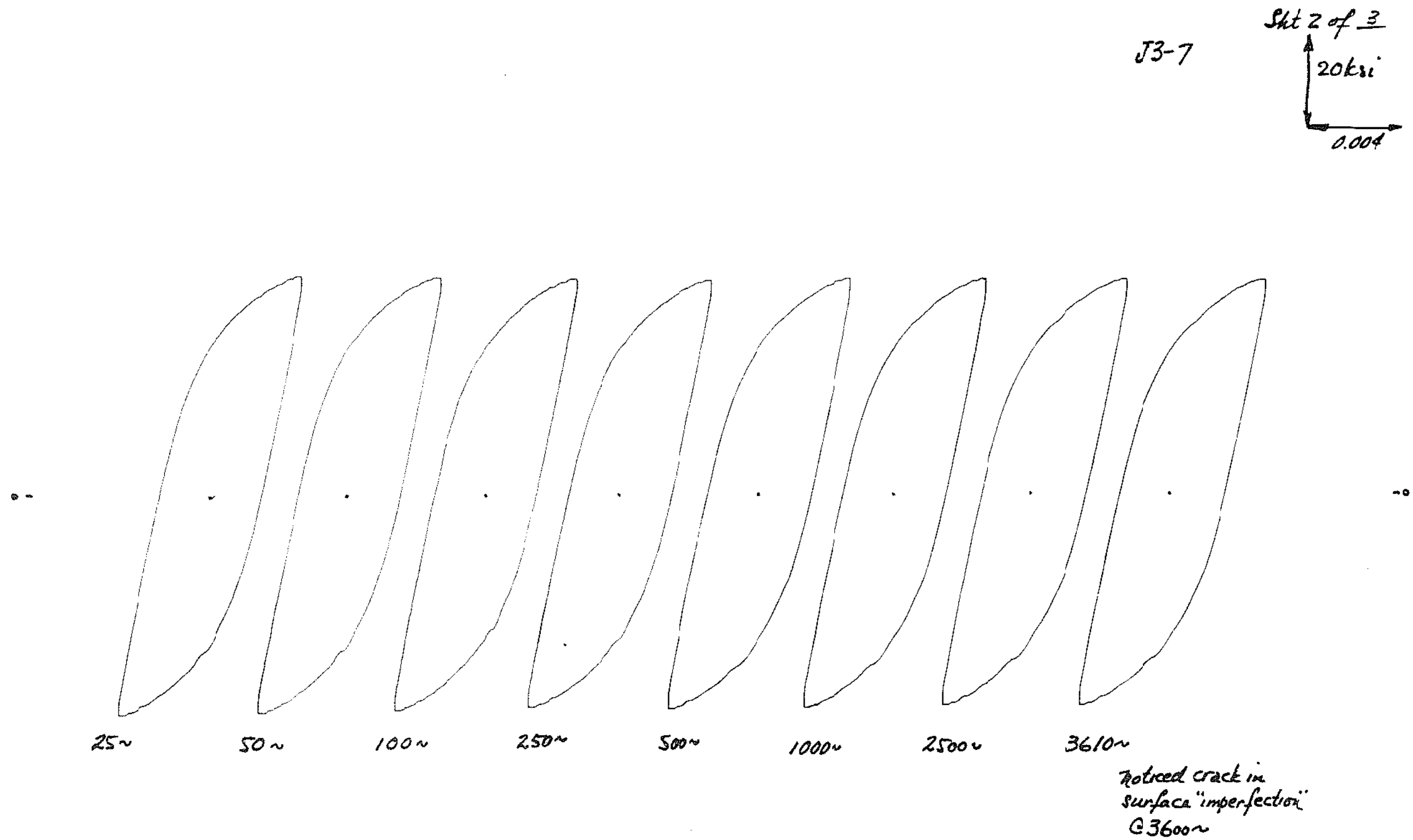
$\frac{\Delta\theta}{2} = \pm 0.004$

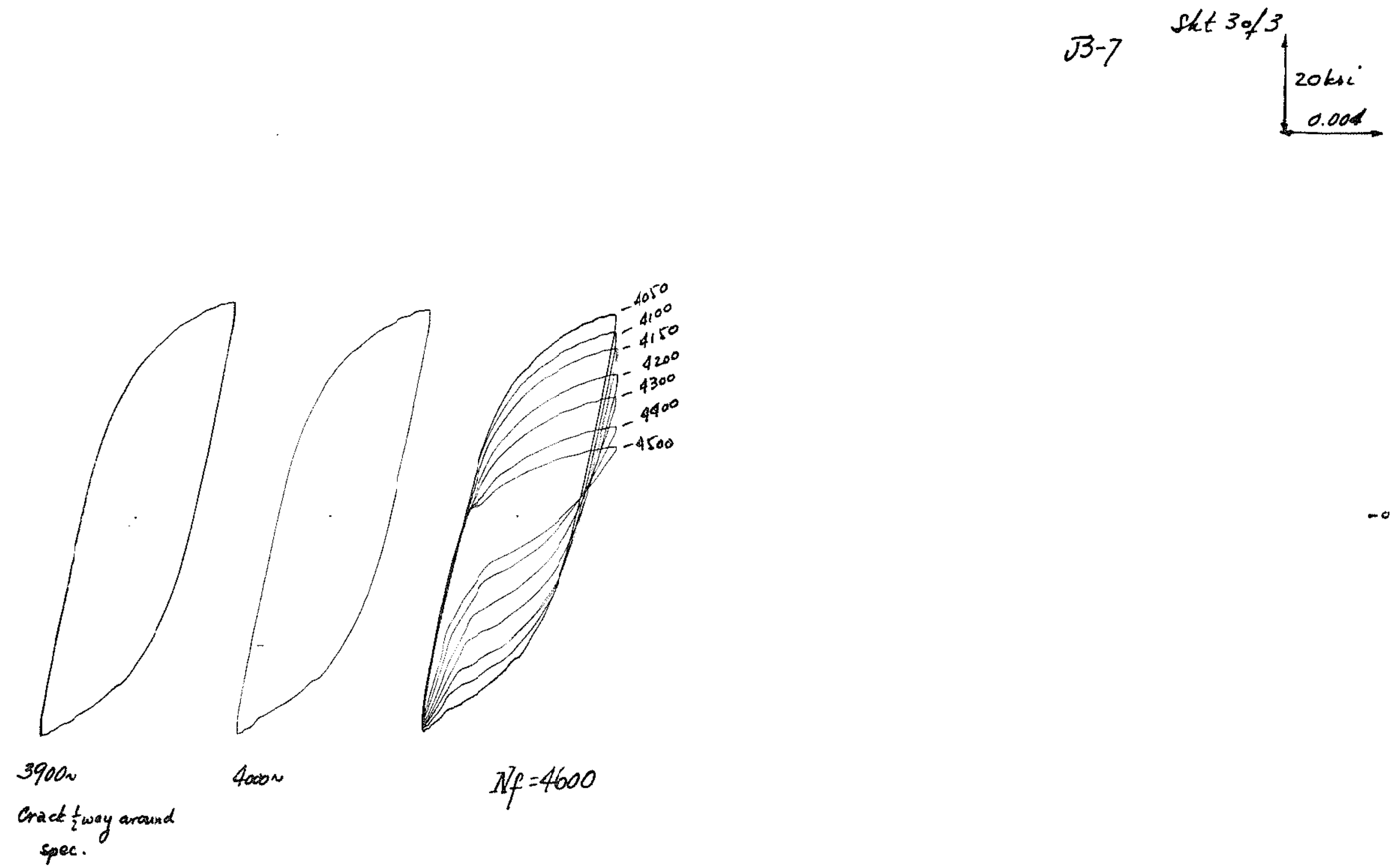
$N_f = 4600$~

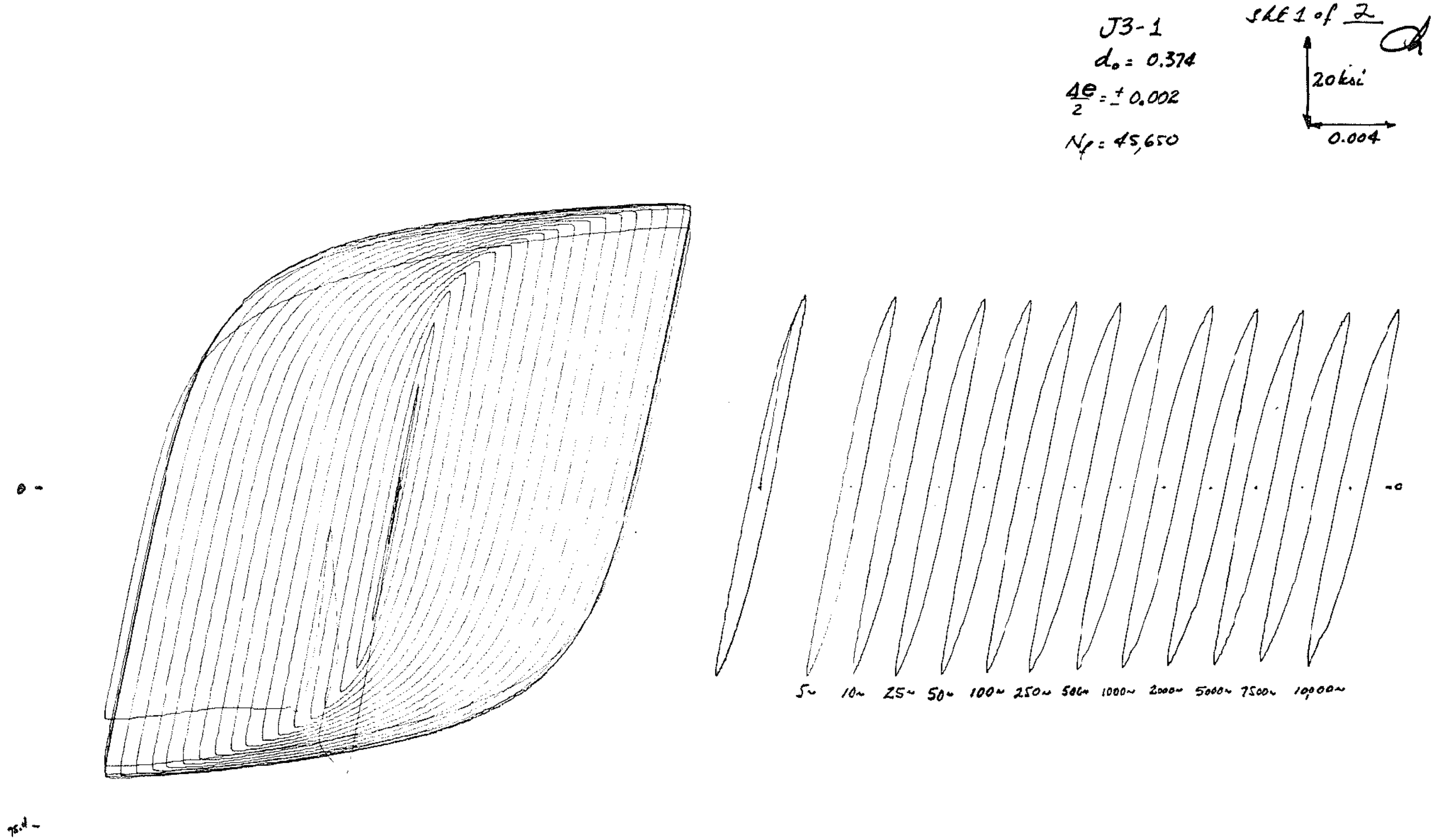


Precycle 5 cycles @ ±0.013

20 cyc. decrease to 0-0.


Sht 2 of 3
J3-7
20ksi
0.004
25~
50~
100~
250~
500~
1000~
2500~
3610~
Noticed crack in
surface "imperfection"
@3600~

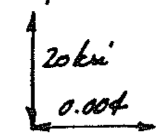

JB-7
Skt 3 of 3
20ksi
0.004
4050
4100
4150
4200
4300
4400
4500
3900~
Crack ½ way around spec.
4000~
Nf = 4600

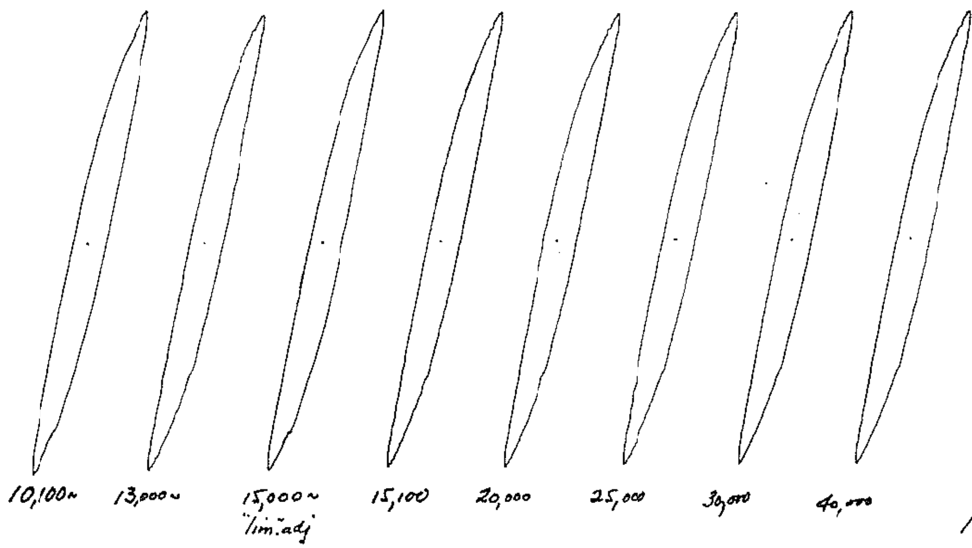


J3-1
d_o = 0.374
$\frac{\Delta e}{2}$ = ± 0.002
N_f = 45,650
sht 1 of 2
20 ksi
0.004
5~
10~
25~
50~
100~
250~
500~
1000~
2000~
5000~
7500~
10,000~

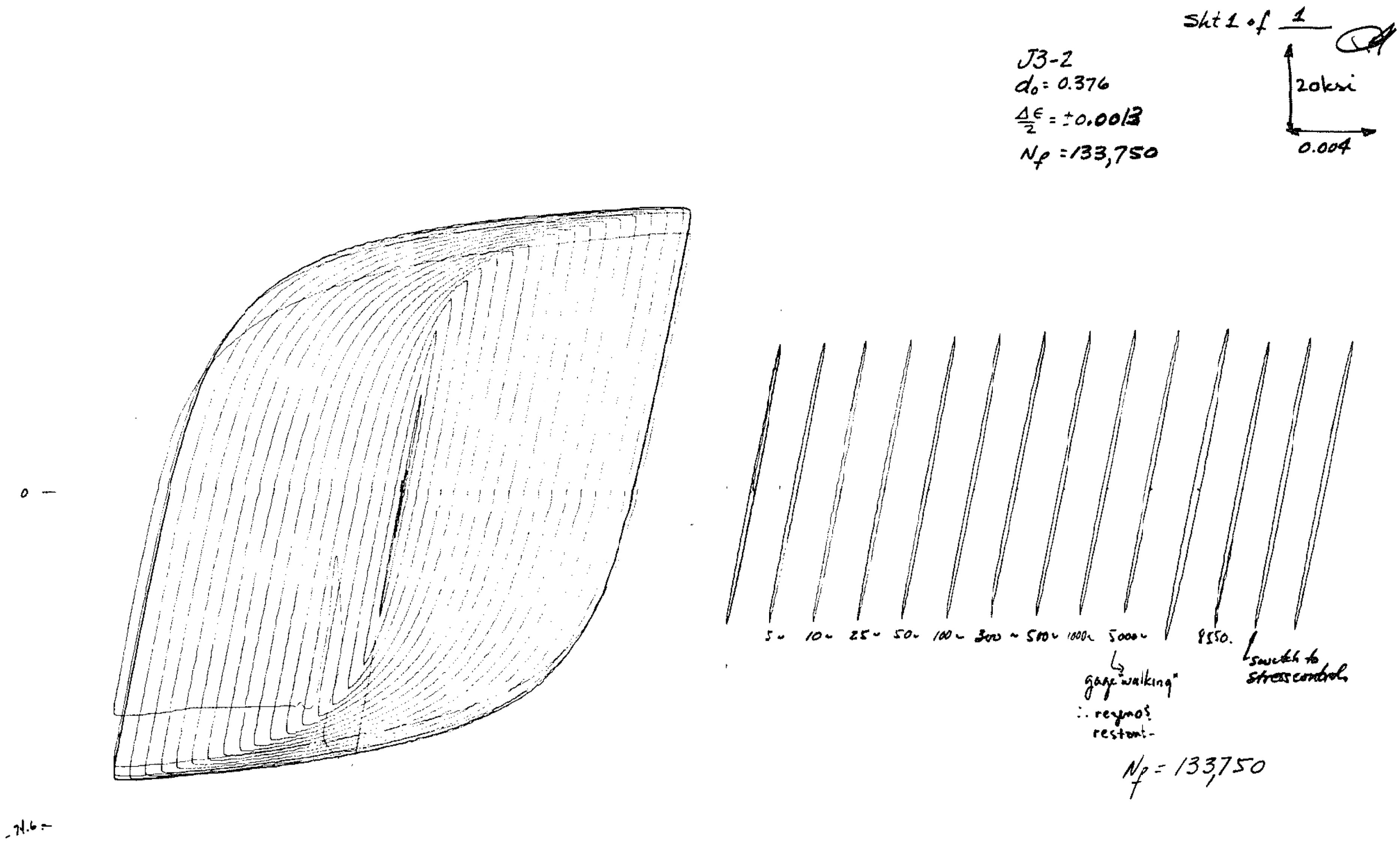
Sht 2 of Z

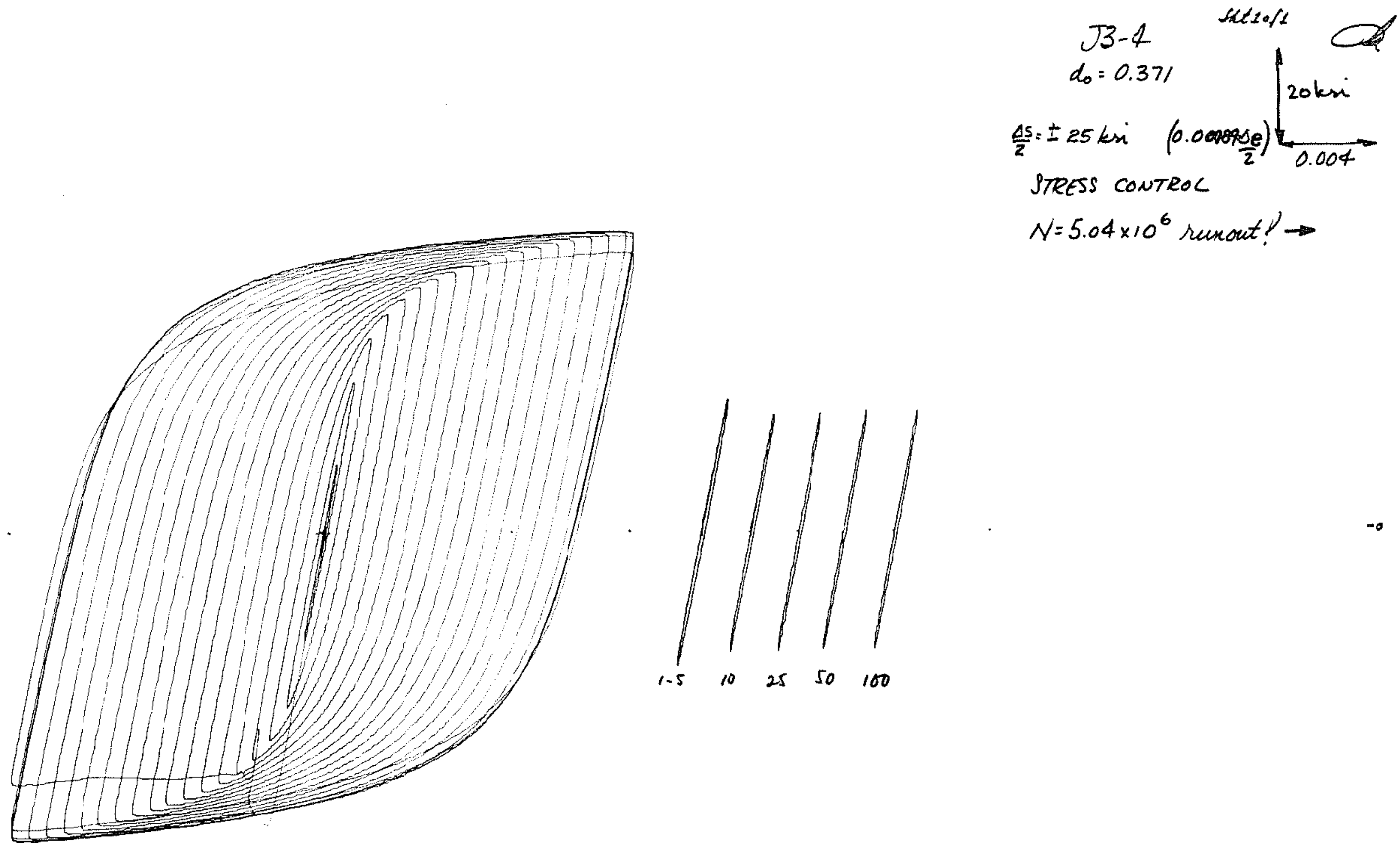
J3-1





N_f: 45,650


Sht 1 of 1
J3-2
d_0 = 0.376
$\frac{\Delta\epsilon}{2}$ = ±0.0013
N_f = 133,750
20ksi
0.004
0
5~ 10~ 25~ 50~ 100~ 300~ 510~ 1000~ 5000~
8550.
switch to stress control
gage "walking" ∴ regmos restart.
N_f = 133750
-N.6-


J3-4
$d_o = 0.371$
$\frac{\Delta S}{2} = \pm 25$ ksi
$(0.00089 \frac{\Delta e}{2})$
STRESS CONTROL
$N = 5.04 \times 10^6$ runout!
20 ksi
0.004
1-5
10
25
50
100

STRAIN-LIFE RESULTS

Specimen Number	Strain Amplitude	Revs. to Failure $2N_f$	Elastic Strain Amplitude $\Delta\epsilon_e/2$	Plastic Strain Amplitude $\Delta\epsilon_p/2$	Saturation* Stress Amplitude $\Delta\sigma/2$, ksi
J3-8	0.01	1,300	0.0021	0.0079	60.0
J3-7	0.004	9,200	0.00164	0.00236	47.0
J3-1	0.002	9.1×10^4	0.00133	0.00067	38.0
J3-2	0.0013	2.7×10^5	0.00110	0.0002	32.0
J3-4	0.00089	1.0×10^{7}**	0.000875	0.000015	25.0

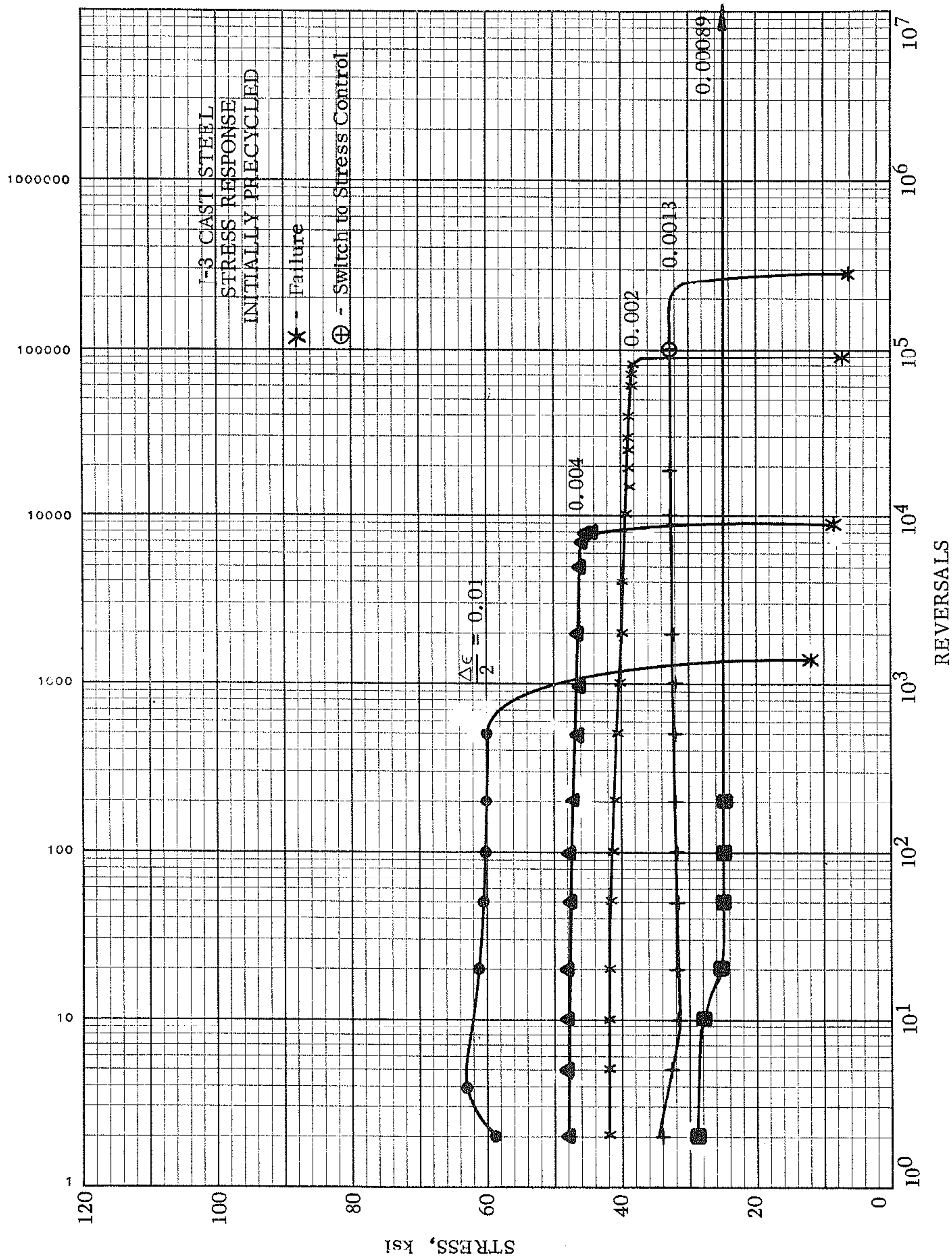
Note: All specimens received an initial precycle of 5 cycles at ±0.013 which was then incrementally decreased to zero stress and strain in 20 cycles.

*Measured at 50% of life to failure.

**Runout, specimen did not fail!

STRESS-TIME RESPONSE TO
CONTROLLED STRAIN FATIGUE TESTS

MODEL DATE



I-3 CAST STEEL
STRESS RESPONSE
INITIALLY PRECYCLED
✱ - Failure
⊕ - Switch to Stress Control
$\frac{\Delta\epsilon}{2} = 0.01$
0.004
0.002
0.0013
0.00089
REVERSALS
STRESS, ksi

ADDITIONAL MATERIAL CHARACTERIZATION SHEETS

DATA SHEET FOR MATERIAL CHARACTERIZATION

Material: J-3 Cast Steel

Condition: Normalized at 1700°F
Tempered at 1200°F

Matrix Hardness: 160 BHN

Converted from: R_B

Monotonic Properties:

Modulus of Elasticity, E	28.6×10^3 ksi
Yield Strength, 0.2% S_y	49.0 ksi
Ultimate Strength, S_u	75.0 ksi
Red. in Area, % RA	67.8%
True Fracture Strength, σ_f	134.0 ksi
σ_f	113.0 ksi (corrected)
True Fracture Ductility, ϵ_f	1.13
Strain Hardening Exponent, n	0.14
Strength Coefficient, K	110 ksi
True Toughness, U_p	112 ksi

Cyclic Properties:

Yield Strength, 0.2% S_y'	47.0* ksi
Strain Hardening Exponent, n'	0.12
Strength Coefficient, K'	107 ksi
Fatigue Strength Coefficient, σ_f'	--- ksi
Fatigue Ductility Coefficient, ϵ_f'	---
Fatigue Strength Exponent, b	-0.11
Fatigue Ductility Exponent, c	-0.68
Transition Fatigue Life, $2N_t$	19,000 rev

*From companion specimen test results

Composition:

w/o C	= 0.20	w/o Mo	= 0.19
w/o Si	= 0.44	w/o Cu	= 0.16
w/o P	= 0.015	w/o Ni	= 0.14
w/o S	= 0.010	w/o Va	= ---
w/o Mn	= 1.13	w/o Al	= 0.035
w/o Cr	= 0.13	w/o B	= 0.001

Grain Size:

Eutectic Cell Size (Cast irons):

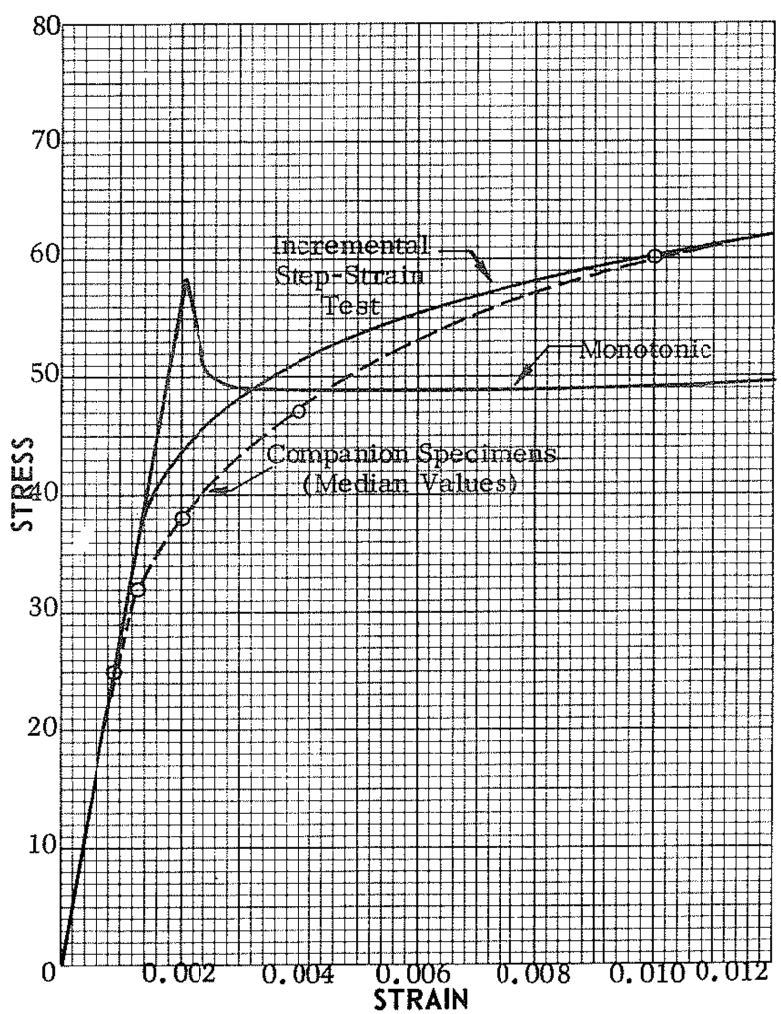
Microstructure:

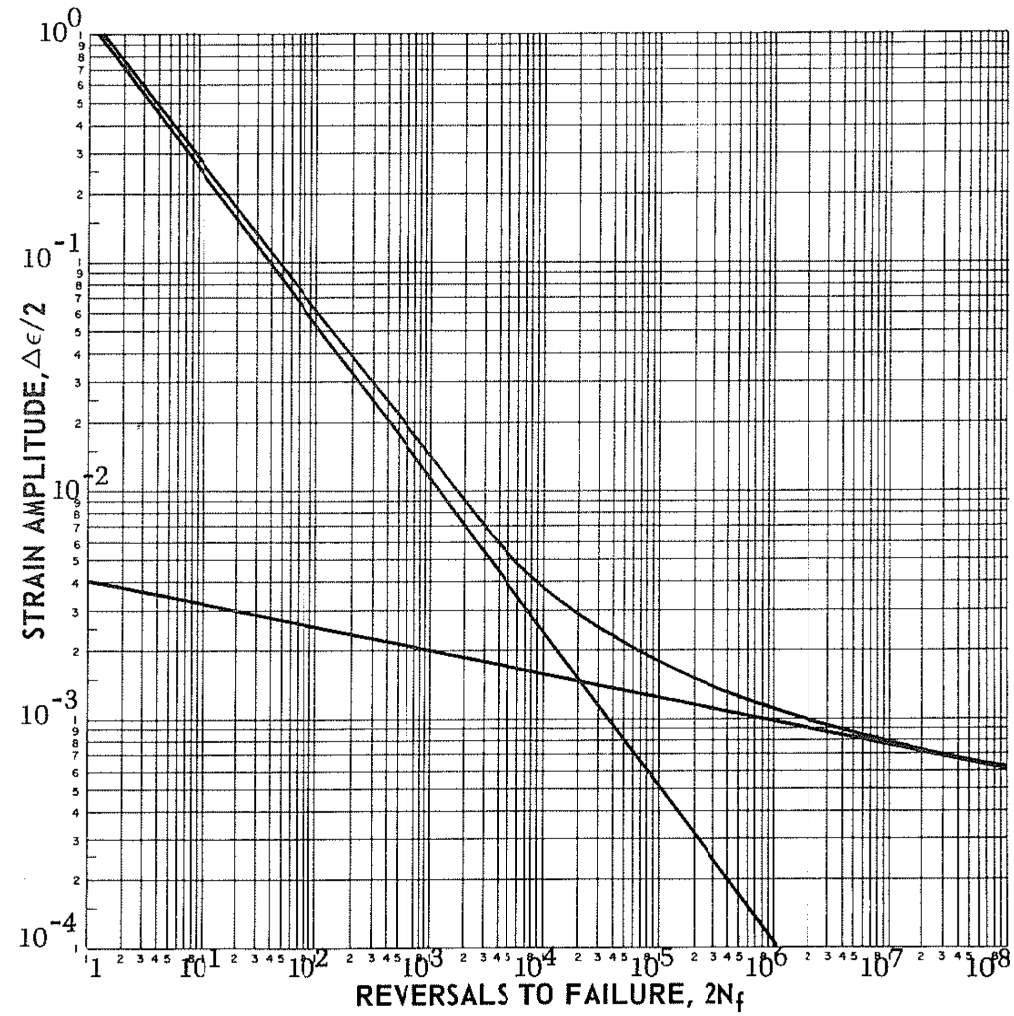
Magnification:

Comments:

Material: J-3 CAST STEEL **Hardness:** 160 BHN

Condition: Normalized at 1700° F
Tempered at 1200° F





FRACTURE CONTROL PROGRAM
UNIVERSITY OF ILLINOIS