APPENDIX (5.1)

Hot Rolling Data Computation

The present appendix includes a print-out of the computer programme used for the computation of the hot rolling data.

```
C********************************************************
C*    COMPUTATION OF MEAN PLANE STRAIN STRENGTH DURING *
C*    HOT ROLLING FROM LABORATORY DATA.                 *
C********************************************************
C
C**** INITIALIZATION OF VARIABLES
C
      DIMENSION H(20),W(20),P(20)
      DIMENSION XRR(20)
      CHARACTER*8 XIDENT,DFILE,RFILE
      R=68.85
      V=203.23
C
C**** READ DATAFILE AND RESULTFILE-NAME
C
      WRITE(*,*)('INPUT DFILE')
      READ (*,10) DFILE
      WRITE(*,*)('INPUT RFILE')
      READ (*,10) RFILE
      OPEN (9,FILE=DFILE)
      OPEN(10,FILE=RFILE)
      READ(9,20) N8
C
C**** BEGINNING OF MAIN LOOP
C
      DO 100 J=1,N8
C
C**** READ DATA AND PERFORM GEOMETRICAL CALCULATIONS
C
       READ(9,30) XIDENT
       READ(9,20) N9
       IF(N9.GT.1) THEN
       READ(9,*) H(1),W(1)
       READ(9,*) H(N9+1),W(N9+1)
       DO 500 I=1,(N9-1)
       READ(9,*) XRR(I)
       H(I+1)=(1-XRR(I))*H(I)
       EL=LOG(H(I)/H(I+1))
       IF (W(1).GT.40.0) GOTO 33
       AA=EL*(0.054*EXP(1.336*H(1)/SQRT(68.85*(H(1)-H(I+1)))))
       GOTO 34
 33    AA=EL*(0.061*(H(1)/W(1))**1.3*EXP(1.265*H(1)/SQRT(68.85*
     1 (H(1)-H(I+1)))))
 34    CONTINUE
 500   W(I+1)=W(1)*EXP(AA)
       ELSE
       DO 200 I=1,N9+1
 200     READ(9,*) H(I),W(I)
       ENDIF
       DO 300 I=1,N9
 300     READ(9,*) P(I)
       WRITE(10,40) XIDENT
       WRITE(10,50)
C
```

Discussion of the programme

Lines	Comments
8-12	Initialization of variables. Peripheral speed, V, and roll radius, R, are 203.23 mm/s and 68.85 mm respectively.
	Read
17	Data-file name; Dfile
19	Result-file name; Rfile
	Dfile and Rfile must not be words with more than 8 characters.
22	Number of schedules to be calculated.
26	For each schedule
	Read
30	Sample identification (no more than 8 characters)
31	Number of passes
32	If its a single pass schedule go to line 47
33-34	Read h_1, w_1, h_2, w_2
35-38	Read decimal reduction. Calculate strain in intermediate passes.
39	If the initial width is greater than 40.0mm go to line 42.
40	If not, calculate the spread (eq.(5.8)).
42	Calculate spread(eq.(5.9)).
45	Calculate intermediate widths.
47-48	Read h_1, w_1, h_2, w_2 for single pass schedule.

```
C**** CALCULATION OF THE MEAN PLANE STRAIN STRENGTH
C
      DO 400 I=1,N9
       RR=(H(I)-H(I+1))/H(I)
       EPS=LOG(H(I)/H(I+1))
       EU=1.155*EPS
       ERPS=(V/(R*(H(I)-H(I+1)))**0.5)*EPS
       ERU=1.155*ERPS
       P(I)=9.81*P(I)
       A=1-(H(I)-H(I+1))/(2*R)
       A=ATAN(SQRT(1-(A**2))/A)
       C1=SQRT(R/H(I+1))
       B=(0.785*LOG(1-RR)+C1*ATAN(SQRT(RR/(1-RR))))/(2*C1)
       B=SIN(B)/(C1*COS(B))
       XN=H(I+1)+2*R*(1-COS(B))
       C2=SQRT((1-RR)/RR)
       C3=1/C2
       Q=1.5708*C2*ATAN(C3)-0.785-C2*C1*LOG(XN/H(I+1))
       Q=Q+0.5*C2*C1*LOG(1/(1-RR))
       WX=(W(I+1)+W(I))/2
       S=1000*P(I)/(WX*SQRT(R*(H(I)-H(I+1)))*Q)
       XX=(LOG(W(I+1)/W(I)))/EPS
       SS=S/(1+XX+XX**2)**0.5
 400   WRITE(10,60)I,RR,EPS,EU,ERPS,ERU,P(I),S,SS
      WRITE(10,70)
      WRITE(10,80)
      DO 600 I=1,N9+1
 600   WRITE(10,90) I,H(I),W(I)
 100  CONTINUE
C
C**** END OF MAIN LOOP
C
      CLOSE(9)
      CLOSE(10)
  10  FORMAT(A8)
  20  FORMAT(I2)
  30  FORMAT(A8)
  40  FORMAT(//1X,'SAMPLE     :',A8)
  50  FORMAT('  Pass   Red%   Eps    Eu   Erps    Eru     PKn  PS,MPa
     1 PSc,MPa')
  60  FORMAT(5X,I2,5(1X,F6.3),3(2X,F6.2))
  70  FORMAT(/,1X,' SAMPLE GEOMETRY')
  80  FORMAT('    Before Pass   Thickness,mm    Width,mm')
  90  FORMAT(8X,I2,5X,2(F10.3,6X))
      STOP
      END
```

Lines	Comments
50-51	Read load in tonnes for each pass.
57	For each pass
58	Re-calculate the reduction
59	Calculate the plane strain and
60	the equivalent strain.
61-62	Calculate the strain rate(eq.(5.11))
63	Convert load from tonnes into kN
64-73	Calculate Q factor (eq.(5.13))
74	W_x is the average width(eq.(5.16))
75	S is the mean plane strain yield stress (eq.(5.12)).
76-77	SS is S corrected for the effect of spread (eq.(5.21)).

Example of application

Typical data-file

```
 2
SAMPLE1
 1
25.04 48.04
19.84 49.46
9.63
SAMPLE2
 4
25.04 48.04
10.41 51.79
0.2077
0.1966
0.1932
9.63
10.34
13.14
14.95
```

Typical result-file

```


SAMPLE      :SAMPLE1
  Pass   Red%    Eps     Eu    Erps    Eru     PKn  PS,MPa PSc,MPa
     1  0.208  0.233  0.269  2.500  2.888   94.47  106.50  113.75

 SAMPLE GEOMETRY
   Before Pass   Thickness,mm    Width,mm
        1          25.040          48.040
        2          19.840          49.460


SAMPLE      :SAMPLE2
  Pass   Red%    Eps     Eu    Erps    Eru     PKn  PS,MPa PSc,MPa
     1  0.208  0.233  0.269  2.500  2.888   94.47  106.31  114.44
     2  0.197  0.219  0.253  2.715  3.136  101.44  126.20  128.99
     3  0.193  0.215  0.248  2.996  3.461  128.90  174.14  178.40
     4  0.190  0.211  0.244  3.307  3.819  146.66  212.54  225.07

 SAMPLE GEOMETRY
   Before Pass   Thickness,mm    Width,mm
        1          25.040          48.040
        2          19.839          49.625
        3          15.939          50.094
        4          12.859          50.606
        5          10.410          51.790
```

Lines	Comments
118-143	Symbols are:

Eps	Plane strain
Eu	Equivalent strain
Erps	Plane strain rate
Eru	Equivalent strain rate
PKn	Load in kN
PS	Mean plane strain yield stress
PSc	Mean plane strain yield stress corrected by using eq. (5.21).

APPENDIX (5.2)

Data Handling of Plane Strain Compression Tests

1. Introduction

Figure(5.16) shows schematically the stages involved in converting raw data from plane strain compression tests into stress-strain curves. The computation procedure includes an interactive programme for origin correction developed by Colás(1983). The programmes were run in Prime750 computer at Sheffield University. Print out copies of programmes TRANSR.F77 and SEVO.F77 are given below. Brief comments are attached to both programme listings.

2. TRANSR.F77 Programme

The punched paper tape generated after each test contains words recorded in ASCII code. The words are formed by two bytes (=two rows of perforations on the tape). These words are converted into their decimal form when the paper tape is loaded into the ICL1906 computer. Programme TRANSR.F77 operates on the decimal form of the transformed words. As a result, real numbers meaning loads (L), displacement (D), and millivolts (T) are generated. A file is created (usually a M_filename file) in which L, D, and T data are preserved for further processing.

A copy of TRANSR.F77 programme is given below.

```
      PROGRAM TRANSR
      DIMENSION IA(5),MEM(2500)
      DIMENSION PLOAD(450),DISP(450),TE(450)
      CHARACTER*8 DFILE,SFILE
   90 WRITE(*,12)
      READ(*,14) DFILE
      OPEN(9,FILE=DFILE,FORM='FORMATTED')
      READ(9,*)(MEM(I),I=1,13)
      IC=MEM(2)-48
      DO 200 M=1,IC
  200 IA(M)=INT((256*MEM(2*M+2)+MEM(2*M+1)+2)/2)
      TELMS=IA(IC)*6+2+2*IC
      ITLINS=INT(TELMS/13)
      DO 300 J=2,ITLINS
      K=(J-1)*13
  300 READ(9,*)(MEM(K+I),I=1,13)
      KK=ITLINS*13
      LLELMS=TELMS-KK
      READ(9,*)(MEM(KK+I),I=1,LLELMS)
      CLOSE(9)
      IK=IA(IC)
      DO 440 N=1,3*IK
      K=N+(IC+1)
      N2=MEM(2*K)
      N1=MEM(2*K-1)
      IF (N2.LT.128) GOTO 210
      N2 =N2-256
  210 NN=N2*256+N1
      IF(N.LE.IK) GOTO 390
      IF(N.LE.2*IK) GOTO 410
      TE(N-2*IK)=NN
      GOTO 440
  390 DISP(N)=NN
      GOTO 440
  410 PLOAD(N-IK)=NN
  440 CONTINUE
      CLOSE(9)
C
C     STORING DATA IN A TEMPORARY FILE FOR FUTURE PROCESSING
C
      WRITE(*,22)
      READ(*,24) SFILE
      OPEN(9,FILE =SFILE,FORM='FORMATTED')
      WRITE(9,26) IC,(IA(J),J=1,IC)
      WRITE(9,28)(DISP(L),L=1,IA(IC))
      WRITE(9,29)(PLOAD(L),L=1,IA(IC))
      WRITE(9,27)(TE(L),L=1,IA(IC))
      CLOSE(9)
      WRITE (*,30)
      READ(*,*) Q
      IF (Q.EQ.1) GOTO 90
      CALL EXIT
   12 FORMAT('DFILE')
   14 FORMAT(A8)
   22 FORMAT('FILE FOR SAVING DATA-SFILE')
   24 FORMAT(A8)
```

Lines	Comments
1-4	Dimensioning variables
5-6	Reads Data-file
9	IC is the number of deformations given during a test.
12	TELMS is the total number of bytes to be read. (1 word = 2 bytes = 2 rows of perforated holes in a paper tape).
14-20	Read in raw data
26-28	Converts 2 byte words into a real number.
29-37	Store values of load , displacement , and millivolts into arrays PLOAD, DISP and TE.
41-48	Store load , displacement and millivolts into a given file (usually a M_filename file).

```
26    FORMAT(6I4)
27    FORMAT(10F8.2)
28    FORMAT(10F8.3)
29    FORMAT(10F8.1)
30    FORMAT('ANOTHER FILE? Y=1,N=0')
      END
```

2. SEVO.F77 Programme

The SEVO.F77 programme takes data corrected for origin from ORIGINCOR.PAS programme (Colás,1983) and gives as a result of calculations a stress-strain curve. The programme was originally developed by Foster(1981) who discussed it in detail. The original version of the programme was written in BASIC language and run in a Hewlett-Packard desk top computer model 9830A. Foster's version was "translated" into FORTRAN.F77 and run on a Prime750 computer at Sheffield University. A new section dealing with the calculation of stress-dtrain curves for axisymmetric compression tests was included. As a whole, however, the original version is still mostly preserved.

```
C
C
      PROGRAM SERVO
C
C     Calculates the stress-strain curves from the Servotest and
C     corrects the stress level due to adiabatic heating.
C
      DIMENSION STRE(450),STRA(450),SRAT(450)
      DIMENSION PLOAD(450),DISP(450),TE(450),IA(5)
      DIMENSION SS(50),V(50),Z(5),IB(5),IR(30),F(4,60),IK(6)
      CHARACTER*8 TITLE,PRDATA
C
C
C
C
C
  569 WRITE (*,10)
      READ (*,12) TITLE
C     READ DATA FROM DATAFILE
      OPEN (9,FILE = TITLE ,FORM ='FORMATTED')
      READ (9,*)IC,(IA(J),J=1,IC)
      READ (9,* ) (PLOAD (L),L=1,IA(IC))
      READ (9,* ) (DISP(L),L=1,IA(IC))
      READ(9,* ) (TE(L),L=1,IA(IC))
      CLOSE (9)
      WRITE (*,35)
      READ(*,*) IP10
      IF (IP10.EQ.2) GOTO 501
      WRITE (*,20)
      GOTO 500
  501 WRITE (*,36)
  500 READ (*,*) TH1,B1,TW1
      WRITE (*,22)
      READ (*,*) FX1,C1
      IF (FX1.EQ.0.OR.IP10.EQ.2) GOTO 101
      V1 = LOG(1/(2*FX1))/FX1
  101 CONTINUE
      WRITE (*,24)
      READ (*,*) P,RANG
      ICONS = IA(IC)
      WRITE (*,26)
      READ(*,*) IP1
      IF (IP1.EQ.0) GOTO 102
      WRITE (*,17)
      READ (*,*) H2
  102 WRITE (*,30)
      READ (*,*) IP2
      IF (IP2.EQ.0) GOTO 104
      WRITE (*,19)
      READ (*,*) T2
      WRITE (*,32)
      READ(*,*) B3,A2
      WRITE(*,28)
      READ(*,*) N2
      DO 144 N=2,N2+1
      WRITE (*,29)N
```

```
144  READ(*,*) SS(N),V(N)
104  CONTINUE
     WRITE (*,31)
     READ (*,*) K1
     IF (K1.EQ.0) GOTO 105
     WRITE (*,27)
     READ (*,*) B4,C2,S3
105  CONTINUE
     L=1
     E6=STRA(1)
     DO 115 M=1,IC
     DO 115 I=L,IA(M)
     STRA(I) =-DISP (I)
     STRE(I)=PLOAD(I)*1000
     IF (STRA(I).LT.E6) GOTO 1620
     GOTO 1150
1620 E6 = STRA(I)
1150 L = L+1
     XI=L
115  CONTINUE
     H3=TH1+E6
     H4=H2-H3
     L=1
     V(1)=T2
     DO 120 M=1,IC
     Z(IC) =0
     DO 125 I=L,IA(M)
     IF (IP1.EQ.0) GOTO 60
     STRA(I)=STRA(I)+H4
60   T1=TH1+STRA(I)
     B= B1*(1+C1-C1*SQRT(T1/TH1))
     F1=(1.155*(B-TW1)+TW1)/B
     IF(IP10.EQ.2) F1=1.0
     STRA(I)= LOG(TH1/T1)*F1
     IF(STRA(I).LT.Z(M)) GOTO 661
     Z(M) = STRA(I)
     IB(M)=I
661  IF(IP10.EQ.2) GOTO 662
     S1=STRE(I)/(TW1*B*F1)
     GOTO 663
662  BB=B*SQRT(TH1/T1)
     S1=STRE(I)/(3.1416*BB**2/4)
663  IF (IP2.EQ.0) GOTO 135
      IF ( STRA(I).LT.0.) GOTO 135
      DO 140 J= 2,N2+1
      IF (STRA(I).LT.SS(J)) GOTO 1910
140   CONTINUE
      N2=N2+1
1910  T3=V(J-1)+(STRA(I)-SS(J-1))*((V(J)-V(J-1))/(SS(J)-SS(J-1)))
      S1=S1+A2*((1/(T2+273))-(1/(T3+273)))/(8.320*B3)
135   CONTINUE
      IF(IP10.EQ.1) GOTO 668
      IF(FX1.EQ.0) GOTO 664
      V1=LOG(0.577/FX1)/FX1
      DC=BB-T1*V1
      DD=FX1*DC/T1
```

```
      CC=FX1*BB/T1
      IF((BB/T1).LE.V1) GOTO 666
      IF(FX1.GE.0.577) GOTO 667
      D1=((2/CC**2)*((DD+1)*EXP(CC-DD)-CC-1))+(DD/CC)**2*(0.577/FX1+
     10.577*DC/3*T1)
      S=S1/D1
      GOTO 665
  666 D1=(2/CC**2)*(EXP(CC)-CC-1)
      S=S1/D1
      GOTO 665
  667 D1=1+0.577*BB/3*T1
      S=S1/D1
      GOTO 665
  664 S=S1
  665 GOTO 175
  668 IF (FX1.EQ.0) GOTO 160
      IF ((TW1/T1).LT.V1) GOTO 165
      IF(FX1.GE.0.389) GOTO 170
      Z1=(T1/(2.*FX1))*ALOG(1/(2*FX1))
      D1=((1/(2*FX1)-1)*T1/(FX1*TW1))+((TW1/2.-Z1)/(FX1*TW1))+
     1((TW1/2.-Z1)**2)/(TW1*T1)
      S=S1/D1
      GOTO 175
  165 D1=(T1/(FX1*TW1))*(EXP(FX1*TW1/T1)-1.)
      S=S1/D1
      GOTO 175
  170 D1=1+(TW1/(4*T1))
      S=S1/D1
      GOTO 175
  160 S=S1
  175 IF (K1.EQ.0) GOTO 161
      E2 = STRA(I)*(1+(2+C2*TH1))
      S= S3+(S-S3)*(EXP((-B4*TH1)/(E2*TW1)))
  161 STRE(I)=S
  125 CONTINUE
      L=IA(M)+1
  120 CONTINUE
      DO 122 I=1,IC
      B2=IA(I)
      IK(I+1)=IA(I)
  122 CONTINUE
      WRITE (*,46)
      READ(*,*) IP4
      IF (IP4.EQ.0) GOTO 180
      WRITE (*,33)
      READ (*,*) T4
      IF (T4.EQ.1) GOTO 2460
      WRITE (*,34)
      READ (*,*) T5
      T5 =T5*40
 2460 CONTINUE
      DO 185 I=1,ICONS
      TE(I)=TE(I) +T5
      TE(I)=-5.781+(0.675*TE(I))-(0.1256*(TE(I)/40.)**2)
     1+(0.0019*(TE(I)/40.)**3)
  185 CONTINUE
```

```
180   CONTINUE
      WRITE (*,48)
      READ(*,*) IP5
      IF (IP5.EQ.0) GOTO 187
      WRITE (*,52)
      READ (*,*) E1
      L=1
      K=0
      IZ7=0
      IZ8=0
      IZ9=0
      IK(1)=0
      E6=0
      W2=0
      W4=0
      W5=0
      W6=0
      W7=0
      W8=0
      IR(1)=0
      DO 3760 J=1,IC
      E9 = STRA(1)
      Z6 = E1 + 0.1
      DO 3650 I = L,IA(J)
      IQ9= 0
      JJ = I
      IG= JJ
      IF (JJ.GT.IB(J)) GOTO 3540
3150  IF (IG.EQ.(IK(J)+1) ) GOTO 3170
      IG =IG-1
3170  IF (JJ.EQ.IB(J)) GOTO 3190
      JJ=JJ+1
3190  IQ9 = JJ-IG
      E9 = STRA(JJ) - STRA(IG)
      IF (E9.LT.0.05.AND.IQ9.LT.10 ) GOTO 3150
      E8=E9*P/IQ9
      SRAT(I)=E8
      IS2 = INT(   SIGN (1.,E8)   )
      IF (IS2.LT.0) GOTO 3570
      IF (IP5.EQ.0) GOTO 3490
      IF (STRA(I).LE.E1) GOTO 3480
      IF ( IZ9.GT.0) GOTO 3330
      E1= E6
3330  IF (IZ7.EQ.0) GOTO 3490
      W5 = STRA(I) -W7
      W4 = (STRE(I)+ W6)/2
      W2 = (W4* W5) + W2
      IZ9 = IZ9 + 1
      IF (STRA(I).GE.Z6.OR.STRA(I).EQ.Z(J) ) GOTO 3410
      IF (I.EQ.ICONS) GOTO 3410
      GOTO 3490
3410  IZ8 =IZ8 + 1
      F(2,IZ8) = W2
      F(3,IZ8)= W2/(STRA(I) -E1)
      F(1,IZ8)= STRA(I)
      F(4,IZ8)= ((STRA(I) - E1 )*P)/IZ9
```

```
      Z6= Z6 + 0.1
      GOTO 3490
 3480 E6 = STRA(I)
 3490 E7 = ALOG (E8)
      GOTO 3550
 3540 E8=0
 3550 CONTINUE
 3570 IF (I.EQ.IA(IC) ) GOTO 3660
      IZ7 = IZ7 + 1
      W7 = STRA (I)
      W6 = STRE (I)
      W8 = E8
 3650 CONTINUE
 3660 IF (J.GT.1) GOTO 3680
      R1 = E1
 3680 E1 = Z(J)
      IR(J+1) =IZ8
 3760 CONTINUE
  187 CONTINUE
      WRITE (*,70)
      READ (*,*) IP7
      IF (IP7 . EQ. 0 ) GOTO 236
      WRITE (*,96 )
      READ (*,12 ) PRDATA
      OPEN ( 9, FILE = PRDATA,FORM='FORMATTED')
      WRITE (9,62) TITLE
      DO 310 M = 1,IC
      WRITE (9,72)
      WRITE (9,74) (I,STRA(I),STRE(I),SRAT(I), TE(I),I=L,IA(M))
      L= IA(M) + 1
  310 CONTINUE
      IF (IP5.EQ.0) GOTO 235
      DO 320 I=1,IC
      WRITE (9,64) I
      WRITE ( 9,66)
      WRITE (9,68)(F(1,N),F(3,N),F(4,N),N=(IR(I)+1),IR(I+1))
  320 CONTINUE
  235 CLOSE (9)
  236 CONTINUE
      WRITE (*,61)
      READ (*,*) IP8
      IF(IP8.EQ.0) GOTO 335
      DO 330 I=1,IC
      WRITE (*,64) I
      WRITE (*,66)
  330 WRITE (*,68) ( F(1,N),F(3,N),F(4,N),N=(IR(I)+1),IR(I+1))
  335 CONTINUE
      WRITE (*,76)
      READ (*,*) IP9
      IF (IP9.EQ.0) GOTO 260
C
C     Plotting routines.
C
      CALL PAPER (1)
C     CALL FILNAM('T$0001',6)
      CALL GHFROR (1)
```

```
      CALL PSPACE (0.13,0.87,0.38,0.94)
      CALL CSPACE (0.,1.,0.,1.)
      CALL QADRNT
      WRITE (*,78)
      READ (*,*) IP10
      IF (IP10.EQ.0) GOTO 245
      WRITE (*,80)
      READ (*,*) ESC1
      WRITE (*,82)
      READ (*,*) ESC2
      CALL MAP (0.,ESC2,0.,ESC1)
      CALL BORDER
      CALL REDPEN
      CALL SCALSI (0.5,50.)
      CALL PLACE (48,49)
      CALL TYPECS ('EQUIVALENT STRAIN',17)
      CALL PLACE (55,3)
      CALL TYPECS (TITLE,8)
      CALL PLACE (6,28)
      CALL CTRORI (1.0)
      CALL TYPECS ('EQ. STRESS',10)
      CALL GRNPEN
      ESC3=-ESC2/5.
      CALL WINDOW (ESC3,ESC2,0.,ESC1)
      CALL PTPLOT (STRA,STRE,1,ICONS,43)
      CALL WINDOW (0.,ESC2,0.,ESC1)
      CALL GHFROR (0)
  245 WRITE (*,84)
      READ (*,*) IP11
      IF (IP10.EQ.1) GOTO 246
      WRITE (*,82)
      READ(*,*) ESC2
  246 IF (IP11.EQ.0) GOTO 250
      DO 255 I=1,ICONS
      IF (SRAT(I).GT.0.) GOTO 255
      SRAT(I)=0.1
  255 CONTINUE
      CALL GHFROR (1)
      CALL FRAME
      CALL PSPACE (0.13,0.87,0.38,0.94)
      CALL MAPYL (0.,ESC2,0.1,205.)
      CALL BORDER
      CALL REDPEN
      CALL SCAYLI (0.1)
      CALL PLACE (48,49)
      CALL TYPECS ('EQUIVALENT STRAIN',17)
      CALL PLACE (55,3)
      CALL TYPECS (TITLE,8)
      CALL PLACE (6,28)
      CALL CTRORI (1.0)
      CALL TYPECS ('STRAIN RATE',11)
      CALL GRNPEN
      CALL PTPLOT (STRA,SRAT,1,ICONS,227)
      CALL GHFROR (0)
  250 WRITE (*,86)
      READ (*,*) IP12
```

```
      IF (IP10.EQ.1) GOTO 251
      WRITE (*,82)
      READ(*,*) ESC2
  251 IF (IP12.EQ.0) GOTO 257
      WRITE (*,88)
      READ(*,*) TMAX,TMIN
      CALL GHFROR (1)
      CALL FRAME
      CALL PSPACE (0.13,0.87,0.38,0.94)
      CALL MAP (0.,ESC2,TMIN,TMAX)
      CALL BORDER
      CALL REDPEN
C     CALL SCALSI (0.5,50)
      CALL PLACE (48,49)
      CALL TYPECS ('EQUIVALENT STRAIN',17)
      CALL PLACE (55,3)
      CALL TYPECS (TITLE,8)
      CALL PLACE (6,28)
      CALL CTRORI (1.0)
      CALL TYPECS ('TEMPERATURE',11)
      CALL GRNPEN
      CALL PTPLOT (STRA,TE,1,ICONS,42)
  257 CALL GREND
  260 CONTINUE
      WRITE (*,99)
      READ (*,*) IP69
      IF (IP69.NE.1) GOTO 569
      IF(IP9.EQ.1) THEN
      WRITE(*,*)('DON''T FORGET TO DELETE PFILE T$0001')
      ELSE
      CONTINUE
      ENDIF
      CALL EXIT
   10 FORMAT ('Identification (A*8)')
   12 FORMAT (A8)
   17 FORMAT ('Final thickness corrected for expansion,mm')
   19 FORMAT ('Nominal Temperature in Degrees Centigrades')
   20 FORMAT ('Thickness, breath and tool width EXP. CORR.')
   22 FORMAT ('Friction and spread coeficients'/'Axisymmetric test?
     1 Spread=0.0')
   24 FORMAT ('Clock frequency and load range')
   26 FORMAT ('F.FOSTER''S Origin correction?y=1,n=0')
   27 FORMAT ('Input Constants B,C and Sigma0')
   28 FORMAT ('No of Strain-Temp readings')
   29 FORMAT ('Eq. Tensile Strain, Av.Sp. Temperature')
   30 FORMAT ('Temperature correction?y=1,n=0')
   31 FORMAT ('Geometry Correction ? y=1,n=0')
   32 FORMAT ('Beta Value and Act Energy (cal/mol)')
   33 FORMAT ('Cold Junction used? y=1,n=0')
   34 FORMAT ('Input room temperature in mv.')
   35 FORMAT ('Plane Strain =1,Axis=2')
   36 FORMAT ('Thickness,diameter,tool width,EXP. CORR.')
   46 FORMAT ('Temperature calculations?y=1,n=0')
   48 FORMAT ('Energy table? y=1,n=0')
   52 FORMAT ('Minimum strain (R)')
   61 FORMAT ('Energy Tables in VDU ?y=1,n=0')
```

```
 62 FORMAT (T30,'****** ',A8,' ******')
 64 FORMAT (T33,'Deformation ',I2)
 66 FORMAT (20X,'Strain',10X,'Av. stress',
   17X,'Av. strain rate')
 68 FORMAT (20X,F6.3,11X,F9.3,13X,F7.3)
 70 FORMAT ('Complete tabulation? y=1,n=0')
 72 FORMAT (2X,'I',5X,'Strain',7X,'Stress',6X,'Strain rate'
   1,5X,'Temperature')
 74 FORMAT (1X,I3,4X,F6.3,6X,F7.3,6X,F7.3,7X,
   1F6.1)
 76 FORMAT ('Do you want any plot? y=1,n=0')
 78 FORMAT ('Stress-strain plot? y=1,n=0')
 80 FORMAT ('Higher limit in stress scale (R)')
 82 FORMAT ('Higher limit in strain scale (R)')
 84 FORMAT ('Strain rate-strain plot? y=1,n=0')
 86 FORMAT ('Temperature-strain plot? y=1,n=0')
 88 FORMAT ('Max and min temperature limits (2*R)')
 96 FORMAT ('File for printouts (A*8)')
 99 FORMAT ('Have you finished? y=1,n=0')
    END
```

Lines	Comments
97	equation (5.40)
111-110	equation (5.47)
112	equation (5.46)
113	equation (5.43)
114	If condition (5.41) is true then go to line 127
115	If sticking friction occurs during test then go to line 130
116-118	equation (5.45)
120-121	equation (5.42)
123	equation (5.44)

276-360	Plotting routines
	The plot-file is stored in the temporary file t$0001 if the programme is compiled using :
	`COMPILE SEVO.F77 -GHOST -GRID`
	In order to have a hard copy of T$0001 output, it should be entered:
	`CC1012`
	An interactive computing section starts and the user should answer the questions put to him by the computer.

APPENDIX 6.1

Print-out of the computer programme for calculation and plotting of theoretical stress-strain curves of austenitic stainless steel type 316L.

```
10 SCALE 0,3,0,400
20 XAXIS 0,0.1,0,3
30 YAXIS 0,10,0,400
40 PEN
50 DISP "GRAIN SIZE , Z";
60 INPUT D,Z
70 E1=2
80 B=-506+37*LGT(Z)
90 B1=-410.2+30.3*LGT(Z)
100 B1=B-B1
110 S0=-565.3+36*LGT(Z)
120 B=B-S0
130 E2=0.097*(Z↑0.032)
140 S1=-474+34.5*LGT(Z)
150 A0=(S1-S0)/((0.1)↑0.5)
160 C=(A0*E2↑0.5/B)↑2
170 C1=-10*E2*(LOG(1-((S1-S0)/B)↑2))
180 PRINT "Z="Z;"D="D;"EP="E2;"B1="B1;
190 PRINT
200 FOR I=3 TO 3
210 E=-0.02
220 E=E+0.02
230 IF E>E1 THEN 330
240 IF E<0.7*E2 AND I=2 THEN 220
250 S=S0+B*(1-EXP(-C*E/E2))↑0.5
260 IF E<0.7*E2 OR I=1 THEN 310
270 S8=B1*(1-EXP(-0.5*(((E-0.7*E2)/E2)↑1.4))),
280 S=S-S8
290 IF I=3 THEN 310
300 S=S8
310 PLOT E,S,-2
320 GOTO 220
330 PEN
340 NEXT I
350 DISP "CONTINUE? YES=1,NO=0";
360 INPUT L
370 IF L=1 THEN 10
380 STOP
390 END
```

APPENDIX (7.1)

The inhomogeneous strain distribution given in figure (7.1) can be grouped as:

Material	Weigth, mg	% of total material
$\varepsilon<0.3$	396.5	42
$0.3<\varepsilon<0.4$	204	22
$0.4<\varepsilon<0.7$	238	36
Total	938.5	100

Figure (7.2) shows that line A is in the region where strains are larger than 0.4. Line B lies in a region where strains are between 0.3 and 0.4. And line C is in the region where strains are lower than 0.3. The fraction recrystallized of the sample deformed at a strain of 0.3 can be calculated as

$$X = \sum_{1}^{n} x_i \, p_i \qquad (1)$$

where:

X = Fraction of the sample which has been recrystallized at a time t.

x_i = Fraction recrystallized of part of the sample at a given strain ε at the same time t.

p_i = Weigth percent of total material of the sample at a given strain ε.

The curve shown in figure (7.3) may be built as shown in the following table:

Time, s	X , %			$x_i p_i$			$\sum_1^n x_i p_i$
	A	B	C	A	B	C	
20	0.44	0.166	0.00	0.16	0.037	0.00	0.20
60	0.73	0.43	0.11	0.262	0.095	0.046	0.40
120	1.00	0.49	0.20	0.36	0.13	0.084	0.57
220	1.00	0.80	0.34	0.36	0.18	0.143	0.68

APPENDIX (7.2)

This appendix contains a commented version of programme FRACTION.F77. The programme was originally written in FORTRAN.F77 and run in a Prime 750 computer at Sheffield University.

FRACTION.F77 was designed to be run interactively. However, the user may choose to submit a job using the Prime Batch System facilities.

It follows a print out of the programme with some comments attached to it.

```
C THIS PROGRAMME CALCULATES THE FRACTION RECRYSTALLIZED FROM A STRAIN
C DISTRIBUTION MAP FOR AUSTENITIC STAINLESS STEEL TYPE AISI316L.
C********************************************************************
      DIMENSION E(15,15),T(15,15),X(15,15),SV(15,15)
     1,SMAX(15,15)
      DIMENSION TIME(100),XU(100),XNU(100),XRATE(100),G(100)
      DIMENSION XNUD(100),XRTD(100),SVD(100),GD(100),SVNU(100)
      CHARACTER*8 DFILE,RFILE
      WRITE (*,*) ('Temp C,Gs,Strain,Strain Rate')
       READ (*,*) T1,GS,E1,E3
       WRITE (*,*) ('Total Time,Time Interval')
       READ(*,*) T2,T3
       WRITE(*,*) ('Lines,Columns')
       READ(*,*) M,N
       IF (M.NE.N) THEN
       WRITE(*,*)('WARNING:YOU MUST INPUT A SQUARE MATRIX')
       STOP
       ELSE
       CONTINUE
       END IF
       WRITE(*,*) ('Input line to start assess "XDIAGONAL" elements')
       READ(*,*) NN
       WRITE(*,*) ('Input DFILE')
       READ (*,10) DFILE
       OPEN(9, FILE=DFILE)
       DO 200 I=1,M
  200       READ(9,*) (E(I,J),J=1,N)
       CLOSE(9)
       Z=E3*EXP(460000/(8.32*(T1+273)))
       E2=6.64E-3*(GS**0.36)*(EXP ( -109000/(8.32*(T1+273))))**(-0.28)
       IF(E1.LT.E2) THEN
       T50=4.0E-15*Z**(-0.38)*GS**(1.3)*E1**(-3.6)
      1*EXP(475000/(8.32*(T1+273.)))
       ELSE
       T50=3.00E-7*Z**(-0.38)*EXP(366000/(8.32*(T1+273.)))
       ENDIF
       T95=4.32*T50
       DO 300 I=1,M
            DO 300 J=1,N
                E(I,J)=E(I,J)*0.1
                SMAX(I,J)=13.78+7.19*E(I,J)
                IF(E(I,J).LT.E2) THEN
                T(I,J)=4.0E-15*Z**(-0.38)*GS**(1.3)*E(I,J)**(-3.6)
      1         *EXP(475000/(8.32*(T1+273.)))
                ELSE
                T(I,J)=3.00E-7*Z**(-0.38)*EXP(366000/(8.32*(T1+273)))
                ENDIF
                T(I,J)=4.32*T(I,J)
  300  CONTINUE
       MN=M*N
       L=INT(T2/T3)
       IF(L.GT.100) THEN
       L=100
       T3=T2/100
       ELSE
       CONTINUE
```

Line	Comment
	Read in
10-11	Test temperature,grain size,strain and strain rate.
12-13	Total annealing time and time interval for calculation to be performed.
14-15	Number of lines and columns of the strain matrix. A square matrix must be input.
22-23	Line number in which the "diagonal" elements are to be assessed.
24-29	Strain matrix from a Datafile.
	Calculate for a sample homogeneously deformed:
30	Zener-Hollomon parameter.
31	Critical strain according to equation (6.12).
33-37	Time for 50% of material to recrystallize (Expressions (6.8) and (6.9)).
38	Time for 95% of material to recrystallize.
	Calculate for a sample inhomogeneously deformed:
41	strain element
42	maximum migrating grain boundary area (expression (7.10)).

```
      ENDIF
      T5=0.0
      NNN=NN-1
      DO 400 K=1,L
         T5=T5+T3
         TIME(K)=T5
         X1=0.0
         D1=0.0
         XX1=0.0
         DD1=0.0
         SV1=0.0
         SSV1=0.0
         MM=0
         DO 500 J=1,N
            DO 500 I=1,M
               X(I,J)=1.-EXP(-3.0*T5/T(I,J))
               SV(I,J)=4*SMAX(I,J)*X(I,J)*(1.-X(I,J))
               X1=X1+X(I,J)
               SV1=SV1+SV(I,J)
 500     CONTINUE
         DO 600 J=1,N
            DO 600 I=1,M
               IF(I.EQ.NN.AND.J.EQ.1) THEN
               XX1=XX1+X(I,J)+X(I,J+1)
               SSV1=SSV1+SV(I,J)+SV(I,J+1)
               MM=MM+2
               ELSE IF(I.EQ.(J+NNN).AND.J.NE.1) THEN
               XX1=XX1+X(I,J-1)+X(I,J)+X(I,J+1)
               SSV1=SSV1+SV(I,J-1)+SV(I,J)+SV(I,J+1)
               MM=MM+3
               ELSE IF(I.EQ.M.AND.J.EQ.N.AND.NNN.EQ.0)THEN
               XX1=XX1+X(I,J-1)+X(I,J)
               SSV1=SSV1+SV(I,J-1)+SV(I,J)
               MM=MM+2
               ELSE
               CONTINUE
               ENDIF
 600     CONTINUE
         XU(K)=1-EXP(-3.0*T5/T95)
         XNU(K)=X1/MN
         SVNU(K)=SV1/MN
         XNUD(K)=XX1/MM
         SVD(K)=SSV1/MM
 400  CONTINUE
      DO 700 K=1,L
         IF(K.EQ.1) THEN
         XRATE(K)=(XNU(1)/T3)
         XRTD(K)=XNUD(1)/T3
         A=XLOG(XNU(1))
         B=XLOG(XU(1))
         AA=XLOG(XNUD(1))
         TA=LOG10(T3)
         ELSE IF (K.EQ.L) THEN
         XRATE(K)=(XNU(K)-XNU(K-1))/T3
         XRTD(K)=(XNUD(K)-XNUD(K-1))/T3
         C=XLOG(XNU(K))
```

44-49	For each element calculate t_{50} (expression (6.8)) and t_{95} (expression(6.9)).
51-60	Some counters and intermediate variables are assessed.
61	For a given time interval equal to T3
62-63	Current time T5=TIME(K) is computed
14-70	variables are cleared from any previous values.
71-77	Fraction recrystallized and migrating grain boundary area (expression (7.9)) are calculated and stored in variables X1 and SV1 respectively
79-95	Fraction recrystallized and migrating grain boundary area for diagonal elements are calculated and stored in XX1and SSV1.
	Calculate:
96	Fraction recrystallized for uniformily deformed samples.
97	Average fraction recrystallized.
98	Average migrating grain boundary area.
99	Average fraction recrystallized for diagonal elements.
100	Average migrating grain boundary area for diagonal elements.

```
          DD=XLOG(XU(K))
          TB=LOG10(K*T3)
          CC=XLOG(XNUD(K))
          ELSE
          XRATE(K)=(XNU(K+1)-XNU(K-1))/(2*T3)
          XRTD(K)=(XNUD(K+1)-XNUD(K-1))/(2*T3)
          ENDIF
          G(K)=XRATE(K)/SVNU(K)
700   GD(K)=XRTD(K)/SVD(K)
      WRITE(*,*)('Input RFILE')
      READ(*,10) RFILE
      OPEN(9,FILE=RFILE)
      WRITE(9,15) T1,GS,E1
      WRITE(9,20)
      WRITE(9,30)
      WRITE(9,40)
      KK=INT(L/20)
      IF (KK.LT.1) THEN
      KK=1
      ELSE
      CONTINUE
      ENDIF
      DO 800 K=1,L,KK
800       WRITE(9,50) TIME(K),XU(K),XNU(K),XRATE(K),SVNU(K),G(K)
      WRITE(9,45)
      WRITE(9,46)
      DO 850 K=1,L,KK
850       WRITE(9,47) TIME(K),XNUD(K),XRTD(K),SVD(K),GD(K)
      SLOPE1=(C-A)/(TB-TA)
      SLOPE2=(DD-B)/(TB-TA)
      SLOPE3=(CC-AA)/(TB-TA)
      WRITE(9,60) SLOPE2
      WRITE(9,70) SLOPE1
      WRITE(9,80) SLOPE3
      CLOSE(9)
10    FORMAT(A8)
15    FORMAT(1X, 'TEMP =',F7.2,' C',10X,'GSIZE =',F7.2,' UM',10X,
     1'STRAIN =',F7.4)
20    FORMAT(//,1X,'TIME,s',5X,'UNIFORM ',5X,'NON-UNIFORM',5X,
     1'XRATE(1/s)',4X,'Sv(1/mm)',5X,'Grate(mm/s)')
30    FORMAT(13X, 'STRAIN',7X,'STRAIN')
40    FORMAT(11X,'AVER. X,%',5X,'AVER X,%')
45    FORMAT(//,1X,'TIME,s',5X,'NON-UNIFORM',5X,'XRATE(1/s)',4X,
     1'Sv(1/mm)',3X, 'Grate(mm/s)')
46    FORMAT(13X,'STRAIN OVER',/,13X,'DIAGONAL',/,13X,'AVER X,%')
47    FORMAT(2(F7.2,5X),3X,E10.3,3X,F8.2,3X,E10.3)
50    FORMAT(1X,3(F7.2,6X),2X,E10.3,5X,F7.2,5X,E10.3)
60    FORMAT(/,1X,'K value for     uniform strain            =' ,F5.3)
70    FORMAT(/,1X,'K value for non-uniform strain            =' ,F5.3)
80    FORMAT(/,1X,'K value for non-uniform strain o/diagonal =' ,F5.3)
      STOP
      END
      FUNCTION XLOG(X)
      XLOG=LOG10(LOG(ABS(1/(1-X))))
      RETURN
      END
```

	For each time interval,
102-120	recrystallization rate is calculated for the whole sample (XRATE(K)) or for diagonal elements only (XRTD(K)).
121	Average grain growth (G(K)) for the whole sample and average grain growth for diagonal elements only are calculated.
123-125	A Result-file is input
	K values are calculated for:
142	samples uniformily deformed. (C is defined in line 113;A in 106; TB and TA in lines 115 and 109 respectively).
143	samples uniformily deformed. (DD and B are defined by lines 114 and 107 respectively).
144	diagonal elements only. (CC and AA are as defined by lines 116 and 108).

3.2 RESULT-FILE

```
TEMP =1025.00 C          GSIZE = 100.00 UM          STRAIN = 0.3450


TIME,s      UNIFORM        NON-UNIFORM       XRATE(1/s)     Sv(1/mm)      Grate(mm/s)
             STRAIN         STRAIN
           AVER. X,%      AVER X,%
  3.00          0.04           0.06          0.205E-01         3.68         0.556E-02
 18.00          0.23           0.28          0.110E-01        10.00         0.110E-02
 33.00          0.39           0.41          0.686E-02        10.08         0.681E-03
 48.00          0.51           0.49          0.463E-02         9.23         0.502E-03
 63.00          0.61           0.55          0.334E-02         8.41         0.397E-03
 78.00          0.68           0.60          0.253E-02         7.74         0.327E-03
 93.00          0.75           0.63          0.200E-02         7.21         0.277E-03
108.00          0.80           0.66          0.163E-02         6.79         0.239E-03
123.00          0.84           0.68          0.136E-02         6.46         0.211E-03
138.00          0.87           0.70          0.116E-02         6.20         0.188E-03
153.00          0.90           0.72          0.101E-02         5.97         0.169E-03
168.00          0.92           0.73          0.890E-03         5.79         0.154E-03
183.00          0.93           0.74          0.794E-03         5.63         0.141E-03
198.00          0.95           0.75          0.715E-03         5.49         0.130E-03
213.00          0.96           0.76          0.649E-03         5.37         0.121E-03
228.00          0.97           0.77          0.594E-03         5.26         0.113E-03
243.00          0.97           0.78          0.547E-03         5.16         0.106E-03
258.00          0.98           0.79          0.506E-03         5.07         0.998E-04
273.00          0.98           0.80          0.471E-03         4.99         0.944E-04
288.00          0.99           0.80          0.440E-03         4.91         0.896E-04


TIME,s      NON-UNIFORM      XRATE(1/s)    Sv(1/mm)   Grate(mm/s)
             STRAIN OVER
             DIAGONAL
             AVER X,%
  3.00         0.12          0.408E-01       7.22     0.565E-02
 18.00         0.52          0.181E-01      15.30     0.119E-02
 33.00         0.72          0.942E-02      11.96     0.788E-03
 48.00         0.82          0.528E-02       8.50     0.621E-03
 63.00         0.89          0.314E-02       6.00     0.524E-03
 78.00         0.92          0.197E-02       4.27     0.462E-03
 93.00         0.95          0.128E-02       3.06     0.419E-03
108.00         0.96          0.861E-03       2.22     0.387E-03
123.00         0.97          0.591E-03       1.63     0.364E-03
138.00         0.98          0.414E-03       1.20     0.345E-03

K value for     uniform strain             =1.000

K value for non-uniform strain             =0.709

K value for non-uniform strain o/diagonal =0.864
```

APPENDIX (8.1)

Determination of the Heat Transfer Coefficient

1. Mathematical Basis

The computational model used to simulate hot rolling (Leduc,1980) as well as the one used for the calculation of temperature distribution during plane strain compression tests rely on the capability of accurately predicting the surface heat transfer coefficient of the sample when it is air cooling or furnace cooling. The subject has been treated previously by Harding(1976) and more recently by Foster(1981) and Puchi(1983). The present appendix is concerned with a brief description of the mathematical procedure used in the calculation of the heat transfer coefficient as well as a description of a programme used to calculate the experimental and theoretical values of the heat transfer coefficient.

During an air cooling process the sample looses heat by convection and radiation to the surroundings. The total amount of heat lost is governed by the heat transfer coefficient at the sample surface, H_s, which in its turn is dependent on the surface temperature, T_s. The heat transfer coefficient can be calculated using

$$H_{theor} = b\,(T_s - T_r) + c\,(T_s^4 - T_r^4) \qquad (A.1)$$

Where H_{theor} is the theoretically predicted net heat loss per unit of area per unit of time, T_s is the surface temperature (in K), T_r is the room temperature (in K), b and c are constants and

$$c = \sigma \, \varepsilon \tag{A.2}$$

σ in equation (A.2) is the Stefan-Boltzmann constant (5.67×10^{-11} kW/m^2) and ε is the emissivity. This is approximately 0.84 for austenitic stainless steels in the temperature range of 800-1100 C (Harding, 1976).

It can be written from the definition of heat transfer coefficient that

$$H_{exp} = \frac{\dot{Q}}{A} \tag{A.3}$$

H_{exp} is the experimental heat transfer coefficient, $\dot{Q}$ = dQ/dT is the rate of heat loss and A is the total transmissive area. However,

$$\dot{Q} = m \, s \, \dot{T} \tag{A.4}$$

and, in the steady state

$$\dot{Q} = m \, s \, \dot{T}_s \tag{A.5}$$

where m is the mass of the sample and s its specific heat. Equation (A.5) can be re-written as

$$\dot{Q} = \rho \, v \, s \, \dot{T}_s \tag{A.6}$$

where ρ and v are the sample density and volume respectively. (A.6) can be substituted for $\dot{Q}$ in equation (A.3) giving

$$H_{exp} = \frac{v}{A} \rho \, s \, \dot{T}_s \tag{A.7}$$

which can be used for calculating the experimental heat transfer coefficient. Figure(8.44) shows a schematic representation of the assumed active surfaces for both rolling samples (a) and plane strain compression ones (b). It can be seen that Q_3 is assumed to be nil for both samples. Therefore, for hot rolling samples,

$$H_{exp} = \left[\frac{w_1 \, a_1}{2a_1 + w_1}\right] \rho \, s \, \dot{T}_s \qquad (A.8)$$

whereas for plane strain compression samples

$$H_{exp} = a_2 \, \rho \, s \, \dot{T}_s \qquad (A.9)$$

the only unknown being $\dot{T}_s$.

Assuming that T_o is an arbitrary temperature at the centre of the sample and T_x is the temperature at the distance x from the centre, it can be shown that when a heat flow steady state is achieved in a small volume element dx

$$\frac{d^2T}{dx^2} = -\frac{\rho \, s}{k} \dot{T} \qquad (A.10)$$

where k is the thermal conductivity of the element, ρ its density, s specific heat and $\dot{T}$ the cooling rate.

If it is assumed that k, ρ, s and $\dot{T}$ are constant over a small time interval, then

$$T_s = -\frac{\rho \, s}{2k} a_1^2 \, \dot{T} + T_o \qquad (A.11)$$

since

$$\left.\frac{dT}{dx}\right|_{x=0} = 0 \text{ and also } \left. T(x)\right|_{x=0} = T_0$$

Similarly, for the plane strain compression sample

$$T_s = -\frac{\rho S}{2k} a_2^2 \dot{T} + T_o \tag{A.12}$$

The only unknow is $\dot{T}$, which can be calculated from a cooling curve obtained by inserting a thermocouple in the centre of the sample.

The difference between an experimental value of H, given by equations (A.8) and (A.9) and a theoretical one, given by equation (A.1) can be written as

$$e_i = H_{expi} - \left[b(T_{si} - T_r) - c\,(T^4_{si} - T^4_r) \right] \tag{A.13}$$

It has been shown (Puchi, 1983) that b and c may be obtained by choosing the values which minimize the sum of the squares of e_i, i.e., when

$$S = \sum_1^n H_{expi} - \left[b\,(T_{si} - T_r) - c\,(T^4_{si} - T^4_r) \right] \tag{A.14}$$

is minimum.

The constants b and c are given by (Puchi,1983)

$$b = \frac{1}{\Delta} \left[\sum_1^n (H_{expi}\ T_i) \sum_1^n (T'_i)^2 - \sum_1^n H_i T'_i \sum_1^n T_i T'_i \right] \tag{A.15}$$

$$c = \frac{1}{\Delta} \left[\sum_1^n T_i^2 \sum_1^n H_i T'_i - \sum_1^n T_i T'_i \sum_1^n H_i T_i \right] \tag{A.16}$$

where

$$\Delta = \left[\sum_{i}^{n} T_i^2 \sum_{1}^{n} T'_i{}^2\right] - \left[\sum_{1}^{n} T_i T'_i\right]^2 \qquad (A.17)$$

and

$$T_i = T_{si} - T_r \qquad (A.18)$$

$$T'_i = T^*_{si} - T^*_r \qquad (A.19)$$

The thermal properties can be calculated as a function of the temperature (Harding,1976) according to:

$$\rho = 7950. - 0.5(T_i-500) \quad kg/m^3 \qquad (A.20)$$

$$s = 622. + 0.0677(T_i-500) \quad J/kgC \qquad (A.21)$$

$$k = 22. + 10.91x10^{-3} (T_i - 500) \quad W/mC \qquad (A.22)$$

and the temperature read in millivolts can be converted into degrees centigrade using equation(5.26).

2. Computer Programme

The programme is written in FORTRAN-77 and run on a Prime750 computer. A print-out is presented and discussed in this section.

2.1 Programme Print-out

```
      COMMON TIME(90),T(90),RTT,RT,A,N,THICK,WIDTH
      COMMON HEXP(90),TS(90),HTHEOR(90)
      DIMENSION XMV(90),ERR(90)
      CHARACTER*8 DFILE,RFILE,XMAT
      WRITE(*,*)('INPUT DATAFILE NAME')
      READ(*,10) DFILE
      OPEN(9,FILE=DFILE)
      READ(9,10) XMAT
      READ(9,20) N
      READ(9,*) THICK,WIDTH,ST,RT
        DO 100 I=1,N
        READ (9,*) TIME(I),XMV(I)
        XMV(I)=XMV(I)+1.0
  100   T(I)=-5.781+26.28*XMV(I)-0.1256*XMV(I)**2+0.0019*XMV(I)**3
      CLOSE(9)
      CALL CALC(HEXP,HTHEOR,B,C,TS,ERR)
      CALL PLOT
      WRITE(*,*)('INPUT RESULTFILE NAME')
      READ(*,10) RFILE
      OPEN( 9, FILE = RFILE,FORM='FORMATTED')
      WRITE(9,30) XMAT
      WRITE(9,35) THICK
      WRITE(9,40) WIDTH
      WRITE(9,50) ST
      WRITE(9,60) (RT-273)
      WRITE(9,70) B,C
      WRITE(9,80)
      DO 300 I=1,N
        WRITE (9,90)TIME(I),TS(I),HEXP(I),HTHEOR(I),ERR(I)
  300   CONTINUE
      CLOSE(9)
      STOP
   10 FORMAT(A8)
   20 FORMAT(I2)
   30 FORMAT (10X,'MATERIAL              : ',A8)
   35 FORMAT (10X,'THICKNESS             :',F7.2,' mm')
   40 FORMAT (10X,'WIDTH                 :',F7.2,' mm')
   50 FORMAT (10X,'SOAKING TEMPERATURE   :',F7.2,'  DEGREES C')
   60 FORMAT (10X,'ROOM    TEMPERATURE   :',F7.2,'  DEGREES C')
   70 FORMAT (10X,'HTHEOR =',F10.4,'*(TS - RT) +',E10.4,'*(TS**4 - RT**4)
     1'///)
   80 FORMAT(6X,'TIME,S',7X,'TS, K',5X,'-HEXP,KW/M**2',5X,'-HTHEOR,KW/M*
     1*2',5X,'ERROR %')
   90 FORMAT(2(5X,F7.2),7X,F7.2,12X,F7.2,9X,F7.2)
      END



      SUBROUTINE CALC(HEXP,HTHEOR,B,C,TS,ERR)
      COMMON TIME(90),T(90),RTT,RT,A,N,THICK,WIDTH
      DIMENSION TS(90),HEXP(90),HTHEOR(90)
      DIMENSION ERR(90)
      DATA SHT,SHTL,STTL,ST2,STL2/5*0.0/
C     PRELIMINARY CALCULATIONS
      RT=RT+273
      RTT=RT**4
```

```
      A=THICK/2000
      W=WIDTH/1000
      WRITE(*,*)('INPUT 0 FOR ROLLING OR 1 FOR PLANE STRAIN')
      READ(*,20) IP2
      DO 100 I=1,N
       RO=7950-0.5*(T(I)-500)
       S=622.0+0.0677*(T(I)-500)
       XK=22.0+10.91E-03*(T(I)-500)
       IF(I.EQ.1) THEN
       T1=T(1)
       T2=T(I+1)
       DTT=TIME(I+1)
       ELSE IF (I.EQ.N) THEN
       T1=T(I-1)
       T2=T(I)
       DTT=(TIME(I)-TIME(I-1))
       ELSE
       DTT=(TIME(I+1)-TIME(I-1))
       T1=(T(I)+T(I-1))
       T2=(T(I+1)+T(I))
       ENDIF
       DT=T2-T1
       CRATE=DT/DTT
       TS(I)=T(I)+(RO*S/(2*XK))*A**2*CRATE
       IF(IP2.NE.0) THEN
       HEXP(I)=RO*S*CRATE*A/1000
       ELSE
       HEXP(I)=(RO*S*CRATE/1000)*((A*W)/(2*A+W))
       ENDIF
  100  CONTINUE
      K=1
      HH=HEXP(1)
      DO 150 I=1,10
      IF (HEXP(I).LT.HH) THEN
      K=I
      ELSE
      CONTINUE
      ENDIF
  150 CONTINUE
      DO 160 I=1,N
      TS(I)=TS(I)+273
  160 T(I)=T(I)+273
      DO 200 I=K,N
        TI=TS(I)-RT
        TIL=TS(I)**4-RTT
        SHT=SHT+HEXP(I)*TI
        SHTL=SHTL+HEXP(I)*TIL
        STTL=STTL+TI*TIL
        ST2=ST2+TI**2
        STL2=STL2+TIL**2
  200  CONTINUE
       DELTA=ST2*STL2-STTL**2
       B=(SHT*STL2-SHTL*STTL)/DELTA
       C=(ST2*SHTL-STTL*SHT)/DELTA
       DO 300 I=1,N
        HTHEOR(I)=B*(TS(I)-RT)+C*(TS(I)**4-RT**4)
```

```
       ERR(I)=((HTHEOR(I)-HEXP(I))/HTHEOR(I))*100
 300   CONTINUE
  20  FORMAT(I2)
      RETURN
      END



      SUBROUTINE PLOT
      COMMON TIME(90),T(90),RTT,RT,A,N,THICK,WIDTH
      COMMON HEXP(90),TS(90),HTHEOR(90)
      DO 100 I=1,N
       HTHEOR(I)=-HTHEOR(I)
 100   HEXP(I)=-HEXP(I)
      HMAX=HEXP(1)
      HMIN=HEXP(1)
      DO 200 I=2,N
       IF (HEXP(I).GT.HMAX) THEN
       HMAX=HEXP(I)
       ELSE IF (HEXP(I).LT.HMIN) THEN
       HMIN=HEXP(I)
       ELSE
       ENDIF
 200   CONTINUE
      WRITE (*,20) TS(N),TS(1)
      WRITE (*,30) HMIN,HMAX
      WRITE(*,*) ('INPUT TS MIN,TS MAX,H MIN,H MAX')
      READ(*,*) XMIN,XMAX,YMIN,YMAX
      WRITE (*,*) ('INPUT TS INTERVAL,HEXP INTERVAL')
      READ(*,*) DX,DY
      CALL PAPER(1)
      CALL FILNAM('T$0001',6)
      CALL GHFROR(1)
      CALL PSPACE(0.15,0.85,0.35,0.95)
      CALL CSPACE(0.,1.,0.,1.)
      CALL QADRNT
      CALL MAP(XMIN,XMAX,YMIN,YMAX)
      CALL BORDER
      CALL GRNPEN
      CALL GRATSI(DX,DY)
      CALL AXESSI(DX,DY)
      CALL PLACE(48,51)
      CALL TYPECS('SURFACE TEMPERATURE , DEGREES K',31)
      CALL PLACE (8,28)
      CALL CTRORI(1.0)
      CALL TYPECS('HEAT TRANSFER COEF (KJ/M**2/s)',30)
      CALL PTPLOT(TS,HEXP,1,N,43)
      CALL REDPEN
      CALL CURVEO(TS,HTHEOR,1,N)
      CALL GHFROR(0)
      CALL GREND
  20  FORMAT ('TS MIN =',F10.4,'    TS MAX = ',F10.4)
  30  FORMAT ('HEXP MIN =',F10.4,'  HEXP MAX=',F10.4)
      RETURN
      END
```

2.2. Discussion of the Programme

Lines	Comments-Main Programme
6	Input of a DATAFILEname in format A8
8-10	Read sample identification, number of pairs temperature millivolt sample thickness and width, slab and room temperatures.
12	Read in the time, t_i, and the millivolts, mv_i.
13	Add 1.0 mv to mv_i
14	Calculation of the temperature using (A.23)
16	Call subroutine CALC where most of the computation in the programme is performed.
17	Call subroutine PLOT
19	Read in a RESULTFILEname in format A8
21-44	Print out the RESULTFILE

Lines	Comments-Subroutine CALC
53	Initialize variables
54-58	Perform some preliminary calculations
60	Input IP2 which is 0 when processing rolling

	data or 1 for plane strain compression samples.
61	For each pair t_i, mv_i
62-64	Calculate ρ, s and k according to equations (A.20), (A.21) and (A.22) respectively
65-67	Set the appropriate time interval, DTT, and for each time interval the initial temperature, T_1, and the final temperature, T_2.
78-79	Calculate the temperature interval, DT, and the cooling rate, Crate.
80	Calculate the surface temperature according to equations (A.11) and (A.12).
81-85	Calculate the experimental heat transfer coefficient, H_{exp}, using equations (A.8) and (A.9).
87-95	Select H_{exp}max from the first 10 values and stores it in HH. The i value is stored in K.
96-98	For each pair t_i, mv_i, transform the surface temperature and the centre temperature units from degree centigrade to Kelvin.
99-107	For each variable which sub-indice is bigger than k, calculate the terms of equations (A.15) (A.16) and (A.17).
108-110	Calculate Delta, b and c as given by equations (A.15) to (A.17).
111-114	For each pair of data, calculate the theoretical heat transfer coefficient using equation (A.1).

The relative error is calculated in line 113.

RETURN to main programme.

Lines	Comments-Subroutine PLOT
124-136	Calculates the maximum and the minimum values of the theoretical heat transfer coefficient and stores them in H_{max} and H_{min} respectively.
137-139	Write on the VDU H_{min}, H_{max}, T_{smin} and T_{smax}.
140	Ask to input plot limits
141-142	Input axis intervals
143-168	Preform the standard GHOST-80 library plot subroutines.
	RETURN to main programme.

APPENDIX(8.2)

Computer Programme for Hot Rolling Simulation.

1.Introduction.

The present appendix contains a complete listing of the modified version of Leduc's programme (Leduc,1980). A detailed line by line discussion of the programme has been provided elsewhere (Leduc,1980). The modified version used for austenitic stainless steels was run in an ICL-1906S computer at Sheffield University.

2.Modifications Carried out in the Original Version.

2.1- Lines 212,251 and 268

Surface heat transfer coefficient calculations using equation(8.1).

2.2- Lines 493 and 920

The Q_{rex}=460 KJ/Mol is introduced for calculation of the Zener-Hollomon parameter.

2.3- Lines 494 and 1208

The temperature-compensated time for recrystallization is calculated using an activation energy of 500 KJ/Mol.

2.4- Lines 517 to 525

Calculation of the time for 50% of the material to recrystallize.

The equations used are given by expressions(6.8) to (6.12). An activation energy for recrystallization of 500 KJ/Mol is used for strains lower than ε_*.

Therefore, the activation energy used in equation(6.12) was slightly modified from 109 KJ/Mol to 134 KJ/Mol.

2.5- Lines 923 to 928 and 932; 1339 to 1344 and 1348

The stress at a given strain value is calculated using equations(6.1) to (6.4). These values are subsequently used in the simulation of the stress-strain curves.

2.6- Lines 937 and 1352

Calculation of the strain to peak stress as given by equation (6.23).

2.7- Lines 1134 to 1145; 1167 to 1169; 1208,1215,1229 to 1240; 1268 to 1270; 1276 and 1277

The recrystallized grain size is calculated and the grain growth assessed during a given inter-pass period. The equations used are (6.16) to (6.20) and (8.13).

2.8- Lines 1181 and 1257

Calculate the fraction recrystallized according to the Avrami equation with a time exponent equal to 1

```
        SHORT LIST
     PROGRAM (ENDA)
     COMPRESS INTEGER AND LOGICAL
     INPUT 1=CR0
     OUTPUT 2=LP0
     OUTPUT 3=LP1
     OUTPUT 4=LP2
     TRACE 2
     END
      MASTER DATAENTRY
C
C      INPUT OF DATA FOR A MAXIMUM OF 20 PASSES OF A 20*20 SLAB MATRIX
C
      LOGICAL UNTEMP,TRISE,LOADS,TORQS,MATPRINT,IFPLOT,STRUCT
      DIMENSION A(60,20),T(61,22),STL(60),G(60),Z(83),SPEED(20),U(20),
     1         P(20),D(20),IR(20),I(63),IAC(42),RTO(20),TRO
     2         (20),RLO(20),DSRY(100),W(100),R(100,20),RST(20),F(101,21)
     3          ,B(20),STIME(21),IW(21),SWC(21),WC(21),WCH(21)
      DIMENSION PRAVTE(20),OXSUTE(20),OXLSUTE(20)
      COMMON/CONDIT/T2,T1,ZP(20)
      COMMON/WORK/E(20),E1(20)
      COMMON/STRENGTH/S0,B1,B5,EP,C5,THICKN(21),RAD(20)
      COMMON /LINK1/D0,D3,SL,UL,NWR0,NUMINT,STRUCT
      COMMON/TEMP/RMEANT(20),NOA(20),YDIF,NP,Y,SPRT(20),W2(20)
      COMMON/STORE/S(50,8,20),SS(50,8,1)
      COMMON/LINK2/R1,S1,VNC,WNR,RAVTEM(20),DEFTEM(20)
      COMMON/PRIOUT/DIST(20)
C
C
C
      READ (1,5000) NUMDATA
      DO 1500 JJ=1,NUMDATA
C
C
C
      READ (1,5020) SPECIMEN
      WRITE (2,6080) SPECIMEN
      READ (1,5010) UNTEMP,TRISE,LOADS,TORQS,MATPRINT,IFPLOT,STRUCT
       READ (1,5000) OXTH
        IF (IFPLOT) WRITE (3,9030) SPECIMEN
      IF (STRUCT) WRITE (4,9030) SPECIMEN
      READ (1,5000) WIDTH,THICKN(1),C1,KPAC,KPR,RTEMP,NWR,NVC,NPA,GS
      IF (STRUCT) READ (1,5000) TIMIN
C     TIMIN=TIME INTERVAL FOR STRUCTURE CALCULATIONS
C
      NPA22=NPA*2+2
      NPA1=NPA+1
      NWR1=NWR+1
      NVC1=NVC+1
      NVC2=NVC+2
      WNR=FLOAT(NWR)
      VNC=FLOAT(NVC)
C
      IF (UNTEMP) GO TO 10
      CALL FTEMPDIST(A,T,STL,U,DTIG,Z1,NVC,NWR,NWR1,NVC1,RTEMP,GS)
      GO TO 35
```

```
C
   10 READ (1,5000) STEMP
      WRITE (2,6000) RTEMP,STEMP
C
   35 READ(1,5000) (P(JP),JP=1,NPA),(D(JP),JP=1,NPA),(SPEED(JP),JP=1,NPA
     1),(STIME(JP),JP=1,NPA1),(RAD(JP),JP=1,NPA),(SWC(JP),JP=1,NPA1),
     2(WC(JP),JP=1,NPA1),(WCH(JP),JP=1,NPA1)
      WRITE(2,6010) (P(JP),JP=1,NPA)
      WRITE(2,6012) (D(JP),JP=1,NPA)
      WRITE(2,6014) (SPEED(JP),JP=1,NPA)
      WRITE(2,6016)(STIME(JP),JP=1,NPA1)
      WRITE(2,6017) (RAD(JP),JP=1,NPA)
      WRITE(2,6018) (SWC(JP),JP=1,NPA1)
      WRITE (2,6022) (WC(JP),JP=1,NPA1)
      WRITE(2,6024) (WCH(JP),JP=1,NPA1)
      IF (TRISE) CALL DEFHEAT(TRO,NPA)
      IF (LOADS) CALL DEFHEAT(RLO,NPA)
      IF (TORQS) CALL DEFHEAT(RTO,NPA)
      C1=C1*1000.
      D2=THICKN(1)/(2.*WNR)
      D1=WIDTH/(2.*VNC)
C
   40 WRITE (2,6020)D1,D2,NWR,NVC,NPA,C1
      MMT=INT(1+NVC/1.732)
      NR=NWR
      RN=FLOAT(NR)
      SS(1,1,1)=100.
      SS(1,4,1)=GS
      SS(1,5,1)=0.
      DO 20 N=1,NWR
      S(1,1,N)=100.
      S(1,4,N)=GS
      S(1,5,N)=0.
      NOA(N)=1
              STL(N)=STEMP
              DO 20 M=1,NVC
              A(N,M)=STEMP
   20 CONTINUE
C
      DO 30 M=1,NVC
              U(M)=STEMP
   30 CONTINUE
C
      Z1=STEMP
      DTIG=0
C
      DO 50 JP=2,NPA1
              THICKN(JP)=THICKN(JP-1)*(1-P(JP-1))
   50 CONTINUE
C
      DO 55 JP=1,NPA
              E(JP)=1.155*ALOG(THICKN(JP)/THICKN(JP+1))
              E1(JP)=E(JP)*SPEED(JP)
              E1(JP)=E1(JP)/SQRT(RAD(JP)*(THICKN(JP)-THICKN(JP+1)))
          IF(E1(JP).GE.10) WRITE (2,6026) JP
   55 CONTINUE
```

```
C
      WRITE(2,6030) (THICKN(JP),JP=1,NPA1   )
      WRITE(2,6090) (E(JP),JP=1,NPA)
      WRITE(2,6100) (E1(JP),JP=1,NPA)
      S1=622.+0.0677*(STEMP-500.)
      R1=7950.-0.5*(STEMP-500.)
      COND=22.6+0.01091*(STEMP-500.)
      CONSTFAC=R1*S1*D1*(WNR-0.75)/(4*COND*WNR**2)
      CONST=2.*D1*WNR
      CONSTFAC1=S1*R1*(3.*WNR-0.75)/(216.*COND*WNR**3)
      Z(4*NPA1-3)=CONSTFAC*(THICKN(NPA1))**2/(CONST+THICKN(NPA1))
      Z(4*NPA1-2)=Z(4*NPA1-3)
      Z(4*NPA1-1)=Z(4*NPA1-2)
C

      DO 60 JP=1,NPA
              B(JP)=1-(THICKN(JP)-THICKN(JP+1))/(2.*RAD(JP))
              B(JP)=RAD(JP)*ATAN(SQRT(1-B(JP)**2)/B(JP))/SPEED(JP)
              Z(4*JP-3)=CONSTFAC*THICKN(JP)**2/(CONST+THICKN(JP))
      Z(4*JP-2)=Z(4*JP-3)
      Z(4*JP-1)=Z(4*JP-2)
              Z(4*JP)=CONSTFAC1*THICKN(JP+1)**2
              IR(JP)=0.99999+ B(JP)/Z(4*JP)
      Z(4*JP)=B(JP)/IR(JP)
              IF (IR(JP).GT.100) GO TO 1500
              IF (IR(JP).GE.3) GO TO 60
            IF (NWR.GT.10) GO TO 60
              IF (.NOT.UNTEMP) GO TO 1500
              NWR=2*NWR
              WNR=FLOAT(NWR)
              NWR1=NWR+1
              D2=0.5*D2
              GO TO 40
   60 CONTINUE
C
      WRITE (2,6040) (B(JP),JP=1,NPA)
      WRITE(2,6045) (IR(JP),JP=1,NPA)
      IF (STRUCT) WRITE (4,9040) NWR
C
      IF (WC(1).EQ.0.) GO TO 65
      IAC(1)=0.99999+ SWC(1)/Z(1)
      Z(1)=SWC(1)/IAC(1)
      I(1)=IAC(1)
      IW(1)=0.99999+ WC(1)/Z(2)
      Z(2)=WC(1)/IW(1)
      I(2)=I(1)+IW(1)
      IAC(2)=0.99999 +(STIME(1)-SWC(1)-WC(1))/Z(3)
      IF (IAC(2).EQ.0) GO TO 63
      Z(3)=(STIME(1)-SWC(1)-WC(1))/IAC(2)
   63 I(3)=I(2)+IAC(2)
      GO TO 67
   65 IAC(1)=0.99999+  STIME(1)/Z(1)
      Z(1)=STIME(1)/IAC(1)
      Z(2)=Z(1)
      Z(3)=Z(2)
      I(1)=IAC(1)
```

```
      I(2)=I(1)
      I(3)=I(2)
C
   67 DO 70 JP=2,NPA1
      IF (WC(JP).EQ.0.) GO TO 69
      IAC(2*JP-1)=0.99999+ (SWC(JP)-STIME(JP-1)-B(JP-1))/Z(4*JP-3)
      IAC(2*JP)=0.99999+ (STIME(JP)-SWC(JP)-WC(JP))/Z(4*JP-1)
      IW(JP)=0.99999+ WC(JP)/Z(4*JP-2)
      Z(4*JP-3)=(SWC(JP)-STIME(JP-1)-B(JP-1))/IAC(2*JP-1)
      Z(4*JP-2)=WC(JP)/IW(JP)
      IF (IAC(2*JP).EQ.0) GO TO 68
      Z(4*JP-1)=(STIME(JP)-SWC(JP)-WC(JP))/IAC(2*JP)
   68 I(3*JP-2)=I(3*JP-3)+IAC(2*JP-1)+IR(JP-1)
      I(3*JP-1)=I(3*JP-2)+IW(JP)
      I(3*JP)=I(3*JP-1)+IAC(2*JP)
      GO TO 70
   69 IAC(2*JP-1)=(STIME(JP)-STIME(JP-1)-B(JP-1))/Z(4*JP-3)+  0.99999
      Z(4*JP-3)=(STIME(JP)-STIME(JP-1)-B(JP-1))/IAC(2*JP-1)
      Z(4*JP-2)=Z(4*JP-3)
      Z(4*JP-1)=Z(4*JP-2)
      I(3*JP-2)=I(3*JP-3)+IAC(2*JP-1)+IR(JP-1)
      I(3*JP-1)=I(3*JP-2)
      I(3*JP)=I(3*JP-1)
   70 CONTINUE
C
      WRITE (2,6050) (IAC(JP),JP=1,NPA22)
C
C
C
C
C
      NP=0
      IU=0
      JP=1
      Y=0
      IPF=1
      IPS=1
      DZ=Z(1)
      KPS=KPAC
      RD=RAD(1)
C**
C      OXIDE TEMPERATURE DEFINITION
C**
      H=0.037*(STEMP-312.0)+0.45790E-10*(STL(N)+273.)**4
      DO 80 M=1,NVC
      OXSUTE(M)=(H*OXTH)/2.51
   80 CONTINUE
      DO 90 N=1,NWR
      OXLSUTE(N)=(H*OXTH)/2.51
   90 CONTINUE
C**
C**
C
C            ATENTION THIS IS THE START OF THE OVERALL LOOP
C
  100 IF (IU.EQ.I(3*JP-2)) DZ=Z(4*JP-2)
```

```
      IF (IU.EQ.I(3*JP-1)) DZ=Z(4*JP-1)
      IF (IU.EQ.I(3*JP)) DZ=Z(4*JP)
      Y=Y+DZ
      IU=IU+1
      COND=22.60+0.01091*(Z1-500.)
      R1=7950.-0.5*(Z1-500.)
      S1=622.0+0.0677*(Z1-500.)
      D11=1000.*D1
      D22=1000.*D2
      CONS1=S1*R1*D1*D2
      CONS2=D22*(WNR-0.25)/(2.*WNR*COND)
      CONS3=D11*(NVC-0.25)/(2.*NVC*COND)
      Z1=0
C
C             HEAT B/W SLAB ELEMENTS
C
      INFINPASS=I(3*JP)+IR(JP)
      DO 230 M=1,NVC
          DO 220 N=1,NWR
              Q=0
            IF (M.EQ.1) GO TO 110
            Q=D2*COND*DZ*(A(N,M-1)-A(N,M))/D1
            IF (M.EQ.NVC) GO TO 120
  110       Q=Q-D2*COND*DZ*(A(N,M)-A(N,M+1))/D1
            GO TO 150
  120 STL(N)=STL(N)-OXLSUTE(N)
       G(N)=0.037*(STL(N)-312.0)+0.45790E-10*((STL(N)+273)**4
     1-1.17E11)
      OXLSUTE(N)=(G(N)*OXTH)/2.51
  140       Q=Q-G(N)*D22*DZ
  150       IF (N.EQ.1) GO TO 160
            Q=Q+D1*COND*DZ*(A(N-1,M)-A(N,M))/D2
            IF (N.EQ.NWR) GO TO 170
  160       Q=Q-D1*COND*DZ*(A(N,M)-A(N+1,M))/D2
            GO TO 210
  170 IF (IU.LE.I(3*JP-2)) GO TO 180
      IF (IU.LE.I(3*JP-1)) GO TO 195
      IF (IU.LE.I(3*JP)) GO TO 180
      CALL EHEATBETWEENSLABROLL (M,A5,COND8,DZ,V1,V8,S8,R8,NRRX,RD,
     1    D1,WNR,D2,COND,S1,R1,NVC1,KPS,IPF,NVC,B3,D3,B2,C,Q,R,DSRY,W,
     2        RST,U,T,F,A,NWR,VNC,MATPRINT)
            GO TO 230
  180 U(M)=U(M)-OXSUTE(M)
      H=0.037*(U(M)-312.0)+0.45790E-10*((STL(N)+273)**4
     1-1.17E11)
      OXSUTE(M)=(H*OXTH)/2.51
      GO TO 200
  195 H=WCH(JP)
  200         Q=Q-H*DZ*D11
  210         T(N,M)=A(N,M)+Q/CONS1
  220     CONTINUE
          U(M)=T(NWR,M)-H*CONS2
  230 CONTINUE
C
      DO 240 N=1,NWR
              STL(N)=T(N,NVC)-G(N)*CONS3
```

```
  240 CONTINUE
C
C
C
      IF (IU.GT.I(3*JP).AND.IU.LE.INFINPASS) GO TO 241
      YDIF=Y-Y1
      IF(IPS.EQ.KPS4.AND.STRUCT.AND.NP.NE.0)GOTO243
      IF ((YDIF.GE.TIMIN.OR.IU.EQ.I(3*JP)).AND.STRUCT.AND.NP.NE.0)
     1            GO TO 243
      IPS=IPS+1
      GO TO 246
  241 DO 242 N=1,NR
      NN=3*N-1
      DEFTEM(N)=(A(NN,MMT)+T(NN,MMT))/2.
  242 CONTINUE
      GO TO 246
C
  243 T5=T5+YDIF
      DL=0
      DT=0
      WRITE (2,6130) Y,T5
      WRITE (2,6133)
      DO 244 N=1,NWR
      PRAVTE(N)=RAVTEM(N)
      RAVTEM(N)=T(N,MMT)
      RMEANT(N)=(PRAVTE(N)+RAVTEM(N))/2.
      OO=E(NP)
      CALL TEMPCOMPTIME(N,OO,DEFTEM,T5)
      JQ1=NOA(N)
      SUM=0
      DO 249 I1=1,JQ1
      IF (S(I1,5,N).NE.0.) GO TO 249
      SUM=SUM+S(I1,1,N)
  249 CONTINUE
      DO 244 I1=1,JQ1
      IF (SUM.EQ.100.) GO TO 247
      XI=1
      IF (JQ1.EQ.1.OR.I1.EQ.1) GO TO 248
      XI=(S(I1,1,N)+S(I1-1,1,N))/100.0
  248 X=S(I1,1,N)/100.
      CONST=EXP(0.866*S(I1,5,N))
      IF (S(I1,5,N).EQ.0)GO TO 245
      DL=DL+X/(S(I1,2,N)*CONST)
      DT=DT+X*CONST/S(I1,2,N)
      GO TO 244
  245 DL=DL+(X**(2./3.)*XI**(1./3.))/S(I1,3,N)
      DT=DT+(X**(2./3.)*XI**(1./3.))/S(I1,3,N)
      GO TO 244
  247 DL=DL+S(I1,1,N)/(100.*S(I1,4,N))
      DT=DT+S(I1,1,N)/(100.*S(I1,4,N))
  244 CONTINUE
      AVGS=RN/SQRT(DL*DT)
      WRITE (2,6134) AVGS
      Y1=Y
      IF (KPS4.GT.4E6) KPS4=4E6
      KPS4=2*KPS4
```

```
      IPS=1
C
C
C
  246 DO 250 M=1,NVC
          DO 250 N=1,NWR
              A(N,M)=T(N,M)
              Z1=Z1+T(N,M)
  250 CONTINUE
      Z1=Z1/(VNC*WNR)
C
C
      IF (IU.NE.I(3*JP).OR.JP .EQ.NPA1)  GO TO 260
C
      DO 257 N=1,NR
            SPRT(N)=T(N,MMT)
  257 CONTINUE
C
      Z0=Z1
C
      CALL CINCREASENUMELMTS (T,G,NVC,NWR,STL,Z,DZ,D2,KPR,NRRX,KPS,A
     1,U,JP,NWR1,D22,WNR,NP,IR,NWR0)
      GO TO 280
  260 IF (JP.EQ.1) GO TO 270
      EPP=STIME(JP-1)+B(JP-1)
      EPP10=EPP+10*DZ
      IF (Y.GT.EPP.AND.EPP10.GT.Y) GO TO 280
  270 IF (IPF.EQ.KPS) GO TO 280
      IF (IU.EQ.I(3*NPA1)) GO TO 280
      IF (IU.EQ.INFINPASS.OR.IU.EQ.I(3*JP-1).OR.IU.EQ.I(3*JP-2)) GOTO280
      IPF=IPF+1
      GO TO 320
C
C             NEXT BLOCK PRINTS MATRIX T
C
  280 TRTI=Y+DTIG
      WRITE (2,6060) Y,TRTI,D22,Z1,DZ
      IF(.NOT.MATPRINT) GO TO 311
      DO 290 M=1,NVC
              DO 290 N=1,NWR
              T(N,M)=A(N,M)
              T(NWR1,M)=U(M)
              T(N,NVC1)=STL(N)
  290 CONTINUE
C                  CALCULATION OF DISTANCES FROM THE SURFACE
      DO 300 N=1,NWR
              T(N,NVC2)=(WNR-N+0.5)*D22
  300 CONTINUE
C
      T(NWR1,NVC2)=0
      T(NWR1,NVC1)=STL(NWR)+U(NVC)-A(NWR,NVC)
C
      DO 310 N=1,NWR1
              IF (NVC.GT.13) GO TO 305
      WRITE (2,6070) (T(N,M),M=1,NVC2)
      GO TO 310
```

```
  305 WRITE (2,6070) (T(N,M),M=1,NVC2,2)
  310 CONTINUE
  311 IF (.NOT.IFPLOT) GO TO 315
      WRITE (3,9000) T(1,1),Z1,U(1),TRTI
      IF (Y.GT.EPP.AND.EPP10.GT.Y) GO TO 315
      KPS=2*KPS
  315 IPF=1
C
  320 IF (IU.EQ.I(3*NPA1)) GO TO 3210
      IF (IU.LT.I(3*JP)) GO TO 100
      IF (IU.EQ.I(3*JP)) GO TO 330
C
C         IF NONE OF THE PREVIOUS IS TRUE  IT SHOULD BE DURING A PASS
C
      CALL BCHANGED2 (IU,INFINPASS,B0,B2,B3,B4,THICKN,RD,NWR,C1,C
     1         ,T,A,U,STL,Z9,Z1,NVC,D2,SPEED,JP,NOA)
      IF (IU.NE.INFINPASS) GO TO 100
      CALL DDECREASENUMELMTS (NWR,NVC,A,T,G,STL,D,D1,D2,KPAC,KPS,Z
     1       ,JP,DZ,WNR,NWR1,D22)
      KPS4=4*KPS
C
      RD=RAD(JP)
      IF(.NOT.STRUCT) GO TO 100
C
C
C         AVERAGE STRUCTURE CALCULATION
C
      IF (NP.EQ.1) NO=1
      IF(NP.EQ.1) GO TO 329
 3210 N1=0
      DO 327 N=1,NR
      N1=N1+NOA(N)
  327 CONTINUE
      IF (N1.GT.50) N1=50
      DO 328 J=1,8
      DO 328 I1=1,N1
      SS(I1,J,1)=0.
  328 CONTINUE
C
      NO=0
      DO 326 N=1,NR
              NN=N+1
              JQ1=NOA(N)
C
              DO 326 I1=1,JQ1
C
            NO=NO+1
                 JQ3=NO
              DO 321 J=1,JQ3
       IF (SS(J,1,1).EQ.0) GO TO 321
              F2=ABS(SS(J,5,1)-S(I1,5,N))
            IF (F2.GE.0.0001) GO TO 321
            NO=NO-1
          GO TO 326
  321         CONTINUE
C
```

```
                 SS(NO,1,1)=S(I1,1,N)
                 PO=S(I1,4,N)*S(I1,1,N)
                 P1=S(I1,1,N)
                 SS(NO,5,1)=S(I1,5,N)
                 K1=I1+1
                 IF(K1.GT.JQ1) GO TO 323
                 DO 322 I2=K1,JQ1
                 F2=ABS(S(I1,5,N)-S(I2,5,N))
                 IF (F2.GE.0.0001) GO TO 322
                 SS(NO,1,1)=SS(NO,1,1)+S(I2,1,N)
                 PO=PO+S(I2,1,N)*S(I2,4,N)
                 P1=P1+S(I2,1,N)
  322            CONTINUE
C
  323               IF(NN.GT.NR) GO TO 325
C
                    DO 324 M=NN,NR
                    JQ2=NOA(M)
C
                    DO 324 I1=1,JQ2
                    F2=ABS(S(I1,5,N)-S(I1,5,M))
                    IF (F2.GE.0.0001) GO TO 324
                    SS(NO,1,1)=SS(NO,1,1)+S(I1,1,M)
                  PO=PO+S(I1,1,M)*S(I1,4,M)
                  P1=P1+S(I1,1,M)
  324               CONTINUE
C
  325               SS(NO,1,1)=SS(NO,1,1)/RN
                  SS(NO,4,1)=PO/P1
  326 CONTINUE
C
      WRITE(2,6125)
      WRITE (2,6127) (SS(I1,1,1),SS(I1,5,1),SS(I1,4,1),I1=1,NO)
      IF (IU.EQ.I(3*NPA1)) GO TO 350
  329 ZZ1=(Z1+Z0)/2.
      CALL LOAD (1,ZZ1,SS,NO,NP)
C
C     STRUCTURE CONDITIONS AFTER PASS
C
      YDIF=B(NP)/2.
      OO=E(NP)
      T5=0.
      DO 336 N=1,NWR
              DEFTEM(N)=(A(N,MMT)+SPRT(N))/2.
              ZP(N)=E1(NP)*EXP(460000./(8.31*(DEFTEM(N)+273)))
              W2(N)=YDIF*EXP(-500000./(8.31*(DEFTEM(N)+273)))
              JQ1=NOA(N)
      SUM=0
      DO 340 I1=1,JQ1
      IF (S(I1,5,N).NE.0.) GO TO 340
      SUM=SUM+S(I1,1,N)
  340 CONTINUE
      NO=0
              DO 334 I1=1,JQ1
      NO=NO+1
              SS(NO,8,1)=0.
```

```
                EO=E(NP)+S(II,5,N)
      IF (SUM.EQ.100.) GO TO 331
      IF (S(II,5,N).NE.0.) GO TO 331
      X=S(II,1,N)/100.0
      XI=(S(II,1,N)+S(II+1,1,N))/100.
          GS=S(II,3,N)



      GO TO 3310
  331           GS=S(II,4,N)
C*
 3310 EC=6.64E-3*GS**0.36*(EXP(-134000./(8.31*(DEFTEM(N)+273.))))
     1**(-0.28)
      IF (EO.LT.EC) GO TO 332
      WRITE (2,6110) N,EO,EC,ZP(N)
C         DYNAMIC RECRYSTALLISATION
       T1=4.32*3.0E-7*ZP(N)**(-0.38)*EXP(366000/(8.31*(DEFTEM(N)+273)))
       GO TO 333
  332  T1=4.32*4.0E-15*ZP(N)**(-0.38)*EO**(-3.6)*GS**1.3
     1*EXP(500000./(8.31*(DEFTEM(N)+273.)))
  333         SS(NO,1,1)=S(II,1,N)
              SS(NO,2,1)=GS
              SS(NO,3,1)=GS
              SS(NO,4,1)=GS
              SS(NO,5,1)=EO
              SS(NO,6,1)=T1
              SS(NO,7,1)=0.
C*
  334 CONTINUE
      NOA(N)=NO
      DO 335 J=1,8
      DO 335 IK=1,NO
      S(IK,J,N)=SS(IK,J,1)
  335 CONTINUE
  336 CONTINUE
C
      WRITE (2,6136)
      WRITE(2,6135) NP
      WRITE(2,6137)
      DO 337 N=1,NWR
      NO=NOA(N)
      DIST(N)=(WNR-N+0.5)*D22
      WRITE(2,6140) (DIST(N),S(IK,1,N),S(IK,4,N),S(IK,5,N),S(IK,6,N),
     1   DEFTEM(N),IK=1,NO)
  337 CONTINUE
      WRITE (2,6136)
C
      DO 338 N=1,NWR
      RAVTEM(N)=T(N,MMT)
  338 CONTINUE
      Y1=Y
      GO TO 100
C
C
  330 CALL ADEFINEROLLCOND (DSRY,W,R,RST,F,NVC,RD,SPEED,D2,D1,R1,S1,
```

```
     1 NWR,TRO,RTO,RLO,H1,IR,THICKN,DZ,B0,B2,B3,B4,NRRX,A5,S8,COND8
     2          ,R8,Z9,V8,WNR,VNC,TRISE,LOADS,TORQS,RTEMP,Z1,C,C1,P,JP)
C
      SL=0.
C
      GO TO 100
C
C
  350 IF (IFPLOT) WRITE(3,9010)
      IF (STRUCT) WRITE(4,9010)
 1500 CONTINUE
      IF (IFPLOT)WRITE(3,9020)
      IF (STRUCT) WRITE (4,9020)
       STOP
C
C
 5000 FORMAT (170G0.0)
 5010 FORMAT (7L3)
 5020 FORMAT(A5)
C
 6000 FORMAT (1H ,20X,'ROLL TEMPERATURE=',F4.0,35X,'INITIAL TEMPERATURE
     1=',F6.0)
 6010 FORMAT (1H ,10X,'REDUCTIONS:',/,5X,20F7.4)
 6020 FORMAT  (9X,'D1=',F7.5,2X,'D2=',F7.5,2X,'NUMBER OF ROWS=',I2,2X,
     1'NUMBER OF COLUMNS=',I2,5X,'NUMBER OF PASSES=',I2,30X,'H.T.C. DURI
     2NG ROLLING=',F10.1)
 6030 FORMAT (1H ,10X,'THICKNESS: (M)',/,5X,21F6.3)
 6040 FORMAT (1H ,10X,'CONTACT TIME:',1X,12F8.5)
 6045 FORMAT (1H ,6X,'ROUND UP QUOTIENT:',12I8)
 6050 FORMAT (1H ,5X,'AIR COOLING ROUND UP QUOTIENTS:',/,5X,44I5)
 6080 FORMAT(1H1,52X,'****',1X,A5,1X,'****')
 6012 FORMAT (1H ,10X,'SPREAD: (%) ',/,5X,20F5.2)
 6014 FORMAT (1H ,10X,'SPEEDS:(M/SEC) ',/,5X,20F7.3)
 6016 FORMAT (1H ,10X,'TIME FOR START OF PASSES: ',/,5X,21F7.2)
 6017 FORMAT (1H ,10X,'ROLL RADIOUS: (M)',/,5X,20F8.5)
 6018 FORMAT (1H ,10X,'WATER COOLING START:',/,5X,21F7.2)
 6022 FORMAT (1H ,10X,'WATER COOLING PERIOD:',/,5X,21F6.2)
 6024 FORMAT (1H ,10X,'WATER COOLING HEAT TRANSFER COEFF:',/,5X,21F9.2)
 6026 FORMAT (1H ,35X,'STRESS STRAIN EQUATIONS ON PASS',I13,'OUT OF RANG
     1E')
 6060 FORMAT (1H0,5X,'TIME=',F9.5,5X,'TRUE TIME=',F9.5,5X,'D2=',F8.5,5X,
     1'MEAN TEMP.=',F10.4,5X,'TIME INCREMENT=',F10.7)
 6070 FORMAT (1H ,15F8.2)
 6090 FORMAT (1H ,10X,'STRAIN:',/,5X,20F6.2)
 6100 FORMAT (1H ,10X,'STRAIN RATE (1/SEC):',/,5X,20F7.2)
 6110 FORMAT (1H ,3X,'!!!! DYNAMIC RECRYSTALLISATION!!!!',5X,
     1'STRAIN ON ROW',I13,'IS',1F7.3,'CRITICAL STRAIN IS',1F7.3,
     22X,'Z=',1E8.2)
 6125 FORMAT (1H ,50X,'*AVERAGE  STRUCTURE*',/,10X,'% OF MATERIAL',
     1 25X,'STRAIN',25X,'GRAIN SIZE')
 6127 FORMAT (1H ,10X,1F9.5,26X,1F9.5,25X,1F9.5)
 6130 FORMAT (1H ,22X,'STRUCTURE AT ',1F6.2,1X,'SEC',35X,
     1  'COOLING TIME ',1F6.2,1X,'SEC')
 6133 FORMAT (1H ,1X,'DISTANCE',8X,'TEMPERATURE',8X,'% OF MATERIAL',9X,
     1  'STRAIN',8X,'REX. G.S.',8X,'ACTUAL G.S.',9X,'MEAN G.S.')
 6134 FORMAT (1H ,10X,'AVERAGE GRAIN SIZE ',1F7.1)
```

```
6135 FORMAT (1H ,'*',42X,'STRUCTURE AFTER PASS',1X,I2,53X,'*')
6136 FORMAT (1H ,120('*'))
6137 FORMAT (1H ,10X,'DISTANCE',10X,'% OF MATERIAL',10X,
    1  'GRAIN SIZE',10X,'STRAIN',10X,'REX. TIME',10X,'DEF.TEMP.')
6140 FORMAT (1H ,'*',10X,1F7.2,13X,1F6.2,16X,
    1  1F6.2,9X,1F9.3,7X,1F12.5,12X,1F7.2,4X,'*')
C
9000 FORMAT (1X,3(F7.2,1X),F10.5)
9010 FORMAT (1X,'END')
9020 FORMAT (1X,'*****')
9030 FORMAT (1X,A5)
9040 FORMAT (1H ,I3)
     END
     SUBROUTINE DEFHEAT (C,NPA)
             DIMENSION C(20)
             READ (1,5000) (C(JP),JP=1,NPA)
             WRITE (2,6000) (C(JP),JP=1,NPA)
     RETURN
C
5000 FORMAT (10G0.0)
6000 FORMAT (1H ,10X,'VARIABLE FOR TEMPERATURE RISE CALCULATION:',10(F9
    1.1,1X))
C
     END
     SUBROUTINE FTEMPDIST(A,T,STL,U,DTIG,Z1,NVC,NWR,NWR1,NVC1,RTEMP,GS)
C
C
C          THIS SUBROUTINE ALLOWS THE INPUT OF A STARTING TEMPERATURE
C     DISTRIBUTION;EACH ROW IS CONSIDERED IN TURN ,WHEN THE LAST ROW HAS
C     BEEN INPUT THEN THE BOTTOM SURFACE TEMPERATURES ARE READ,WHEN THIS
C     HAS BEEN DONE THE SIDE SURFACE TEMPERATURES ARE INPUT.READING AND
C     PRINTING OF THE MEAN TEMPERATURE,GRAIN SIZE AND CURRENT TIME IS ALSO DONE.
C
C
             DIMENSION A(60,20),T(61,22),STL(60),U(20)
             READ (1,5000) DTIG,Z1,GS
             READ (1,5000) ((A(N,M),M=1,NVC),N=1,NWR),((U(M),M=1,NVC),
    1        STL(N),N=1,NWR)
             T(NWR1,NVC1)=0
C
             DO 10 M=1,NVC
                T(NWR1,M)=U(M)
                DO 10 N=1,NWR
                T(N,M)=A(N,M)
   10        CONTINUE
C
             DO 20 N=1,NWR
                T(N,NVC1)=STL(N)
   20        CONTINUE
C
             WRITE (2,6000) DTIG,Z1,RTEMP
C
             DO 40 N=1,NWR1
                IF (NVC.GT.14) GO TO 30
                WRITE (2,6010) (T(N,M),M=1,NVC1)
                GO TO 40
```

```
  30            WRITE (2,6010) (T(N,M),M=1,NVC1,2)
  40         CONTINUE
      RETURN
C
 5000 FORMAT (20G0.0)
C
 6000 FORMAT (1H ,'TIME OF DIST.=',F8.5,1X,'MEAN TEMP.=',F7.2,1X,
     1'ROLL TEMP.=',F2.0)
 6010 FORMAT (1H ,15F8.2)
C
      END
      SUBROUTINE CINCREASENUMELMTS (T,G,NVC,NWR,STL,Z,DZ,D2,KPR,NRRX,
     1            KPS,A,U,JP,NWR1,D22,WNR,NP,IR,NWRO)
C
C  SUBROUTINE TO INCREASE THE NUMBER OF ELEMENTS BY A FACTOR OF 3,
C  THE ELEMENT THICKNESS IS REDUCED ACORDINGLY AND THE
C  NEW ELEMENTS TEMPERATURES EXTRAPOLATED
C
      DIMENSION  T(61,22),G(60),Z(83),A(60,20),U(20),STL(60),IR(20)
C
      C13=1./3.
      C23=2./3.
      C43=4./3.
      C16=1./6.
      C56=5./6.
C
      DO 10 M=1,NVC
            DO 10 N=1,NWR
            T(3*N-1,M)=A(N,M)
   10 CONTINUE
C
      DO 20 M=1,NVC
            T4=2.*A(2,M)-A(1,M)-A(3,M)
          IF (T4.EQ.0.) GO TO 15
            T5=A(3,M)+3.*A(1,M)-4.*A(2,M)
            T(1,M)=A(1,M)+(T5**2)/(8.*T4)-T4/2.*(T5/(2.*T4)-C13)**2
            T(3,M)=A(1,M)+(T5**2)/(8.*T4)-T4/2.*(T5/(2.*T4)+C13)**2
          GO TO 20
   15 T(1,M)=(A(1,M)-A(2,M))/3.+A(1,M)
              T(3,M)=2.*(A(1,M)-A(2,M))/3.+A(2,M)
   20 CONTINUE
C
      NWRO=NWR-1
      DO 30 M=1,NVC
          DO 30 N=2,NWRO
          T4=2.*A(N,M)-A(N-1,M)-A(N+1,M)
        IF (T4.EQ.0.) GO TO 25
          T5=A(N+1,M)+3.*A(N-1,M)-4.*A(N,M)
          T(3*N-2,M)=A(N-1,M)+(T5**2)/(8.*T4)-T4/2.*(T5/(2.*T4)+C23)**2
          T(3*N,M)=A(N-1,M)+(T5**2)/(8.*T4)-T4/2.*(T5/(2.*T4)+C43)**2
        GO TO 30
   25         T(3*N-2,M)=(A(N-1,M)-A(N,M))/3.+A(N,M)
              T(3*N,M)=2.*(A(N-1,M)-A(N,M))/3.+A(N,M)
   30 CONTINUE
C
      DO 40 M=1,NVC
```

```
          T4=2.*A(NWR-1,M)-A(NWR-2,M)-A(NWR,M)
          T5=A(NWR,M)+3.*A(NWR-2,M)-A(NWR-1,M)*4.
          T6=A(NWR-2,M)+(T5**2)/(8.*T4)-T4/8.*(T5/T4+3.)**2
C
          T4=2.*A(NWR,M)-T6-U(M)
          T5=U(M)+3.*T6-4.*A(NWR,M)
C
          T(3*NWR-2,M)=T6+(T5**2)/(8.*T4)-2.*T4*(T5/(4.*T4)+C16)**2
          T(3*NWR,M)=T6+(T5**2)/(8.*T4)-2.*T4*(T5/(4.*T4)+C56)**2
   40 CONTINUE
C
C
C
      DO 50 N=1,NWR
          G(3*N-1)=STL(N)
   50 CONTINUE
C
      T4=2.*STL(2)-STL(1)-STL(3)
      IF(T4.EQ.0.) GO TO 52
      T5=STL(3)+3.*STL(1)-4.*STL(2)
      G(1)=STL(1)+(T5**2)/(8.*T4)-T4/2*(T5/(2.*T4)-C13)**2
      G(3)=STL(1)+(T5**2)/(8.*T4)-T4/2*(T5/(2.*T4)+C13)**2
      GO TO 54
   52 G(1)=(STL(1)-STL(2))/3.+STL(1)
      G(3)=2.*(STL(1)-STL(2))/3.+STL(2)
C
   54 DO 60 N=2,NWRO
          T4=2.*STL(N)-STL(N-1)-STL(N+1)
        IF (T4.EQ.0.) GO TO 55
          T5=STL(N+1)+3.*STL(N-1)-4.*STL(N)
C
          G(3*N-2)=STL(N-1)+(T5**2)/(8.*T4)-T4/2.*(T5/(2.*T4)+C23)**2
          G(3*N)=STL(N-1)+(T5**2)/(8.*T4)-T4/2.*(T5/(2.*T4)+C43)**2
        GO TO 60
   55           G(3*N-2)=(STL(N-1)-STL(N))/3.+STL(N)
            G(3*N)=2.*(STL(N-1)-STL(N))/3.+STL(N)
   60 CONTINUE
C
      T4=2.*STL(NWR-1)-STL(NWR-2)-STL(NWR)
      T5=STL(NWR)+3.*STL(NWR-2)-4.*STL(NWR-1)
      T6=STL(NWR-2)+(T5**2)/(8.*T4)-T4/8.*(T5/T4+3.)**2
C
      T4=STL(NWR)-T6+A(NWR,NVC)-U(NVC)
      T5=3.*T6-A(NWR,NVC)+U(NVC)-3.*STL(NWR)
      G(3*NWR-2)=T6+(T5**2)/(8.*T4)-2.*T4*(T5/(4.*T4)+C16)**2
      G(3*NWR)=T6+(T5**2)/(8.*T4)-2.*T4*(T5/(4.*T4)+C56)**2
C
      NWR=3*NWR
      NWRO=NWR-1
      WNR=FLOAT(NWR)
      D2=D2/3.
      NWR1=NWR+1
      D22=1000.*D2
      NRRX=IR(JP)
      KPS=KPR
      DZ=Z(4*JP)
```

```
C
      DO 70 M=1,NVC
         DO 70 N=1,NWR
      A(N,M)=T(N,M)
   70 CONTINUE
C
      DO 80 N=1,NWR
         STL(N)=G(N)
   80 CONTINUE
C
      NP=JP
C
      RETURN
      END
C
      SUBROUTINE ADEFINEROLLCOND (DSRY,W,R,RST,F,NVC,RD,SPEED,D2,D1,
     1       R1,S1,NWR,TRO,RTO,RLO,H1,IR,THICKN,DZ,B1,B2,B3,B4,NRRX,A5
     1 ,S8,COND8,R8,Z9,V8,WNR,VNC,TRISE,LOAD,TORQS,RTEMP,Z1,C,C1,P,JP)
C
C  DEFINE ROLLING CONDITIONS AT THE BEGINNING OF THE PASS
C
      DIMENSION DSRY(100),W(100),R(100,20),RST(20),F(101,21),SPEED(20),
     1                TRO(20),IR(20),RTO(20),RLO(20),THICKN(21),P(20)
      COMMON/LINK1/DO,D3,SL,UL,NWRO,NUMINT,STRUCT
      COMMON/WORK/E(20),E1(20)
C
      LOGICAL TRISE,LOAD,TORQS,STRUCT
      NAMELIST/CHECKING/CONTLENGTH,STRAIN,STRENGTH,Z9NL
C
      DO 10 IRCB=1,NVC
            DO 10 IRRA=1,NRRX
            R(IRRA,IRCB)=RTEMP
            RST(IRCB)=RTEMP
   10 CONTINUE
C
      Z3=RTEMP
      S8=527.184
      COND8=46.4424
      R8=7790
      A5=1.4*SQRT(DZ*2.*1.E-08*COND8/(S8*R8))
      V8=A5*D1
      DSRY(1)=RD-SQRT(RD**2-2.E+04*A5*RD)
      W(1)=SQRT((RD**2 +(RD-DSRY(1))**2)/2.)
      DS1=DSRY(1)
C
      DO 20 IRRA=2,NRRX
            DSRY(IRRA)=RD-SQRT((RD-DSRY(IRRA-1))**2-A5*2.E+04*RD)
            W(IRRA)=SQRT(((RD-DSRY(IRRA))**2+(RD-DSRY(IRRA-1))**2)
     1/2.)
   20 CONTINUE
C
      B4=SPEED(JP)*DZ/RD
      B1=1.-(THICKN(JP)-THICKN(JP+1))/(2.*RD)
      TE=SQRT(1.-B1*B1)
      B1=ATAN(TE/B1)
      B2=B1-B4/2.
```

```
      DO=D2
      D2=(RD*(1-COS(B2))+THICKN(JP+1)/2.)/WNR
C
      C=C1
C
      B3=B1-B4
      D3=(RD*(1.-COS(B3))+THICKN(JP+1)/2.)/WNR
C
      IF (TRISE) GO TO 30
      IF (LOAD) GO TO 40
      IF (TORQS) GO TO 50
      IF (STRUCT) GO TO 25
      WRITE(2,6020) Z9
   25 RETURN
   30 Z9=TRO(JP)/IR(JP)
      WRITE(2,6020) Z9
      RETURN
C
C     STRENGTH IS ESTIMATED FROM ALEXANDER'S FORMULAE P=WKL(PI/2+L/H1+H2)
C
   40 CONTLENGTH=SQRT(RD*(THICKN(JP)-THICKN(JP+1)))
      STRENGTH=0.833*RLO(JP)/(VNC*D1*CONTLENGTH*(1.57+CONTLENGTH/(THICKN
     1(JP)+THICKN(JP+1))))
      STRAIN=1.155*ALOG(1/(1-P(JP)))
      Z9=STRENGTH*STRAIN/(R1*S1*IR(JP))
      Z9NL=Z9
      WRITE (2,CHECKING)
C
      WRITE(2,6020) Z9
      RETURN
   50 Z9=RTO(JP)/(2.*D1*VNC*R1*S1*IR(JP)*SQRT(THICKN(JP)*THICKN(JP+1
     1)))
      WRITE (2,6020) Z9
      RETURN
C
 6020 FORMAT (1H ,40X,'TEMP.RAISE DURING INTERVAL:',3X,F6.2)
C
      END
C
      SUBROUTINE GADDTEMPRISE (A,U,STL,Z9,Z1,NVC,NWR,SPEED,B0,B3,JP,NOA
     1         ,RD,T)
C
C  SUBROUTINE TO ADD THE TEMPERATURE RISE AT EACH INTERVAL DURING THE PASS
C
      DIMENSION T(61,22),A(60,20),NOA(20),U(20),STL(60),SPEED(20)
      COMMON/LINK1/DO,D3,SL,UL,NWRO,NUMINT,STRUCT
      COMMON/STORE/S(50,8,20),SS(50,8,1)
      COMMON/WORK/E(20),E1(20)
      COMMON/STRENGTH/S0,B1,B2,EP,C,THICKN(21),RAD(20)
      COMMON/LINK2/R1,S1,VNC,WNR,RAVTEM(20),DEFTEM(20)
      EXTERNAL ASINH
      LOGICAL STRUCT
      IF (STRUCT) GO TO 40
C
      DO 10 M=1,NVC
          DO 10 N=1,NWR
```

```
        A(N,M)=A(N,M)+Z9
  10 CONTINUE
C
     DO 20 M=1,NVC
        U(M)=U(M)+Z9
  20 CONTINUE
C
     DO 30 N=1,NWR
        STL(N)=STL(N)+Z9
  30 CONTINUE
C
     Z1=Z1+Z9
C
     GO TO 80
  40 EINC=1.155*ALOG(D0/D3)
     E1INC=EINC*SPEED(JP)/(RD*(B0-B3))
     NUMINT=10
     UL=SL+EINC
     Z1=0.
C
C
     DO 70 N=2,NWR0,3
     NN=N/3+1
           Z=E1INC*EXP(460000/(8.31*(DEFTEM(NN)+273)))
           NO=NOA(NN)
           AREAT=0.
C      SIGMA SS EXTRAPOLETED
       B1=(-506.0+37.0*ALOG10(Z))*1000.0
C      SIGMA SS
      B2=(-410.2+30.3*ALOG10(Z))*1000.0
C      SIGMA S0
      S0=(-565.3+36.0*ALOG(Z))*1000.0
      B2=B1-B2
         B1=B1-S0
C       SIGMA S01
        S01=(-474.0+34.5*ALOG10(Z))*1000.0
         A0=(S01-S0)/SQRT(0.1)
         C=(A0/B1)**2
C
           DO 50 I=1,NO
         EP= 0.097*(Z**0.032)
           CALL SIMPINT(I,STR,3,AREA,S,NN,JP)
           AREAT=AREAT+S(I,1,NN)*AREA/100.
  50       CONTINUE
C
           AREAT=AREAT*1.E+3
           Z9=AREAT/(R1*S1)
           STL(N)=STL(N)+Z9
C
           DO 60 M=1,NVC
           A(N,M)=A(N,M)+Z9
         A(N-1,M)=A(N-1,M)+Z9
         A(N+1,M)=A(N+1,M)+Z9
         Z1=Z1+A(N,M)+A(N-1,M)+A(N+1,M)
  60       CONTINUE
C
```

```
              IF (N.LT.NWRO) GO TO 70
C
              DO 65 M=1,NVC
              U(M)=U(M)+Z9
   65     CONTINUE
   70 CONTINUE
      SL=UL
      Z1=Z1/(VNC*WNR)
   80 DO 90 M=1,NVC
      DO 90 N=1,NWR
      T(N,M)=A(N,M)
   90 CONTINUE
      RETURN
      END
C
      SUBROUTINE EHEATBETWEENSLABROLL(M,A5,COND8,DZ,V1,V8,S8,R8,NRRX,RD
     1    ,D1,WNR,D2,COND,S1,R1,NVC1,KPS,IPF,NVC,B3,D3,B2,C,Q,R,DSRY,W,
     2        RST,U,T,F,A,NWR,VNC,MATPRINT)
C
C  CALCULATION OF HEAT TRANSFER BETWEEN SLAB AND ROLL
C  AND ROLL TEMPERATURE DISTRIBUTION
C
      DIMENSION R(100,20),DSRY(100),W(100),RST(20),T(61,22),F(101,21),
     1        A(60,20),U(20)
      LOGICAL MATPRINT
C
C
      IRCB=M
      CONST=A5*COND8*DZ/D1
      CONST1=D1*COND8*DZ*1.E-04
      QUOT=V8*S8*R8
      NRRX1=NRRX+1
      RNRX=FLOAT(NRRX)
C
C             BACKWARDS DO LOOP JD IS A DUMMY COUNTER
C
      DO 50 JD=1,NRRX
              IRRA=NRRX1-JD
              HRJ=0
              IF (IRCB.EQ.1) GO TO 10
              HRJ=(R(IRRA,IRCB-1)-R(IRRA,IRCB))*CONST
              IF (IRCB.EQ.NVC)GO TO 20
   10         HRJ=HRJ-(R(IRRA,IRCB)-R(IRRA,IRCB+1))*CONST
   20         IF (IRRA.EQ.1) GO TO 30
              HRJ=HRJ+(R(IRRA-1,IRCB)-R(IRRA,IRCB))*CONST1*(RD-DSRY(IRR
     1        A-1))/(RD*(W(IRRA-1)-W(IRRA)))
              IF (IRRA.EQ.NRRX) GO TO 40
              HRJ=HRJ-(R(IRRA,IRCB)-R(IRRA+1,IRCB))*CONST1*(RD-DSRY(IRR
     1        A))/(RD*(W(IRRA)-W(IRRA+1)))
              GO TO 40
   30         HRJ=HRJ-(R(IRRA,IRCB)-R(IRRA+1,IRCB))*CONST1*(RD-DSRY(IRR
     1        A))/(RD*(W(IRRA)-W(IRRA+1)))
              D4=(2.*WNR*D2/3.-SQRT(0.4444*(WNR*D2)**2-8.*WNR*COND*DZ/(3
     1        .*S1*R1)))/D2
              D5=RD**2-2*RD*CONST1/QUOT
              A1=Q/(D1*D2*S1*R1)-HRJ/QUOT
```

```
              A2=C*DZ/10.*(1./(D2*R1*S1*COS(B2))+D1*1.E-04/QUOT)
              A3=C/2.*(D3*D4*(WNR-D4/4.)/(WNR*COND*COS(B3))+(RD**2-D5)
     1        /(RD*COND8))
              A3=C*(A(NWR,M)-R(1,IRCB)+A1-A2*(U(M)-RST(IRCB)))/
     1        (9.*A2+A3+1)
              A1=C*(U(M)-RST(IRCB))
              A2=(A1+9.*A3)/10.
C
              T(NWR,M)=A(NWR,M)+Q/(D1*D2*S1*R1)-A2*DZ/(D2*S1*R1*COS(B2))
              U(M)=T(NWR,M)-A3*D3*D4*(WNR-D4/4.)/(2.*WNR*COND*COS(B3))
              F(1,IRCB)=R(1,IRCB)+(HRJ+A2*D1*1.E-04*DZ)/QUOT
              RST(IRCB)=F(1,IRCB)+A3*(RD**2-D5)/(2.*RD*COND8)
              IF (M.EQ.NVC) GO TO 60
              GO TO 110
   40         F(IRRA,IRCB)=R(IRRA,IRCB)+HRJ/QUOT
   50 CONTINUE
C
   60 Z3=0
C
      DO 70 IRCB=1,NVC
              DO 70 IRRA=1,NRRX
              R(IRRA,IRCB)=F(IRRA,IRCB)
              Z3=Z3+R(IRRA,IRCB)
   70 CONTINUE
C
      Z3=Z3/(RNRX*VNC)
      IF (IPF.NE.KPS) GO TO 110
C
C             PRINTING OF ROLL TEMPERATURES
C
      DO 80 IRCB=1,NVC
              DO 80 IRRA=1,NRRX
              F(1,IRCB)=RST(IRCB)
              F(IRRA+1,IRCB)=R(IRRA,IRCB)
              F(IRRA+1,NVC+1)=W(IRRA)*1000.
   80 CONTINUE
C
      F(1,NVC1)=RD*1000.
C
      WRITE(2,6000) Z3
      IF (.NOT.MATPRINT) GO TO 110
C
      DO 100 IRRA=1,NRRX1
              IF (NVC.GT.13)GO TO 90
              WRITE (2,6010) (F(IRRA,IRCB),IRCB=1,NVC1)
              GO TO 100
   90         WRITE (2,6010) (F(IRRA,IRCB),IRCB=1,NVC1,2)
  100 CONTINUE
C
  110 RETURN
C
 6000 FORMAT (1H0,10X,'MEAN ROLL TEMP=',2X,F6.2)
 6010 FORMAT (1H ,15F8.2)
C
      END
C
```

```
      SUBROUTINE BCHANGED2 (IU,INFINPASS,B0,B2,B3,B4,THICKN,RD,NWR,C1,C
     1                    ,T,A,U,STL,Z9,Z1,NVC,D2,SPEED,JP,NOA)
C
C SUBROUTINE TO DECREASE ELEMENTAL THICKNESS AFTER EACH INTERVAL DURING THE PASS
C
      DIMENSION THICKN(21),NOA(20),A(60,20),U(20),STL(60),SPEED(20)
      DIMENSION T(61,22)
      COMMON/LINK1/D0,D3,SL,UL,NWR0,NUMINT,STRUCT
      COMMON/STORE/S(50,8,20),SS(50,8,1)
      COMMON/WORK/E(20),E1(20)
      COMMON/LINK2/R1,S1,VNC,WNR,RAVTEM(20),DEFTEM(20)
      IF (IU.EQ.INFINPASS) GO TO 10
      CALL GADDTEMPRISE (A,U,STL,Z9,Z1,NVC,NWR,SPEED,B0,B3,JP,NOA,RD,T)
      B0=B3
      B2=B2-B4
      B3=B3-B4
      D0=D3
      D2=(THICKN(JP+1)/2.+(1.-COS(B2))*RD)/WNR
      D3=(THICKN(JP+1)/2.+(1.-COS(B3))*RD)/WNR
      RETURN
   10 B2=B2-B4/2.
      D2=(THICKN(JP+1)/2.+(1.-COS(B2))*RD)/WNR
      D3=D2
      CALL GADDTEMPRISE (A,U,STL,Z9,Z1,NVC,NWR,SPEED,B0,B3,JP,NOA,RD,T)
      C=C1
      RETURN
      END
C
      SUBROUTINE DDECREASENUMELMTS (NWR,NVC,A,T,G,STL,D,D1,D2,KPAC,KPS,Z
     1          ,JP,DZ,WNR,NWR1,D22)
C
C DECREASES THE NUMBER OF ELEMENTS BY A FACTOR OF 3
C AND INCREASES THE ELEMENTAL THICKNESS AT THE END OF THE PASS
C
      DIMENSION A(60,20),T(61,22),G(60),STL(60),D(20),Z(83)
      NWR=NWR/3
      WNR=FLOAT(NWR)
      NWR1=NWR+1
C
      DO 10 M=1,NVC
              DO 10 N=1,NWR
              A(N,M)=(T(3*N-2,M)+T(3*N-1,M)+T(3*N,M))/3.
              T(N,M)=A(N,M)
   10 CONTINUE
C
      DO 20 N=1,NVC
              G(N)=(STL(3*N-2)+STL(3*N-1)+STL(3*N))/3.
              STL(N)=G(N)
   20 CONTINUE
C
      D2=D2*3.
      D22=1000.*D2
      D1=D1*(1+D(JP)/100.)
      KPS=KPAC
      JP=JP+1
C
```

```
      DZ=Z(4*JP-3)
C
      RETURN
C
C
      END
      SUBROUTINE EQUIAXGRAINS (D,I,E0,K,NO,T,T0)
C
C  CALCULATES GRAIN GROWTH AFTER COMPLETE RECRYSTALLISATION
C
      COMMON /STORE/A(50,8,20),B(50,8,1)
      COMMON/CONDIT/T2,T1,Z(20)
C
      EC=0.18*D**0.30
      IF (E0.LT.EC) GO TO 5
      D1=2647.*(Z(K)**(-0.1))
      GO TO 6
    5 D1=470.*(D**0.30)*(E0**(-1))*(Z(K)**(-0.1))
    6 B(NO,7,1)=(T2-T1)*EXP((500000./8.31)*(1/(T+273)-1/(T0+273)))
C
      D2=(D1**3)+5.25E14*EXP(-305000/(8.31*(T+273)))*B(NO,7,1)
C
C
C
      D2=D2**0.33
      B(NO,1,1)=A(I,1,K)
      IF (B(NO,1,1).LT.0.000001) GO TO 30
      B(NO,2,1)=A(I,4,K)
      B(NO,3,1)=D1
      B(NO,4,1)=D2
      B(NO,5,1)=0
      B(NO,6,1)=T1
      B(NO,8,1)=T
      GO TO 40
   30 NO=NO-1
   40 RETURN
      END
      SUBROUTINE MIXEDSTRUCT (I,D,E0,K,NO)
C
C  CALCULATES FRACTIONS OF MATERIAL WITH DIFFERENT ACUMULATED STRAINS
C
      COMMON /STORE/A(50,8,20),B(50,8,1)
      COMMON/CONDIT/T2,T1,Z(20)
      B(NO,1,1)=A(I,1,K)*(1-EXP(-3*(T2/T1)**1))
      IF (B(NO,1,1).LT.0.000001) GO TO 10
      B(NO,2,1)=A(I,4,K)
      EC= 0.18*D**0.30
      IF (E0.LT. EC) GO TO 5
      D1=2647.*Z(K)**(-0.1)
      GO TO 6
    5 D1=470.0*(D**0.30)*(E0**(-1))*(Z(K)**(-0.1))
    6 B(NO,3,1)=D1
      B(NO,4,1)=D1
      B(NO,5,1)=0
      B(NO,6,1)=T1
      B(NO,7,1)=0.
```

```
      B(NO,8,1)=0.
      GO TO 20
   10 NO=NO-1
   20 NO=NO+1
      B(NO,1,1)=A(I,1,K)-A(I,1,K)*(1-EXP(-3*(T2/T1)**1))
      IF (B(NO,1,1).LT.0.000001) GO TO 30
      B(NO,2,1)=A(I,4,K)
      B(NO,3,1)=A(I,4,K)
      B(NO,4,1)=A(I,4,K)
      B(NO,5,1)=E0
      B(NO,6,1)=T1
      B(NO,7,1)=0.
      B(NO,8,1)=0.
      GO TO 40
   30 NO=NO-1
   40 RETURN
      END
      SUBROUTINE TEMPCOMPTIME (K,OO,DEFTEM,T5)
C
C  CALCULATES STRUCTURAL CHANGES DURING AIR COOLING
C
      DIMENSION DEFTEM(20)
      COMMON /STORE/ A(50,8,20),B(50,8,1)
      COMMON/TEMP/RMEANT(20),NOA(20),W5,N,TI,SPRT(20),W2(20)
      COMMON/CONDIT/T2,T1,ZP(20)
      COMMON/PRIOUT/DIST(20)
      JQ1=NOA(K)
      T=RMEANT(K)
      TO=DEFTEM(K)
      Z=ZP(K)
      T2=W5
      W2(K)=W2(K)+T2*EXP(-500000./(8.31*(T+273)))
      NO=0
C
      DO 170 I=1,JQ1
      NO=NO+1
        EC=0.18*A(I,2,K)**0.3
      T1=A(I,6,K)
      T2=W2(K)*EXP(500000./(8.31*(TO+273)))
      TGG=A(I,8,K)
            IF (T1.GT.T2) GO TO 80
           IF (A(I,4,K).GT.A(I,3,K)) GO TO 120
           IF (A(I,5,K).EQ.0.) GO TO 170
       IF (I.EQ.1) GO TO 35
       IF (A(I,6,K).NE.A(I-1,6,K)) GO TO 75
           B(NO,1,1)=A(I,1,K)+A(I-1,1,K)
           B(NO,2,1)=A(I,2,K)
           B(NO,3,1)=A(I-1,3,K)
      GO TO 40
   35 B(NO,1,1)=A(I,1,K)
      B(NO,2,1)=A(I,2,K)
       IF (A(I,5,K).LT.EC) GO TO 37
       B(NO,3,1)=2647.*(Z**(-0.1))
       GO TO 40
   37 B(NO,3,1)=470.0*(Z**(-0.1))*(A(I,2,K)**0.30)/A(I,5,K)
   40 B(NO,8,1)=T
```

```
      TGG=T
      T2=(T2-T1)*EXP((500000./8.31)*(1/(T+273)-1/(T0+273)))
      B(NO,7,1)=T2
C
          D2=(B(NO,3,1)**3)+5.25E14*EXP(-305000/(8.31*(TGG+273)))*(T2)
C
C
          D2=D2**0.33
          B(NO,4,1)=D2
          B(NO,5,1)=0.
          B(NO,6,1)=A(I,6,K)
      IF (NO.EQ.1) GO TO 170
          DO 70 J=1,8
            B(NO-1,J,1)=B(NO,J,1)
       B(NO,J,1)=0.
   70     CONTINUE
      NO=NO-1
          GO TO 170
   75 CALL EQUIAXGRAINS (A(I,2,K),I,A(I,5,K),K,NO,T,T0)
      GO TO 170
   80     IF (A(I,5,K).EQ.0.0) GO TO 170
          IF (NO.EQ.1) GO TO 100
      IF (A(I,6,K).EQ.A(I-1,6,K).AND.A(I,5,K).EQ.A(I-1,5,K))GO TO100
          IF (A(I,6,K).NE.A(I-1,6,K)) GO TO 100
        B(NO-1,1,1)=A(I-1,1,K)+A(I,1,K)*(1-EXP(-3*(T2/T1)**1))
          B(NO,1,1)=A(I-1,1,K)+A(I,1,K)-B(NO-1,1,1)
          DO 90 J=2,8
          B(NO-1,J,1)=A(I-1,J,K)
          B(NO,J,1)=A(I,J,K)
   90     CONTINUE
      GO TO 170
  100 CALL MIXEDSTRUCT(I,A(I,2,K),A(I,5,K),K,NO)
          GO TO 170
  120     IF (A(I,5,K).EQ.0.) GO TO 130
      IF (A(I,5,K).LT.EC) GO TO 125
       D1=2647.*Z**(-0.1)
      GO TO 140
  125  D1=470.0*(Z**(-0.1))*(A(I,2,K)**0.30)/A(I,5,K)
       GO TO 140
  130     D1=A(I,3,K)


  140  CONTINUE
       T2=W5*EXP(-305000/(8.31*(T+273)))
        T2=T2*EXP(305000/(8.31*(TGG+273)))+A(I,7,K)
       B(NO,7,1)=T2
          D2=(D1**3)+5.25E14*EXP(-305000/(8.31*(TGG+273)))*(T2)
        D2=D2**0.33
           B(NO,4,1)=D2
          B(NO,1,1)=A(I,1,K)
          B(NO,2,1)=A(I,2,K)
          B(NO,3,1)=D1
          B(NO,5,1)=0.
          B(NO,6,1)=A(I,6,K)
             B(NO,8,1)=A(I,8,K)
  170 CONTINUE
```

```
C
C
      DO 175 J=1,8
              DO 175 I=1,NO
              A(I,J,K)=B(I,J,1)
  175 CONTINUE
C
      DL=0
      DT=0
      DO 180 I=1,NO
      IF(B(I,1,1).EQ.100.AND.B(I,5,1).EQ.0)GO TO 178
      XI=1
      IF (NO.EQ.1.OR.I.EQ.1) GO TO 179
      XI=(B(I,1,1)+B(I-1,1,1))/100.
  179 X=B(I,1,1)/100.
      CONST=EXP(0.866*B(I,5,1))
      IF (B(I,5,1).EQ.0)GO TO 177
      DL=DL+X/(B(I,2,1)*CONST)
      DT=DT+X*CONST/B(I,2,1)
      GO TO 180
  177 DL=DL+(X**(2./3.)*(XI**(1./3.)))/B(I,3,1)
      DT=DT+(X**(2./3.)*(XI**(1./3.)))/B(I,3,1)
      GO TO 180
  178 DL=DL+100./(B(I,1,1)*B(I,4,1))
      DT=DT+100./(B(I,1,1)*B(I,4,1))
  180 CONTINUE
      AVGS=1/SQRT(DL*DT)
      WRITE(2,6000) (DIST(K),T,A(I,1,K),A(I,5,K),A(I,3,K),
     1   A(I,4,K),AVGS,I=1,NO)
      NOA(K)=NO
      WRITE(4,6030) K,T,AVGS,TI
      RETURN
C
 6000 FORMAT (1H ,1F9.2,11X,1F7.2,14X,1F6.2,12X,
     1   1F5.3,10X,1F7.2,12X,1F7.2,11X,1F7.2)
 6030 FORMAT (1H ,I3,3(2X,F10.2))
C
      END
      SUBROUTINE LOAD (K,T,A,NO,N)
C
C  CALCULATES LOAD AND TORQUE IN THE PASS FROM SIMS THEORY
C
      DIMENSION A(50,8,1)
      COMMON/WORK/E(20),E1(20)
      COMMON/STRENGTH/S0,B1,B2,EP,C,H(21),R(20)
      COMMON/LINK1/D0,D3,SL,UL,NWRO,NUMINT,STRUCT
      EXTERNAL ASINH
      Z=E1(N)*EXP(460000/(8.31*(T+273)))

C
C         SIGMA SS EXTRAPOLETED
       B1 = (-506.0+37.*ALOG10(Z))*1000.0
C         SIGMA SS
       B2 = (-410.2 +30.3*ALOG10(Z))*1000.0
C         SIGMA SO
       S0=(-565.3 + 36.0*ALOG10(Z))*1000.0
```

```
      B2=B1-B2
      B1=B1-S0
C       SIGMA S01
       S01=(-474.0+34.5*ALOG10(Z))*1000.0
      A0=(S01-S0)/SQRT(0.1)
      C=(A0/B1)**2
C
            STRTOR=0.
            STRLOAD=0.
      DO 10 I=1,N0
       EP = 0.097*Z**0.032
            CALL SIMPINT (I,STR,1,AREA,A,1,N)
          STRTOR=STRTOR+A(I,1,K)*STR/100.
            CALL SIMPINT(I,STR,2,AREA,A,1,N)
            STRLOAD=STRLOAD+A(I,1,K)*STR/100.
   10 CONTINUE
C
      ALPHA=1-(H(N)-H(N+1))/(2.*R(N))
      ALPHA=ATAN (SQRT(1-ALPHA**2)/ALPHA)
      TETHA=(ATAN(ALPHA*((R(N)/H(N+1))**(0.5)))-0.785*ALOG (H(N)/
     1      H(N+1))*((R(N)/H(N+1))**(-0.5)))/2.
      TETHA=((R(N)/H(N+1))**(-0.5))*SIN(TETHA)/COS(TETHA)
      HN=H(N+1)+2.*R(N)*(1-COS(TETHA))
      QP=SQRT(H(N+1)/(4*(H(N)-H(N+1))))*(3.14159*ATAN(((H(N)-H(N+1))/
     1  H(N+1))**0.5)-((R(N)/H(N+1))**0.5)*ALOG(HN**2/(H(N)*H(N+1))))
     2     -0.785
      FLOAD=STRLOAD*SQRT(R(N)*(H(N)-H(N+1)))*QP
      TORQUE=2.*R(N)*R(N)*STRTOR*(ALPHA/2.-TETHA)
      TNL=T
      NAMELIST/NL1/QP,S0,B1,EP,A0,C,STRLOAD,STRTOR,ALPHA,TETHA,HN,TNL,Z
      WRITE (2,NL1)
      WRITE (2,6000) FLOAD,TORQUE
      RETURN
 6000 FORMAT (1H ,'LOAD(KN/M):',1F16.4,10X,'TORQUE(KN-M/M):',1F16.4)
      END
      SUBROUTINE SIMPINT (I,STR,L,AREA,A,K,N)
C
C  NUMERICAL INTEGRATION BY SIMPSOM METHOD
C
      DIMENSION A(50,8,K)
      COMMON/WORK/E(20),E1(20)
      COMMON/STRENGTH/S0,B1,B2,EP,C,H(21),R(20)
      COMMON/LINK1/D0,D3,SL,UL,NWRO,NUMINT,STRUCT
      EXTERNAL FUNCT
      IF (L.EQ.2) GO TO 10
      IF (L.EQ.3) GO TO 25
      SL=0.
      UL =E(N)
      GO TO 20
   10 UL=0.
      SL=1-(H(N)-H(N+1))/(2.*R(N))
      SL=ATAN (SQRT(1-SL**2)/SL)
   20 FA=FUNCT(SL,L,N,I,A,1)
      FB=FUNCT(UL,L,N,I,A,1)
      NUMINT=ABS ((UL-SL)/0.02)
      KK=MOD(NUMINT,2)
```

```
      NUMINT=NUMINT+KK
      GO TO 27
   25 FA=FUNC1(SL,I,A,K)
      FB=FUNC1(UL,I,A,K)
   27 DELTA=(UL-SL)/NUMINT
      M1=NUMINT-1
      M2=NUMINT-2
C
      FODD=0.
      DO 30 J=1,M1,2
            VALUE=J*DELTA
            F=FUNCT(VALUE,L,N,I,A,K)
            FODD=FODD+F
   30 CONTINUE
C
      FEVEN=0.
      DO 40 J=2,M2,2
            VALUE=J*DELTA
            F=FUNCT(VALUE,L,N,I,A,K)
            FEVEN=FEVEN+F
   40 CONTINUE
C
      AREA=DELTA*(FA+FB+4*FODD+2.*FEVEN)/3.
      STR=AREA/(UL-SL)
      RETURN
      END
      FUNCTION ASINH(X)
      ASINH=ALOG(X+SQRT(X*X+1))
      RETURN
      END
      FUNCTION FUNCT(VALUE,L,N,I,A,K)
      DIMENSION A(50,8,K)
      COMMON/STRENGTH/S0,B1,B2,EP,C,H(21),R(20)
      EXTERNAL FUNC1,FUNC2
      IF (L.EQ.1.OR.L.EQ.3) FUNCT=FUNC1(VALUE,I,A,K)
      IF (L.EQ.2) FUNCT=FUNC2(VALUE,N,I,A,K)
      RETURN
      END
      FUNCTION FUNC1(VALUE,I,A,K)
      DIMENSION A(50,8,K)
      COMMON/STRENGTH/S0,B1,B2,EP,C,H(21),R(20)
      FUN=1.155*(S0+B1*((1-EXP(-C*(VALUE+A(I,5,K))))**0.5))
      FUNC1=FUN
      IF(VALUE+A(I,5,K).LT.0.7*EP) GO TO 10
      FUNC=B2*(1-EXP(-0.49*(((VALUE+A(I,5,K)-0.7*EP)/EP)**1.4)))
      FUNC1=FUN-FUNC
   10 RETURN
      END
      FUNCTION FUNC2(VALUE,N,I,A,K)
      DIMENSION A(50,8,K)
      COMMON/STRENGTH/S0,B1,B2,EP,C,H(21),R(20)
      VAL=ABS(1.155*ALOG(H(N)/(H(N+1)+2.*R(N)*(1-COS(VALUE)))))
      FUN=1.155*(S0+B1*((1-EXP(-C*(VAL+A(I,5,K))))**0.5))
      FUNC2=FUN
      IF (VAL+A(I,5,K).LT.0.7*EP) GO TO 10
      FUNC=B2*(1-EXP(-0.49*(((VAL+A(I,5,K)-0.7*EP)/EP)**1.4)))
```

```
      FUNC2=FUN-FUNC
   10 RETURN
      END
      FINISH
```

Symbols used in tables

Symbol	Basic Meaning	Superscript	Subscript	Meaning
d	grain size		o	original
d	"		rex	recrystallized
ε	equivalent strain		p	strain for the peak stress
$\dot{\varepsilon}$	equivalent strain rate			
k	Avrami time exponent			
Q	activation energy		def	for deformation
Q	"		rex	for recrystallization
σ	equivalent stress		o	at strain equal 0.02
σ	"		0.1	at strain equal 0.1
σ	"		p	at the maximum stress
σ	"		ss	at strain equal 1.5
$\bar{\sigma}'$	mean plane strain strength			
t	time		1, 2 and 3	as defined in figure(7.7)
t	"		50	for 50% material to recrystallize
t	'		gg	for grain growth
T	temperature	mc		measured at the centre
T	"	cc		calculated at the centre
T	"		entry	at the roll gap entry
X, X'	fraction recrystallized			
Z	Zener-Hollomon parameter			

TABLE (2.1)

Strength during hot working of AISI316L steel.

Alloy C/NI/Cr/Mo	Testing Mode	do (μm)	T (C)	σ_{ω} (MPa)	σ_p (MPa)	ε_p	$\dot{\varepsilon}$ (s^{-1})	Qdef (KJ/mol)	Reference
17.2/10.9/0.07/2.92	Torsion	---	1100	151	172	0.60	3.93	460	(1)
				142	162	0.60	0.98		
				92	103	0.40	0.12		
				54	63	0.30	0.08		
			1000	139	232	0.80	3.93		
				139	204	0.60	0.98		
				139	181	0.40	0.12		
				113	124	0.40	0.08		
			900	211	323	0.80	3.93		
				171	288	0.50	0.98		
				135	247	0.45	0.12		
				104	219	0.48	0.08		
			800	287	403	1.10	3.93		
				271	379	0.80	0.98		
				262	339	0.50	0.12		
				241	283	0.40	0.08		
16.9/12.4/0.02/2.76	Torsion	---	1100	70	77	0.49	0.10	410	(2)
			1000	116	129	0.42	0.10		
			900	165	190	0.72	0.10		
				196	223	0.72	1.00		
				220	263	0.84	5.00		
15.8/14.0/0.03/4.30	Axisymmetric	75	1150	112	145	0.28	0.50	---	(3)
		170		117	145	0.57	0.50		
		225		99	145	0.74	0.50		
17.4/12.8/0.55/2.14	Torsion	60	900	176	298	0.75	3.99	499	(4)
				176	283	0.52	1.82		
			1000	115	230	0.75	3.99		
				115	199	0.52	1.82		
				---	184	----	0.19		
			1100	92	161	0.75	3.99		
				92	145	0.58	1.82		
				---	92	----	0.19		
			1200	77	107	0.58	3.99		
				61	84	0.23	1.82		
				23	69	0.29	0.19		
16.7/12.2/0.02/2.63	Axisymmetric	20	1006	148	186	0.52	0.53	---	(5)
				161	209	0.54	1.04		
				170	216	0.55	2.11		
				193	241	0.60	5.17		
				205	---	----	10.8		
				229	277	0.55	21.1		
				255	300	0.60	50.2		
	Plane Strain	19	910	219	295	0.37	5.30		
				248	284	0.40	2.14		
				268	271	0.41	1.08		

References:
1- Hughes,1971
2- Ryan et al.,1982
3- Roberts et al.,1979
4- Teodosiu et al.,1979
5- Colàs,1983

TABLE (2.2)

Strength During Hot Working of AISI304

Alloy Cr/NI/C	Testing Mode	d_o (μm)	T (C)	σ_{ss} (MPa)	σ_p (MPa)	ε_p	$\dot{\varepsilon}$ (s^{-1})	Q_{def} (KJ/mol)	Reference
18.2/11.3/0.05	Torsion	160	800	270	330	1.08	1	410	(1)
			850	242	280	0.68	1		
			950	184	210	0.61	1		
			1050	128	148	0.60	1		
			1150	94	108	0.54	1		
			950	185	211	0.67	1		
			950	125	136	0.58	0.02		
			1150	94	116	0.62	1.00		
			950	75	88	0.52	0.0009		
			1150	43	55	0.54	0.024		
			1150	21	28	0.50	0.0008		
18.3/9.3/0.042	Axisymmetric	170	1100	100	128	0.62	0.5	-	(2)
19.6/9.3/0.066	Torsion	24	800	330	326	0.38	0.39	383	(3)
			900	264	268	0.36	2.83		
			900	220	234	0.48	0.39		
			900	214	230	0.50	0.38		
			1000	184	190	0.42	2.87		
			1000	142	152	0.38	0.38		
			1000	122	140	0.42	2.85		
			1105	94	100	0.40	0.39		
18.5/11.4/0.064	Torsion	120	740	232	300	1.34	0.184	424	(4)
			840	186	222	1.0	0.184		
			940	121	153	0.54	0.184		
			1040	82	98	0.50	0.184		
			1140	62	68	0.38	0.184		
			740	153	222	0.79	0.003		
			840	117	147	0.75	0.003		
			940	68	88	0.42	0.003		
			1040	33	49	0.38	0.003		
			1140	16	26	0.17	0.003		
18/8/-	Compression	-	1100	153	216	0.7	100	414	(5)
			1100	138	189	0.6	40		
			1100	99	162	0.55	8		
			1100	92	130	0.45	1.5		
	Torsion	-	1100	92	118	0.6	2.5		
			1100	84	105	0.5	1.1		
			1100	73	94	0.45	0.41		
			1100	57	71	0.35	0.13		
			1100	46	59	0.35	0.065		
			1100	29	40	0.30	0.018		
			1100	17	23	0.25	0.005		
			1100	14	21	0.25	0.002		
			1100	10	15	0.20	0.001		
18.32/9.34/0.042	Axisymmetric	50	1000	94	132	0.5	0.06	396	(6)
			1050	60	94	0.48	0.06		
			1100	44	74	0.40	0.06		
			900	160	262	0.62	0.96		
			1000	122	186	0.67	0.96		
			1050	100	144	0.52	0.96		
			1100	88	120	0.50	0.96		
		400	1000	102	136	0.66	0.06		
			1100	60	80	0.50	0.06		
			1200	46	60	0.33	0.06		
			900	200	270	0.65	0.96		
			1000	140	184	-	0.96		
			1050	110	132	0.64	0.96		
			1100	100	132	0.64	0.96		
			1200	70	90	0.59	0.96		
			1250	60	72	0.45	0.96		

References:
1- Barraclough,1974
2- Roberts et al.,1979
3- Harding,1976
4- Cole,1979
5- Sellars and Tegart,1972
6- Ahlblom,1977

TABLE (3.1)

Static Recrystallization Data on AISI316

Alloy Cr/Ni/C/Mo	Testing Mode	do (μm)	$\dot{\varepsilon}$ (s^{-1})	T (C)	k	Q_{rex} (KJ/mol)	ε	t_{50} (s)	Reference
17.3/12.0/0.052/2.5	Rolling	230	10	900	1.61	525	0.77	2228	(1)
				900	1.55		0.53	4580	
				1000	0.86		0.65	168	
				1100	-		0.61	14	
				1100	-		0.41	14	
				1100	0.87		0.19	61	
		95	10	900	1.18		0.72	560	
				1000	-		0.72	87	
				1000	-		0.42	117	
17.2/13.3/0.022/2.8	Tensile	-	1	1000	-		0.11	18	(2)
				1100	1.44		0.11	5	
				1200	1.44		0.11	4	
17.5/13.2/0.017/2.8	Tensile	-	1	1100	-		0.11	25	
				1200	1.22		0.11	1.3	
16.92/12.42/0.017/2.76	Torsion	-	1.0	1100	-	336	0.2	0.87	(3)
				1000	-		0.2	9.4	
				900	-		0.2	16.0	
17.1/12.1/0.033/2.48	Torsion	300	3.6	1150	1.04	-	0.44	1.6	(4)
				1050	1.18		0.44	12.6	
				1000	1.00		0.44	100	
18.0/14.0/0.03/4.3	Tensile	80	2.0	1000	3.35	-	0.26	19.0	(5)
		80		1100	0.88		0.26	3.0	
				1100	1.71		0.18	13.0	
		120		1150	1.13		0.26	1.8	
				1150	1.72		0.18	4.13	
				1150	2.76		0.10	24.0	
		200		1200	1.53		0.26	0.20	
				1200	1.53		0.18	3.0	
				1200	1.28		0.10	7.5	
		250		1250	1.18		0.18	0.2	
				1250	1.15		0.10	5.6	

References:
1- Towle and Gladman,1979
2- Liljestrand,1972
3- Ryan et al.,1982
4- Lombry et al.,1980
5- Nörstrom,1977

TABLE (3.2)

Static Recrystallization Data on AISI304

Alloy Cr/Ni/C	Testing Mode	do (μm)	$\dot{\varepsilon}$ (s^{-1})	T (C)	k	Q_{rex} (KJ/mol)	ε	t_{50} (s)	Reference
18.7/10.0/0.050	Rolling	180	10	900	2.49	365	0.19	1610	(1)
				900	-		0.77	196	
				900	2.24		0.47	336	
				1000	0.98		0.66	23	
				1000	-		0.36	23	
				1000	-		0.20	609	
				1100	-		0.66	15.2	
				1100	-		0.41	15.2	
				1100	0.93		0.19	35.0	
		100	10	900	-		0.78	31.0	
				900	1.33		0.44	50.0	
				900	-		0.25	16.4	
				1000	-		0.78	31.0	
				1000	-		0.44	23.0	
				1000	-		0.25	42.0	
18.32/9.34/0.042	Axisymmetric	400	0.96	900	0.87		0.17	1720	(2)
			0.96	1000	0.86			100	
			0.96	1200	0.86			3	
			0.96	900	0.90		0.28	666	
			0.96	1000	0.90			49	
			0.96	1100	0.90			15	
			0.96	1200	0.90			3	
			0.06	1000	1.40			115	
			0.96	1000	1.31			49	
			0.06	1100	1.59			13	
			0.96	1100	1.09			11.5	
17.9/7.29/0.079	Tensile and Axisymmetric	548	6.0	1100	1.75	334	0.26	23.0	(3)
			0.0006	1100	1.34		0.26	155.0	
			6.0	1100	1.41		0.20	74.0	
			6.0	1100	1.53		0.15	1000.0	
			0.0006	1100	1.45		0.15	300.0	
		548	0.0006	1100	1.53		0.10	1350	
			6.0	1162	-		0.20	45.0	
			0.06	1162	-		0.26	0.90	
			6.0	1162	-		0.15	111.0	
			0.0006	1162	-		0.26	122.0	
			0.0006	1162	-		0.15	670.0	
			0.0006	1162	-		0.10	2015.0	
			6.0	1162	-		0.05	2721.0	
			6.0	1232	-		0.15	25.0	
			6.0	1232	-		0.10	55	
			6.0	1037	-		0.15	1650	
18.06/9.19/0.09	Rolling	250	20	1100	0.57	351	0.46	12.0	(4)
			20	1000	1.05		0.46	32.0	
			20	900	0.96		0.46	1368.0	
			20	900	1.14		1.39	69.0	
			20	900	0.89		0.80	130.0	
18.2/11.3/0.05	Torsion	160	0.047	950	-	425	0.28	1000	(5)
			0.047	950	-		0.44	353.0	
			0.047	950	-		0.55	181.0	
			0.047	950	-		0.28	305.0	
			1.0	1050	2.0		0.16	262.0	
			1.0	1050	2.0		0.28	35.3	
			1.0	1050	2.0		0.55	9.3	
			1.0	1050	2.0		0.80	5.12	
			1.0	1150	-		0.28	65.0	
		140	1.0	1050	2.35		0.50	6.6	
		230	1.0	1050	1.27		0.50	11.6	
		530	1.0	1050	0.97		0.50	39.5	

TABLE (3.2) cont.

Alloy Cr/Ni/C	Testing Mode	do (μm)	$\dot{\varepsilon}$ (s^{-1})	T (C)	k	Q_{rex} (KJ/mol)	ε	t_{50} (s)	Reference
18.1/9.4/0.05	Torsion	200	3.6	1200	2.15		0.44	1.0	(6)
			3.6	1150	2.26		0.44	1.2	
			3.6	1050	1.73		0.44	6.6	
			3.6	1000	1.50		0.44	27.3	
18.31/8.68/0.069	Torsion		10	900	-	353	0.2	3.06	(7)
			10	1000	-		0.2	1.42	
			10	1100	-		0.2	0.36	

References:
1- Towle and Gladman,1979
2- Ahlblom,1977
3- Campbell et al.,1974
4- Kozasu and Shimizu,1971
5- Barraclough and Sellars,1979
6- Lombry et al.,1980
7- Ryan et al.,1982

TABLE (3.3)

Recrystallized grain size after hot working AISI316

Alloy Cr/Ni/C/Mo	Testing Mode	do (μm)	ε	$\dot{\varepsilon}$ (s^{-1})	T (C)	d_{rex} (μm)	Reference
18.0/14.0/0.03/4.3	Tensile	250	0.26	2.0	1250	116	(1)
			0.18	2.0	1250	132	
			0.09	2.0	1250	180	
		200	0.26	2.0	1200	76	
			0.18	2.0	1200	84	
			0.09	2.0	1200	100	
		80	0.26	2.0	1150	56	
			0.18	2.0	1150	68	
			0.26	2.0	1100	44	
			0.18	2.0	1100	50	
18.7/10.0/0.052/2.50	Rolling	95	0.771	10	900	20	(2)
		230	0.771	10	900	36	

References:
1- Nörstrom,1977
2- Towle and Gladman,1979

TABLE (3.4)

Recrystallized grain size after hot working AISI304

Alloy Cr/Ni/C	Testing Mode	do (μm)	ε	$\dot{\varepsilon}$ (s^{-1})	T (C)	d_{rex} (μm)	Reference
18.7/10.0/0.050	Rolling	180	0.18	10	1100	100	(1)
			0.39	10	1100	73	
			0.64	10	1100	49	
			0.18	10	1000	77	
			0.34	10	1000	62	
			0.64	10	1000	42	
			0.75	10	900	35	
		100	0.24	10	1000	46	
			0.42	10	1000	26	
			0.75	10	1000	24	
			0.24	10	900	38	
			0.42	10	900	29	
			0.75	10	900	20	
17.9/7.29/0.079	Tensile and Axisymmetric	548	0.15	0.0006	1093	370	(2)
			0.26	0.0006	1093	247	
			0.26	0.0006	1162	253	
			0.26	0.06	1162	180	
			0.10	6	1232	260	
			0.15	6	1232	213	
			0.20	6	1232	153	
			0.05	6	1162	373	
			0.10	6	1162	247	
			0.15	6	1162	200	
			0.20	6	1162	133	
			0.26	6	1162	80	
			0.10	6	1093	227	
			0.15	6	1093	166	
			0.20	6	1093	120	
			0.26	6	1093	80	

TABLE (3.4) cont.

Alloy Cr/Ni/C	Testing Mode	do (μm)	ε	$\dot{\varepsilon}$ (s^{-1})	T (C)	d_{rex} (μm)	Reference
18.3/9.34/0.042	Axisymmetric	400	0.66	0.96	1000	46	(3)
			0.28	0.96	1000	75	
			0.17	0.96	1000	83	
			0.66	0.96	1100	36	
			0.28	0.96	1100	60	
			0.17	0.96	1100	73	
			0.66	0.96	1200	25	
			0.28	0.96	1200	39	
			0.17	0.96	1200	55	
18.2/11.3/0.05	Torsion	160	0.25	1.0	950	48	(4)
			0.51	0.05	950	37	
			0.39	0.05	950	46	
			0.26	0.05	950	63	
			0.15	1.0	1150	108	
			0.28	1.0	1150	59	

References:
1- Towle and Gladman,1979
2- Campbell et al.,1974
3- Ahlblom,1977
4- Barraclough and Sellars,1979

TABLE (5.1)

Chemical Compositions of the steel employed

Element	Weight, %	Accuracy	Method
C	0.024	*	*
Cr	16.70	± 0.02	Quantometer
Ni	12.20	"	"
Mo	2.63	"	"
Mn	1.50	"	"
Si	0.29	"	"
N	390 ppm	±10ppm	Chemical

* C was analysed using a Leco equipment model CS244 Carbon Sulphur analyser giving an accuracy of ±0.001%.

TABLE (6.1)

Stress-strain data for samples tested in plane strain compression with an original grain size 100μm.

Test Number	T (C)	$\dot{\varepsilon}$ (s^{-1})	Z (s^{-1})	ε_p	σ_p (MPa)	σ_0 (MPa)	$\sigma_{0.1}$ (MPa)	σ_{ss} (MPa)
R37	950	5.24	2.25×10^{20}	0.33	245	190	227	185
R38	950	5.24	2.28×10^{20}	0.45	245	190	228	196
R39	950	5.22	2.24×10^{20}	0.45	251	176	220	198
R41	950	5.18	2.22×10^{20}	0.38	245	183	222	-
R45	950	5.22	2.24×10^{20}	0.38	245	175	217	-
R81	955	2.89	9.60×10^{19}	0.45	237	154	212	198
R82	955	0.50	1.58×10^{19}	0.41	206	144	186	183
R83	955	0.05	0.53×10^{18}	0.37	168	107	155	153
R3	1025	1.00	4.11×10^{18}	0.36	192	150	180	160
R11	1025	5.28	1.67×10^{19}	0.38	224	165	206	182
R12	1025	5.16	1.63×10^{19}	0.38	221	167	205	170
R47	1025	5.23	1.64×10^{19}	0.39	200	-	182	-
R115	1025	5.00	1.58×10^{19}	0.35	206	162	189	180
R116	1025	5.00	1.58×10^{19}	0.35	208	170	195	182
R117	1025	5.00	1.58×10^{19}	0.44	200	157	184	189
R120	1025	5.00	1.58×10^{19}	0.38	206	160	186	166
R121	1025	5.42	1.71×10^{19}	0.41	208	156	185	175
R122	1025	5.31	1.67×10^{19}	0.41	214	161	189	-
R84	1025	0.05	$1.92\text{X}10^{17}$	0.36	128	103	114	112
R85	1025	0.50	1.75×10^{18}	0.37	166	131	151	145
R88	1025	5.37	2.01×10^{19}	0.43	207	153	188	174
R27	1100	6.78	2.80×10^{18}	0.38	177	138	160	-
R30	1100	5.00	1.54×10^{18}	0.40	174	133	158	-
R32	1100	1.00	3.08×10^{17}	0.38	152	100	135	115

Symbols:
σ_0 = Stress at strain equal to 0.02
σ_{ss} = Stress at strain equal to 1.50
Other symbols have their usual meaning.

TABLE (6.2)

Dependence of maximum stress and strain to peak stress on the original grain size.

Test Number	d_o (μm)	$\dot{\varepsilon}$ (s^{-1})	T (C)	Z (s^{-1})	σ_p (MPa)	ε_p
RF2	64±4	5.04	950	2.17×10^{20}	250	0.42
R38	104±8	5.24	950	2.28×10^{20}	245	0.45
R89	278±18	5.00	950	2.15×10^{20}	240	-
R85	104±8	0.54	1025	1.70×10^{18}	166	0.37
R98	278±18	0.55	1025	1.73×10^{18}	164	0.37
R84	104±8	0.05	1025	1.48×10^{17}	128	0.36
R99	278±18	0.05	1025	1.58×10^{17}	132	-
R88	104±8	6.15	1025	1.94×10^{19}	207	0.43

TABLE (6.3)

Static Recrystallization Data for Samples Deformed in Plane Strain Compression at 950 C with Original Grain Size 260 μm.

Test Number	ε	$\bar{\varepsilon}$	time (s)	T (C)	X (%)	Log[ln[1/(1-X)]]	X' (%)
R101-1	0.21	0.21	147	954	22±2	-0.61	
R101-2	0.21		600	954	33±3	-0.39	
R101-3	0.21		3600	954	47±3	-0.20	
R71	0.28	0.28	60	950	30±4	-0.45	
R71-1	0.28		240	958	36±3	-0.34	
R71-2	0.28		480	954	41±3	-0.28	
R52	0.30		2640	954	54±3	-0.11	
R79-1	0.42	0.42	60	954	34±3	-0.38	
R78	0.43		120	958	41±3	-0.28	
R55	0.39		280	947	49±4	-0.17	
R56	0.41		420	947	50±3	-0.16	
R79-2	0.42		780	954	50±4	-0.16	
R57	0.85	0.86	4	950	33±3	-0.40	
R58	0.86		8	950	44±3	-0.24	
R59	0.87		12	950	50±4	-0.16	
57-1	0.85		43	954	59±3	-0.05	
R103	1.54	1.52	1.0	958	0.0	-	24±1
R91	1.50		6.0	958	41	-0.27	69±4
R100	1.52		40.0	958	75	0.14	81±2

TABLE (6.4)

Static Recrystallization Data for Samples Deformed in Plane Strain Compression at 1025 C with Original Grain Size 260 μm.

Test Number	ε	$\bar{\varepsilon}$	time (s)	T (C)	X (%)	Log[ln[1/(1-X)]]	X' (%)
R106-1	0.26	0.26	139	1026	26±4	-0.52	
R106-2	0.26		900	1026	64±4	0.02	
R106-3	0.26		3600	1026	77±3	0.17	
R104	0.55	0.51	2	1024	17±2	-0.74	
R63	0.51		100	1025	70±3	0.08	
R64	0.50		210	1025	82±3	0.24	
R65	0.48		300	1025	87±2	0.32	
R66	0.97	0.97	3	1025	33±3	-0.40	
R67	0.94		6	1025	47±4	-0.19	
R68	0.99		9	1025	61±4	0.03	
R95	1.73	1.72	0.0	1024	0.0	-	61±4
R94	1.70		2.0	1024	35	-0.36	75±2

TABLE (6.5)

Static Recrystallization Data for Samples Deformed in Plane Strain Compression at 950 C with Original Grain Size 100 μm.

Test Number	ε	$\bar{\varepsilon}$	time (s)	T (C)	X (%)	Log[ln[1/(1-X)]]	X' (%)
R46	0.39	0.36	10	947	11±2	-0.94	
R40	0.34		35	949	24±3	-0.56	
R33	0.35		70	949	34±3	-0.38	
R34	0.34		175	949	50±3	-0.16	
R41	0.79	0.79	1.0	949	16±2	-0.76	
R35	0.80		2.0	949	18±2	-0.70	
R36	0.77		3.0	949	22±2	-0.60	
R39	1.79	1.79	1.0	949	0.0	-	55±3
R37	1.79		2.0	949	15	-0.79	62±4
R38	1.79		3.0	949	27	-0.49	67±3
R37-2	1.79		11	949	33	-0.39	70±3
R39-2	1.79		23	949	60	-0.04	82±3
R39-1	1.79		102	949	84	0.27	93±2

TABLE (6.6)

Static Recrystallization Data for Samples Deformed in Plane Strain Compression at 1025 C with Original Grain Size 100 μm.

Test Number	ε	$\bar{\varepsilon}$	time (s)	T (C)	X (%)	Log[ln[1/(1-X)]]	X' (%)
R124	0.33	0.30	20	1025	29±4	-0.47	
R19	0.31		60	1021	36±3	-0.34	
R20	0.31		120	1021	59±4	-0.04	
R21	0.29		220	1021	69±3	0.08	
R123	0.35	0.37	5	1021	24±3	-0.57	
R18	0.38		24	1021	42±4	-0.26	
R76	0.51	0.47	2	1021	23±3	-0.58	
R16	0.45		6	1021	31±3	-0.43	
R47	0.48		10	1025	48±4	-0.19	
R17	0.45		13	1021	46±4	-0.21	
R13	0.94	0.99	0.0	1021	0.0	-	44±2
R15	0.96		1.5	1021	24	-0.55	58±3
R122	1.07		6.0	1025	57	-0.08	76±3
R121	1.50	1.52	0.0	1025	0.0	-	73±3
R120	1.55		1.0	1025	27	-0.50	78±2
R118	1.50		5.0	1025	49	-0.17	87±2

TABLE (6.7)

Static Recrystallization Data for Samples Deformed in Plane Strain Compression at 1100 C with Original Grain Size 100 μm.

Test Number	ε	$\bar{\varepsilon}$	time (s)	T (C)	X (%)	Log[ln[1/(1-X)]]
R302	0.18	0.19	10	1100	28±4	-0.48
R170	0.18		80	1100	54±3	-0.11
R171	0.20		95	1100	56±4	-0.09
R172	0.20		140	1100	59±3	-0.05
R156	0.39	0.39	8	1090	48±4	-0.18
R28	0.36		17	1090	73±2	0.11
R157	0.41		18	1090	68±3	0.06
R158	0.39		28	1090	70±3	0.08
R23	0.36		42	1090	84±3	0.27
R304	0.50	0.51	1.0	1100	28±3	-0.47
R24	0.51		5.0	1090	51±3	-0.06
R155	0.48		5.0	1090	63±3	0.02
R25	0.54		6.5	1100	69±3	0.06
R305	0.50		10	1100	81±4	0.22
R29	0.70	0.73	4.0	1090	63±3	0.01
R167	0.76		9.0	1090	80±3	0.21
R255	1.14	1.14	2.0	1100	49±4	-0.17
R257	1.14		4.0	1100	76±3	0.15
R256	1.12		9.0	1100	94±2	0.44

TABLE (6.8)

Static Recrystallization Data for Samples Hot rolled at 950 C with Original Grain Size 191 μm.

Sample Number	ε	time (s)	T (C)	X (%)	Log[ln[1/(1-X)]]
HR61-1	0.22	720	950	29±2	-0.52
HR61-2	0.22	1800	950	36±2	-0.35
HR61-3	0.22	3420	950	54±2	-0.11
HR61-4	0.22	5460	950	68±2	0.06
HR64	0.35	900	950	61±2	-0.03
HR63-1	0.43	180	950	37±2	-0.33
HR63-2	0.43	300	950	48±3	-0.19
HR63-3	0.43	420	950	55±3	-0.010
HR63-4	0.43	720	950	78±3	0.18
HR62	0.53	900	950	90±3	0.36

TABLE (6.9)

Static Recrystallization Data for Samples Deformed in Axisymmetric Compression at 1025 C with Origin Grain Size 100 μm

Test Number	ε	$\bar{\varepsilon}$	time (s)	T (C)	X (%)	Log[ln[1/(1-X)]]	X' (%)
A6	0.14	0.14	127	1025	21±2	-0.63	
A7	0.14		330	1025	36±2	-0.35	
A8	0.15		720	1025	53±3	-0.12	
A9	0.15		1560	1025	64±3	0.00	
A2	0.25	0.24	60	1025	27±2	-0.50	
A3	0.25		130	1025	42±3	-0.26	
A4	0.22		270	1025	52±3	-0.13	
A32	0.49	0.49	1	1022	21±2	-0.63	
A28	0.50		5	1022	72±3	0.10	
A31	0.48		17	1022	91±2	0.38	
A38	0.97	0.98	0.0	1022	0.0	-	44±2
A37	0.99		1.0	1022	18	-0.71	54±2
A35	0.95		3.0	1022	34	-0.38	65±3
A34	0.99		5.0	1022	59	-0.05	82±3
A33	1.00		17.0	1022	77	0.45	94±2

TABLE (6.10)

Time for 50% of Material to Recrystallize Statically

Test Type	d_o (μm)	T (C)	ε	t_{50} (s)
Plane Strain	260	950	0.21	4926
			0.28	2177
			0.42	500
			0.86	16
			1.52	16
		1025	0.26	608
			0.57	44
			0.97	8
			1.72	8
	100	950	0.36	165
			0.79	22
			1.79	22
		1025	0.30	94
			0.37	38
			0.47	16
			0.99	7
			1.52	7
		1100	0.19	70
			0.39	8
			0.51	3
			0.73	2.4
			1.14	2.0
Axisymmetric	100	1025	0.14	800
			0.24	230
			0.49	7.0
			0.98	7.0
Rolling	100	950	0.22	3062
			0.35	600
			0.43	317
			0.53	200

TABLE (6.11)

Recrystallized Grain Size for Samples Tested in Plane Strain Compression and Hot Rolled

Sample Number	Test Type	d_o (μm)	T (C)	ε	drex (μm)
R52	Plane Strain	260	950	0.30	73±7
R56				0.42	49±5
R59				0.87	26±3
R100				1.52	23±2
R101	Plane Strain	100	950	0.21	72±7
R34				0.36	43±4
R37				0.79	24±2
R36				1.79	25±2
R106	Plane Strain	260	1025	0.26	105±7
R65				0.48	60±6
R68				0.99	35±4
R93				1.72	32±2
R135	Plane Strain	100	1025	0.36	66±3
R16				0.45	54±4
R76				0.51	46±4
R14				0.95	31±3
R10				2.30	32±2
R158	Plane Strain	100	1100	0.39	72±7
R305				0.50	55±5
R29				0.70	46±5
R26				1.02	47±5
R86				2.41	53±5
HR61	Rolling	191	956	0.22	62±4
HR62			954	0.35	49±3
HR63			946	0.43	41±3
HR64			948	0.53	32±3

TABLE (6.12)

Isothermal Grain Growth of AISI316L

Sample Number	T (C)	ε	$\bar{\varepsilon}$	t_{gg} (s)	d (μm)
R135	1024	0.36	0.39	78	61± 4
R136	1024	0.39		118	64± 4
R138	1024	0.43		138	62± 4
R137	1024	0.39		158	65± 6
R167	1100	0.76	0.77	0	44±3
R168	1100	0.73		10	49±3
R169	1100	0.79		51	56±4
R253	1100	0.80		171	71±5

TABLE (7.1)

Fraction Recrystallized at Lines of Constant Strain

Test Number	ε	Delay Time (s)	L (mm)	a (mm)	T/A	X (%)		
						$\varepsilon < 0.3$	0.3-0.4	$\varepsilon > 0.4$
R19	0.31	60	105	45	0.40	11±1	43±2	73±4
R20	0.31	120	110	40	0.47	20±2	59±3	-
R21	0.29	220	105	45	0.40	34±2	80±3	-
R124	0.33	20	105	45	0.40	-	17±1	45±3

TABLE (7.2)

Restoration Kinetics of Samples Tested in Plane Strain Compression with Original Grain Size 100μm

Test Number	T (C)	ε	Delay Time (s)	σ_2 (MPa)	σ_1 (MPa)	σ_3 (MPa)	R (%)
R184	1033	0.33	1.0	215	130	212	4
R183			5.0	213	135	185	36
R185			10.0	205	118	155	57
R186			25.0	205	125	148	71
R182			70.0	220	132	145	85
R189	1033	0.90	1.0	210	110	175	35
R187			2.0	205	108	165	41
R193	960	0.29	20	243	148	225	19
R195			60	243	145	180	64
R194			175	238	145	165	78

TABLE (8.1)

First pass hot rolling strength of AISI316L

Sample number	ε	$\dot{\varepsilon}$ (s^{-1})	T_{entry}^{mc} (C)	$\overline{T}$ (C)	Log10 Z	$\overline{\sigma}'$ (MPa)
P1	0.33	3.22	1098	1036	18.85	207
P2	"	"	1098	1049	18.67	208
P4	"	"	1084	1039	18.81	199
P25	"	"	1136	1089	18.14	194
R14	"	"	1030	1005	19.29	220
R15	"	"	1091	1063	18.48	199
R21	"	"	1086	1044	18.74	205
R22	"	"	1064	1016	19.14	206
R29	"	"	1082	1037	18.84	209
R30	"	"	1082	1037	18.84	200
R31	"	"	1082	1037	18.84	198
R71	"	"	1136	1087	18.16	174
R83	"	"	NR	-	-	NR
R86	"	"	990	970	19.83	229
R87	"	"	1058	1023	19.04	192
R88	"	"	890	870	21.52	280
R90	"	"	NR	-	-	NR
P5	"	"	1084	1039	18.81	192
R13	0.37	3.41	1221	1187	16.98	151
R65	0.35	3.33	1098	1056	18.59	211
R66	0.37	3.33	1148	1099	18.02	166
R69	0.35	3.34	1124	1076	18.32	178
R80	0.35	3.33	1130	1079	18.29	168
R81-1	0.34	3.25	952	920	20.64	270
R82-1	0.34	3.24	908	887	21.21	277
R84-1	0.33	3.22	850	834	22.20	299
R85-1	0.33	3.21	798	788	23.14	314
R81-2	0.33	3.71	850	841	22.12	303
R82-2	0.32	3.67	802	800	22.94	323
R84-2	0.33	3.68	754	756	23.90	334
R85-2	0.33	3.71	882	872	21.54	286
R81-3	0.30	4.05	836	820	22.58	300
R82-3	0.34	4.31	802	800	23.01	331
R84-3	0.33	4.29	726	726	24.67	349
R85-3	0.32	4.23	692	708	25.10	276

TABLE (8.2)

Second pass hot rolling strength of AISI316L

Sample number	ε	$\dot{\varepsilon}$ (s^{-1})	T_{entry}^{mc} (C)	$\bar{T}$ (C)	Log10 Z	$\bar{\sigma}'$ (MPa)
P1	0.33	3.72	992	963	19.99	283
P2	"	"	1004	978	19.79	272
P4	"	"	1004	978	19.76	248
P25	"	"	1056	1015	19.22	243
R14*	"	"	956	926	20.60	284
R15	"	"	992	967	19.93	255
R21	"	"	992	958	20.08	264
R22	"	"	1006	973	19.84	259
R29	"	"	1006	973	19.84	260
R30	"	"	992	961	20.02	265
R31	"	"	992	963	19.99	245
R71	"	"	1044	1004	19.37	232
R83	"	"	822	807	22.80	300
R86*	"	"	848	831	22.32	342
R87	"	"	870	854	21.88	285
R88*	"	"	840	818	22.58	344
R90*	"	"	750	752	23.99	371

* Unrecrystallized sample
Others are partially recrystallized samples.

TABLE (8.3)

Third pass hot rolling strength of AISI316L

Sample number	ε	$\dot{\varepsilon}$ (s^{-1})	T_{entry}^{mc} (C)	$\overline{T}$ (C)	Log10 Z	$\overline{\sigma}'$ (MPa)
P1	0.36	4.46	916	870	21.66	365
P2	0.36	4.52	916	895	21.21	333
P4	0.38	4.64	912	903	21.08	303
R14	0.33	4.26	878	858	21.86	372
R15	0.33	4.26	904	856	21.89	350
R21	0.35	4.44	878	883	21.42	369
R29	0.36	4.46	916	897	21.17	310
R30	0.36	4.46	904	887	21.35	334
R31	0.36	4.46	904	873	21.60	334
R71	0.36	4.46	946	919	20.79	310
R83	0.30	4.05	744	748	24.13	425
R86	0.29	3.96	688	700	25.27	490
R87	0.32	4.19	754	768	23.69	445
R88	0.31	4.10	798	804	22.91	412
R90	0.32	4.16	685	680	25.81	454

TABLE (8.4)

Microstructural Evolution Simulation of Hot Rolled Samples. Samples were deformed in a single 25% reduction pass.

Hot Rolling Data					Theoretical Data			
Sample	d_o (μm)	X (%)	$\bar{d}$ (μm)	T_{entry}^{mc} (C)	X (%)	$\bar{d}$ (μm)	T_{entry}^{cc} (C)	$\bar{T}$ (C)
R4	100±10	31±2	72±7	1156	34	78	1156	1115
R9		43±3	74±7	1150	48	72	1155	1112
R12		21±2	90±9	1160	7	93	1156	1113
R13		71±3	87±9	1218	100	84	1221	1187
R65	107±9	44±3	49±5	1096	60	68	1100	1064
R66		83±3	53±5	1148	83	72	1144	1100
R67		7±1	83±8	1030	12	77	1027	995
R68		31±2	78±8	1056	12	79	1050	1018
R69		69±3	52±5	1118	59	71	1177	1081
R80	113±7	40±2	55±6	1130	21	85	1134	1097
R104	200±20	0	200±20	1010	0.29	187	1000	979
R105		0	200±20	1036	0.54	183	1032	1009
R107		0	200±20	904	0.15	188	913	900
R113		46±2	130±13	1150	34	122	1159	1132
R114		16±2	144±14	1107	23	119	1098	1070
R115		0	200±20	1004	0.56	181	1002	983
R116		1.4±0.2	200±20	1057	1.63	169	1043	1020
R117		5.0±0.5	187±19	1076	2.67	163	1064	1039
R119	100±10	82±4	56±6	1176	88	86	1180	1151
R120		3.0±0.3	100±10	1044	5.4	84	1064	1029
R121		17±1	88±9	1062	9.7	82	1084	1059
R122		77±3	74±7	1170	8.2	81	1168	1135
R128		44±2	61±6	1134	76	78	1135	1118
R129		43±2	68±7	1118	31	77	1127	1100
R130		27±2	68±7	1108	22	77	1105	1077

TABLE (8.5)

Microstructural Evolution Simulation of Hot Rolled Samples. Samples were deformed in two passes of 25% reduction each.

Hot Rolling Data					Theoretical Data			
Sample	d_o (μm)	X (%)	$\bar{d}$ (μm)	T_{entry}^{mc} (C)	X (%)	$\bar{d}$ (μm)	T_{entry}^{cc} (C)	$\bar{T}$ (C)
R3	110±11	9±1	63±6	1058	10	57	1052	1015
R5		51±3	31±3	1044	57	36	1060	1015
R8		38±3	30±3	*NR	52	34	1077	1040
R11		43±3	33±3	1058	59	39	1060	1015
R79	113±7	47±3	35±4	1028	50	39	1035	994
R125	100±10	39±3	45±5	1064	54	38	1057	1023
R126		54±3	39±4	1166	49	51	1167	1129
R127		31±3	40±4	1092	57	43	1098	1063
R131	200±10	19±1	94±9	1084	11	90	1089	1054

NR= Not Recorded

TABLE (8.6)

Microstructural Evolution Simulation of Hot Rolled Samples. Samples were deformed in three passes of 25% reduction each.

Hot Rolling Data					Theoretical Data			
Sample	d_o (μm)	X (%)	$\bar{d}$ (μm)	T_{entry}^{mc} (C)	X (%)	$\bar{d}$ (μm)	T_{entry}^{cc} (C)	$\bar{T}$ (C)
R1	100±10	18±2	26±3	992	27	27	994	957
R2		29±2	29±3	1012	43	26	1002	963
R6		18±2	26±3	936	16	29	939	904
R10		26±2	23±3	966	18	26	962	925
R16		6±2	22±2	866	4	30	884	858
R20		17±2	34±3	992	33	24	983	946
R71	113±7	14±2	25±3	946	15	27	957	925

TABLE (9.1)

Hot Rolling Simulation Using Plane Strain Compression Tests. Samples were deformed in a single 25% reduction pass.

Hot Rolling					Plane Strain	
Sample	d_o (μm)	$\bar{T}$ (C)	$\bar{d}$ (μm)	X (%)	$\bar{d}$ (μm)	X (%)
R113	200	1132	130	46	128	33
R114		1070	144	16	150	12
R115		983	200	0	200	0
R116		1020	200	2	180	6
R117		1039	187	5	175	8
R4	100	1115	72	31	65	45
R9		1112	74	43	65	45
R119		1151	56	82	65	62
R120		1029	100	3	88	8
R121		1059	88	17	72	18
R122		1135	74	77	65	55
R118		1118	61	44	65	47
R129		1100	68	43	66	38
R130		1071	68	27	69	25

TABLE (9.2)

Hot Rolling Simulation Using Plane Strain Compression Tests. Samples were deformed in a two 25% reduction pass schedule.

Rolling				Plane Strain		
Sample	d_o (μm)	$\bar{T}$ (C)	$\bar{d}$ (μm)	X (%)	$\bar{d}$ (μm)	X (%)
R5	100	1015	31	51	45	30
R8		1040	30	38	40	36
R11		1015	33	43	45	30
R79		994	35	47	51	25
R125		1023	45	39	42	31
R126		1129	39	54	38	58
R127		1063	40	31	39	41

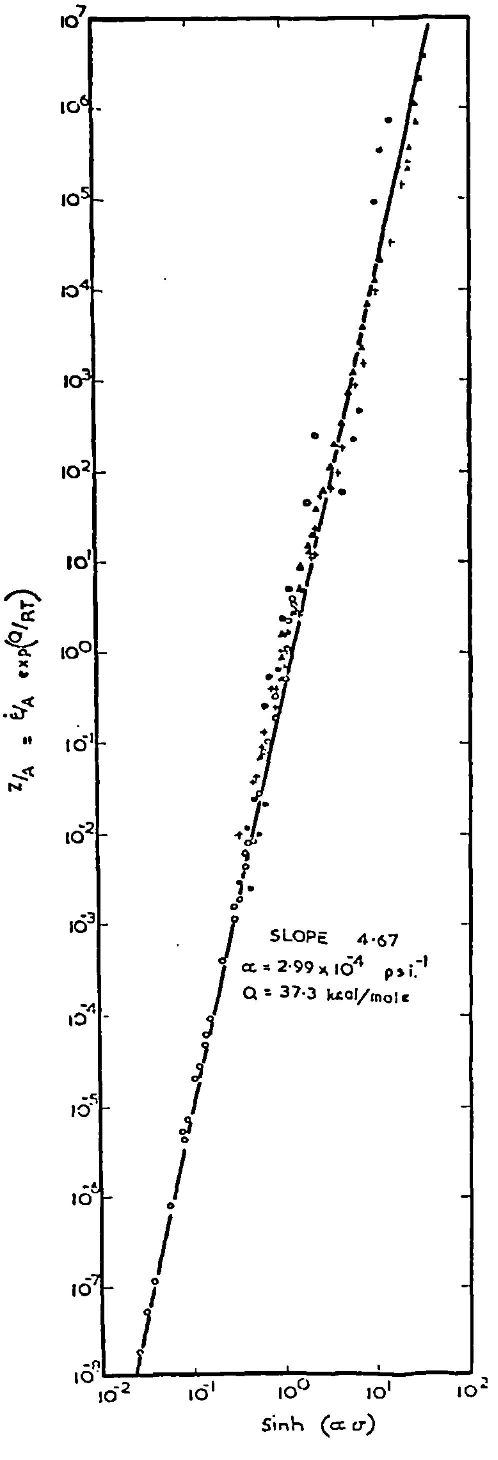


Figure 2.1: Linear relationship between log Z/A and log[sinh($\alpha\sigma$)] illustrating the validity of equation(2.3) for aluminium. The effect of purity differences between the experimental materials has been normalized by using Z/A in place of Z. (After Wong and Jonas.).

+ Extrusion 320-610 C(IS 99.73%Al)
▲ Compression 250-550 C(2S 99.2%Al)
● Torsion 195-550 C(super-purity Al)
○ Creep 204-593 C(SP 99.9945% Al)
(After Jonas et al., 1969).

FIGURE 2.2 : Computational procedure for the stress-strain curve. The lower broken curve is subtracted from the upper one to predict the solid line. The dotted line is experimental for the condition of interest. (After Leduc,1980).

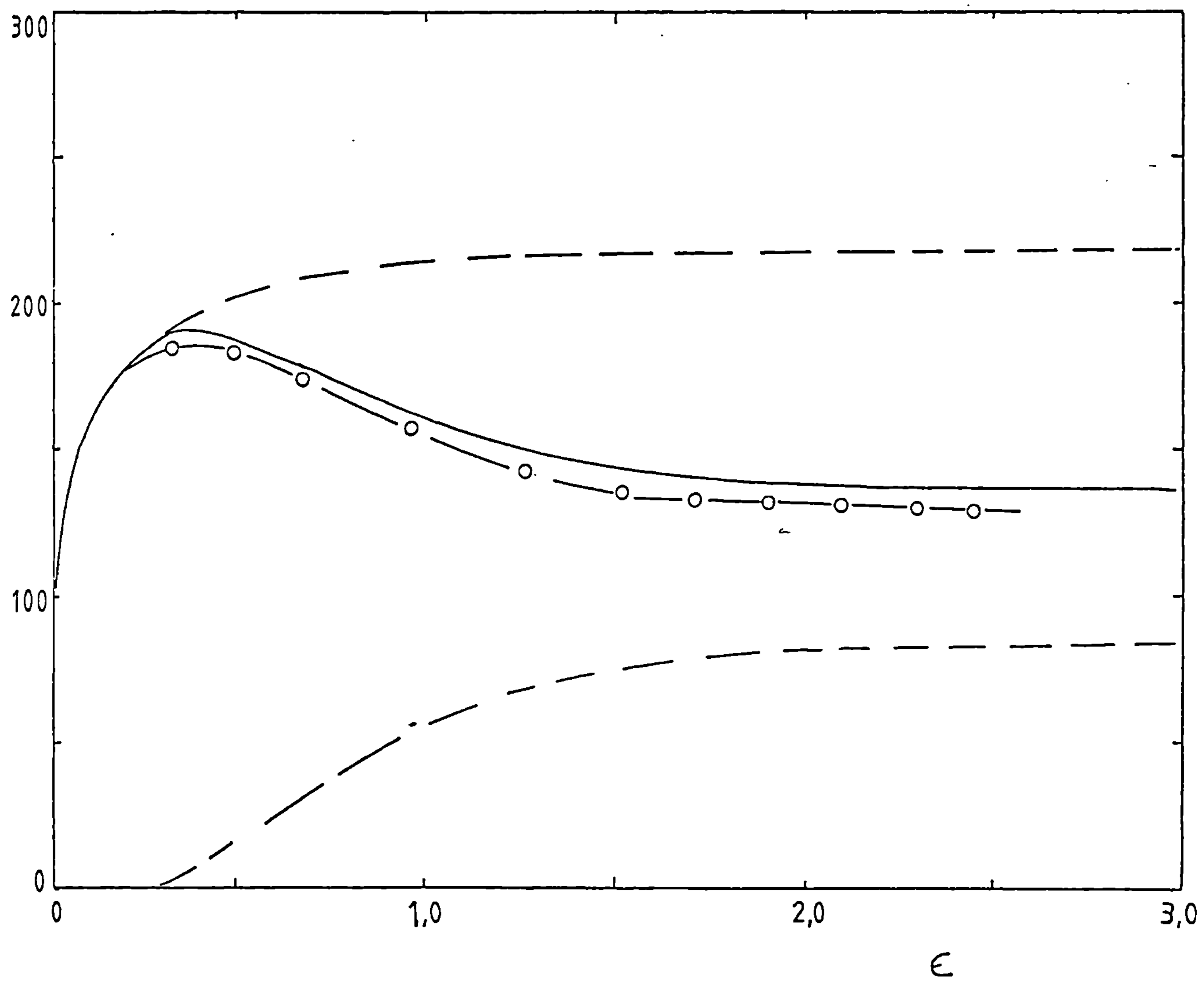

300
200
100
0
σ (N/mm²)
0
1,0
2,0
3,0
ϵ

FIGURE 2.6 : The effect of the Zener-Hollomon parameter on the stress to 0.1 strain for 304 type steel. Symbols are the same as in figure(2.5).

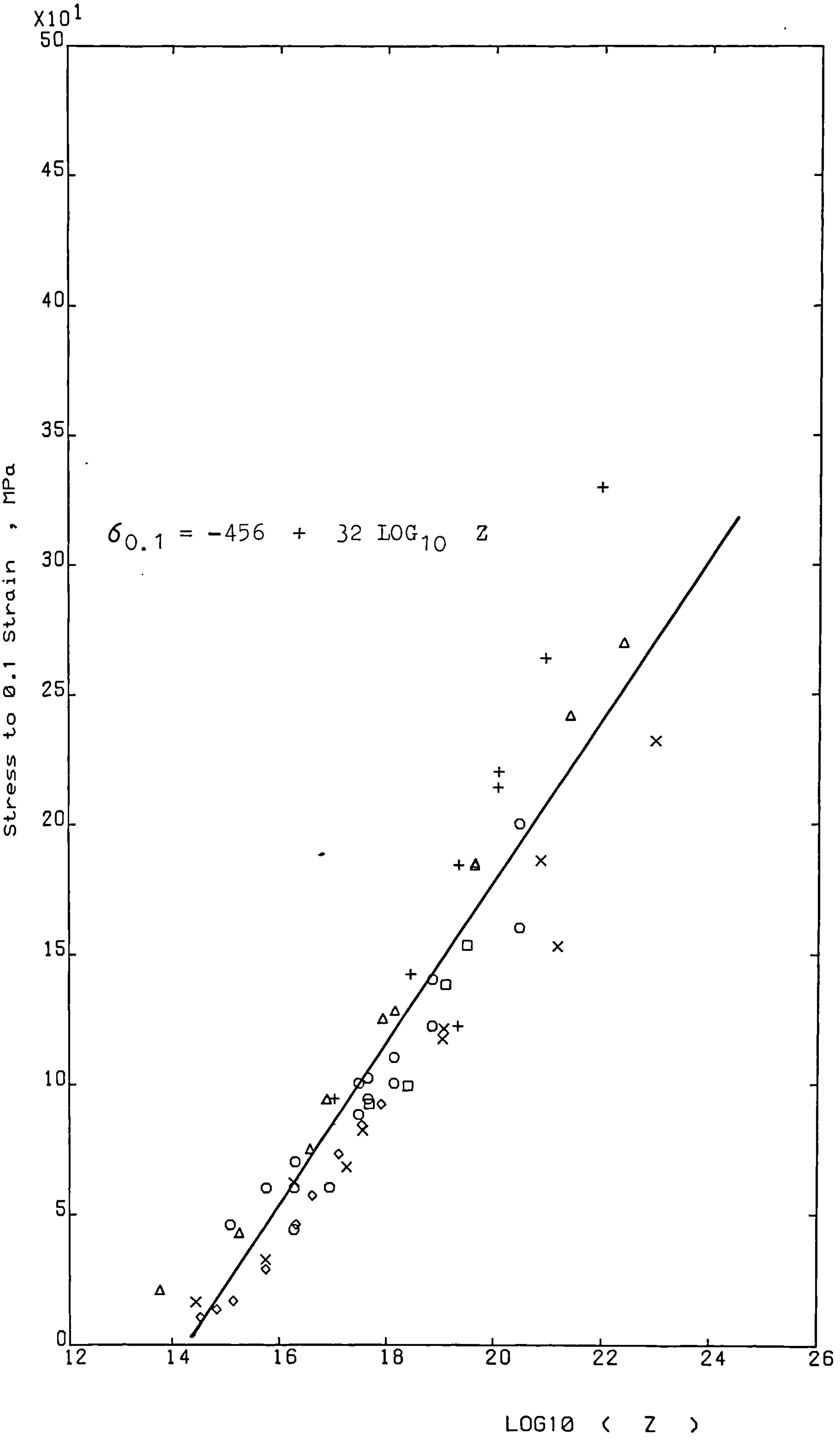
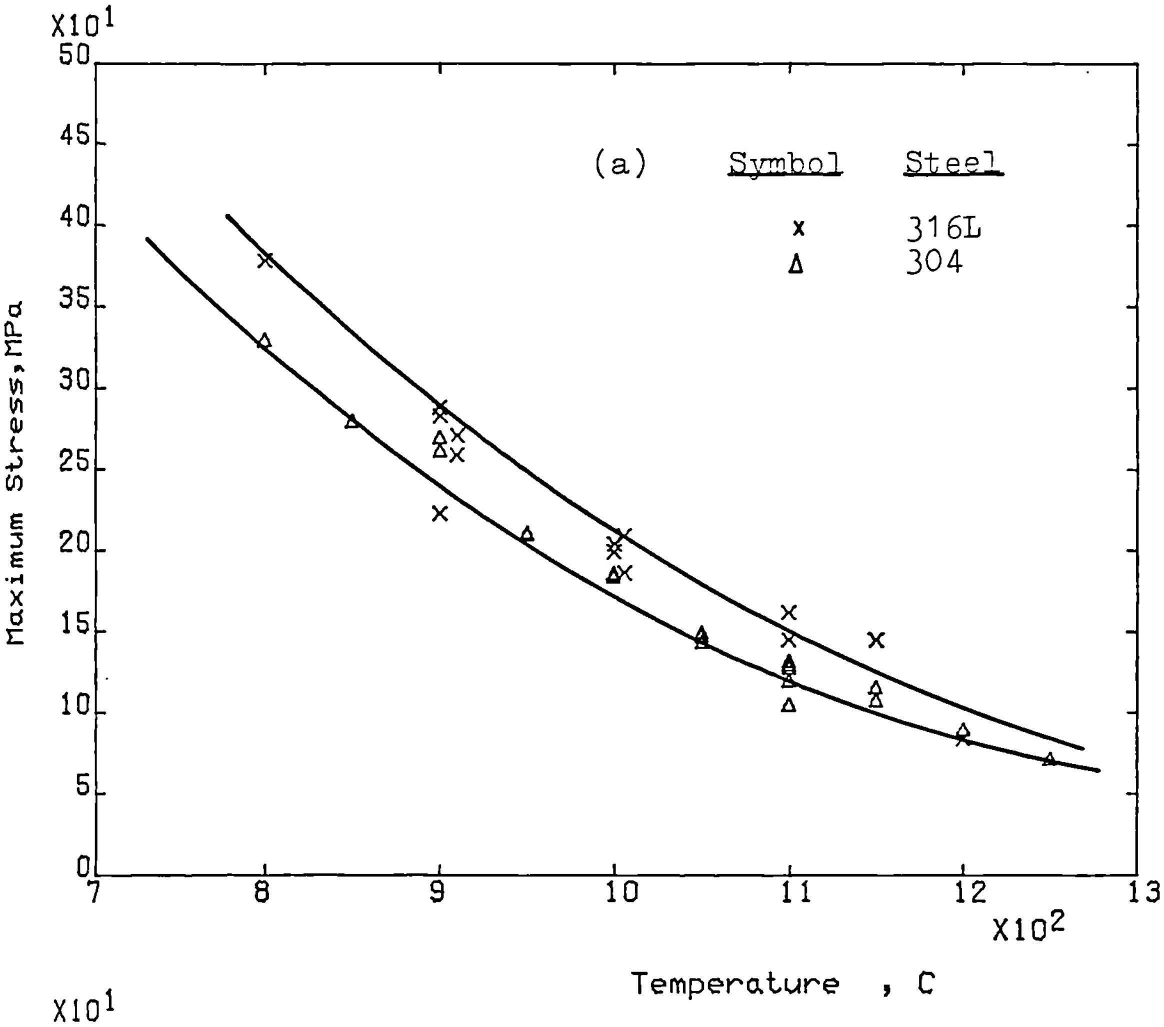

X10^1
50
45
40
35
30
25
20
15
10
5
0
Stress to 0.1 Strain , MPa
$\sigma_{0.1} = -456 + 32 \log_{10} Z$
12
14
16
18
20
22
24
26
LOG10 (Z)

FIGURE 2.7 : Comparison between AISI316 and AISI304 hot rolling strengths.

a- maximum stress

b- stress at strain equal 0.1

Samples were assumed to be worked at constant strain rate.


X10^1
50
45
40
35
30
25
20
15
10
5
0
7
8
9
10
11
12
13
X10^2
Temperature , C
Maximum Stress,MPa
(a)
Symbol
Steel
x 316L
Δ 304

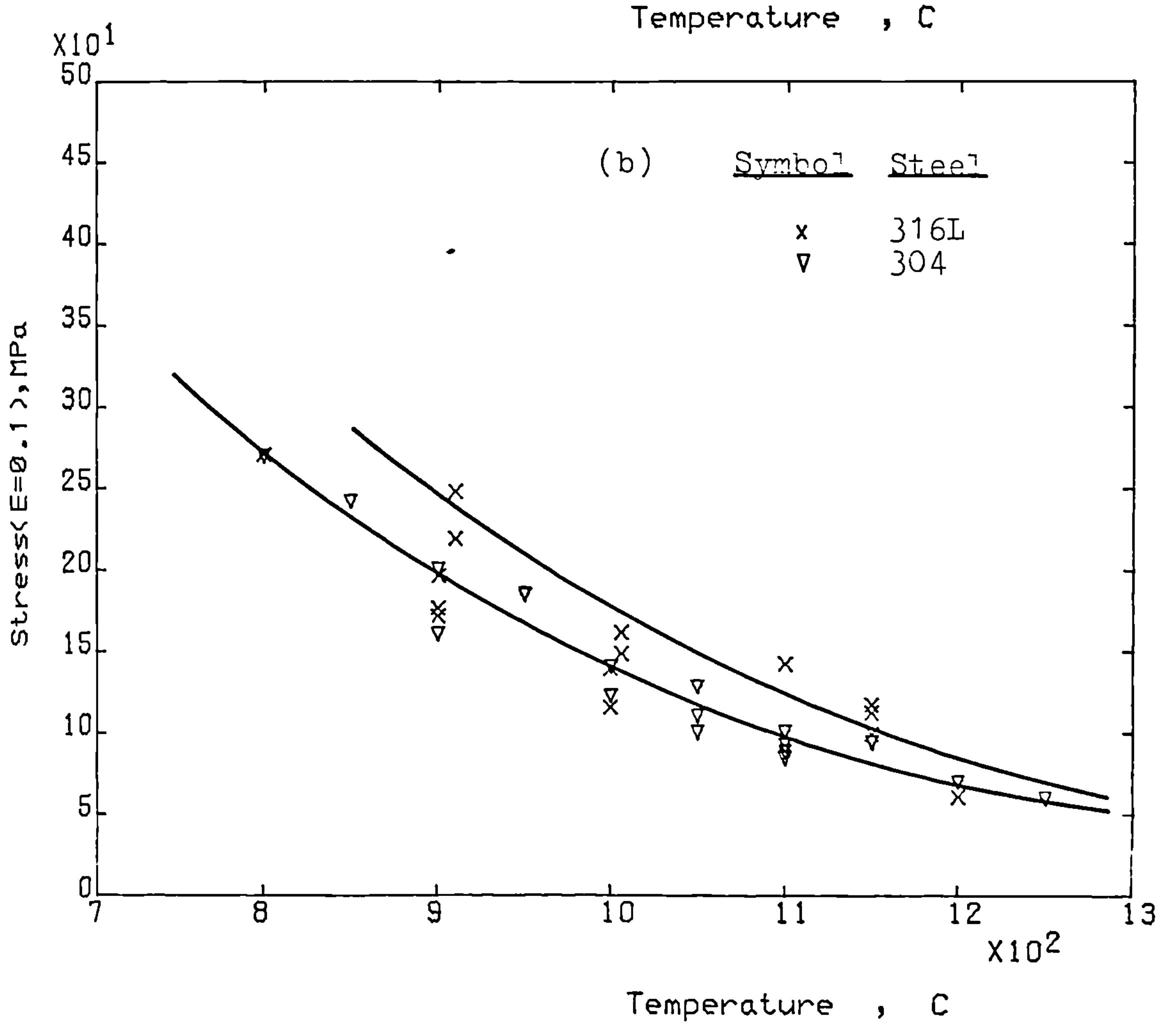
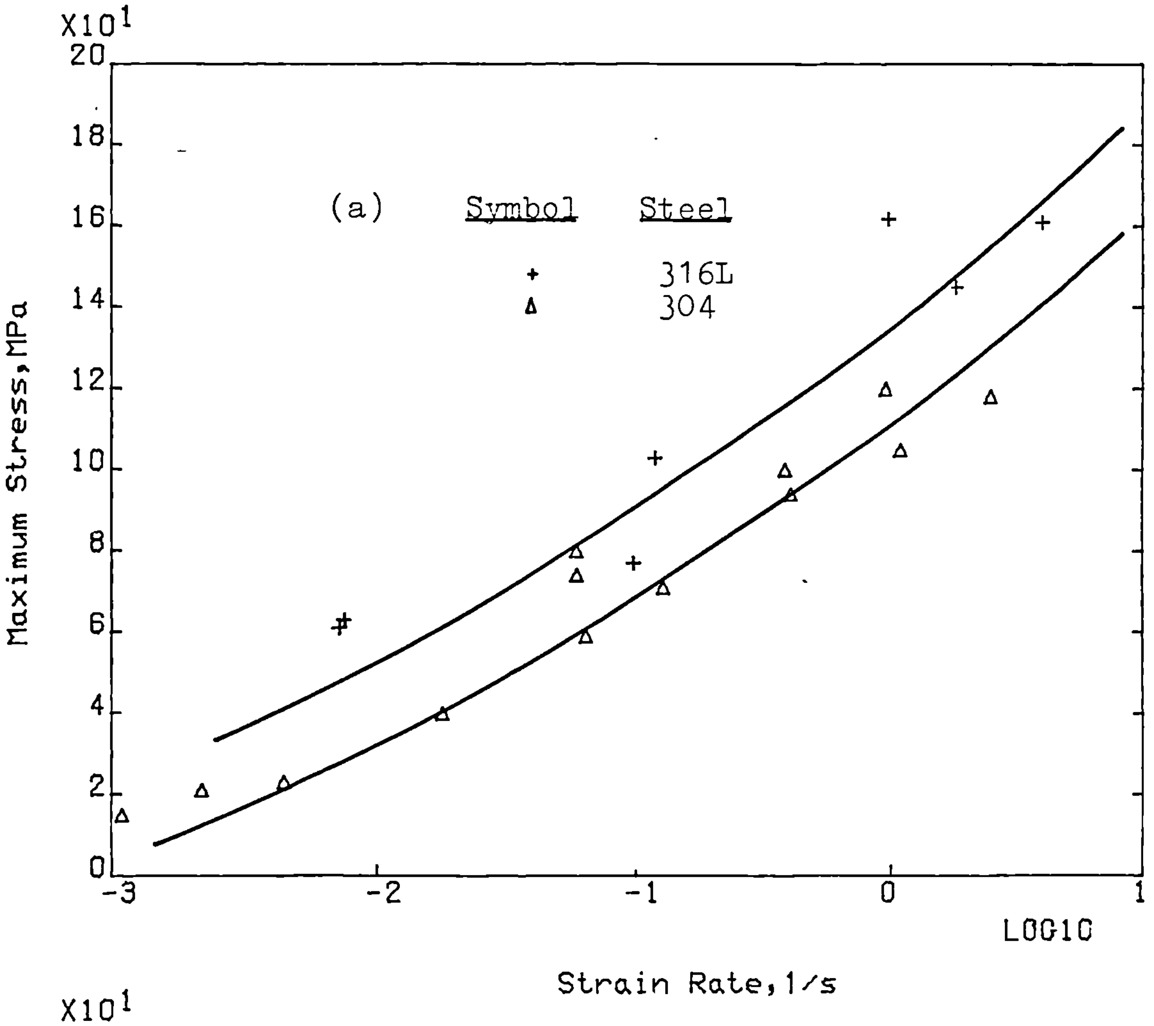

X10^1
50
45
40
35
30
25
20
15
10
5
0
7
8
9
10
11
12
13
X10^2
Temperature , C
Stress(E=0.1),MPa
(b)
Symbol
Steel
x 316L
∇ 304

FIGURE 2.8 : Comparison between AISI316 and AISI304 hot rolling strengths.

a- maximum stress

b- stress at strain equal 0.1

Samples were assumed to be worked at 1100 C and several strain rates.


X10^1
20
18
16
14
12
10
8
6
4
2
0
Maximum Stress,MPa
(a)
Symbol
Steel
+
316L
Δ
304
-3
-2
-1
0
1
LOG10
Strain Rate,1/s

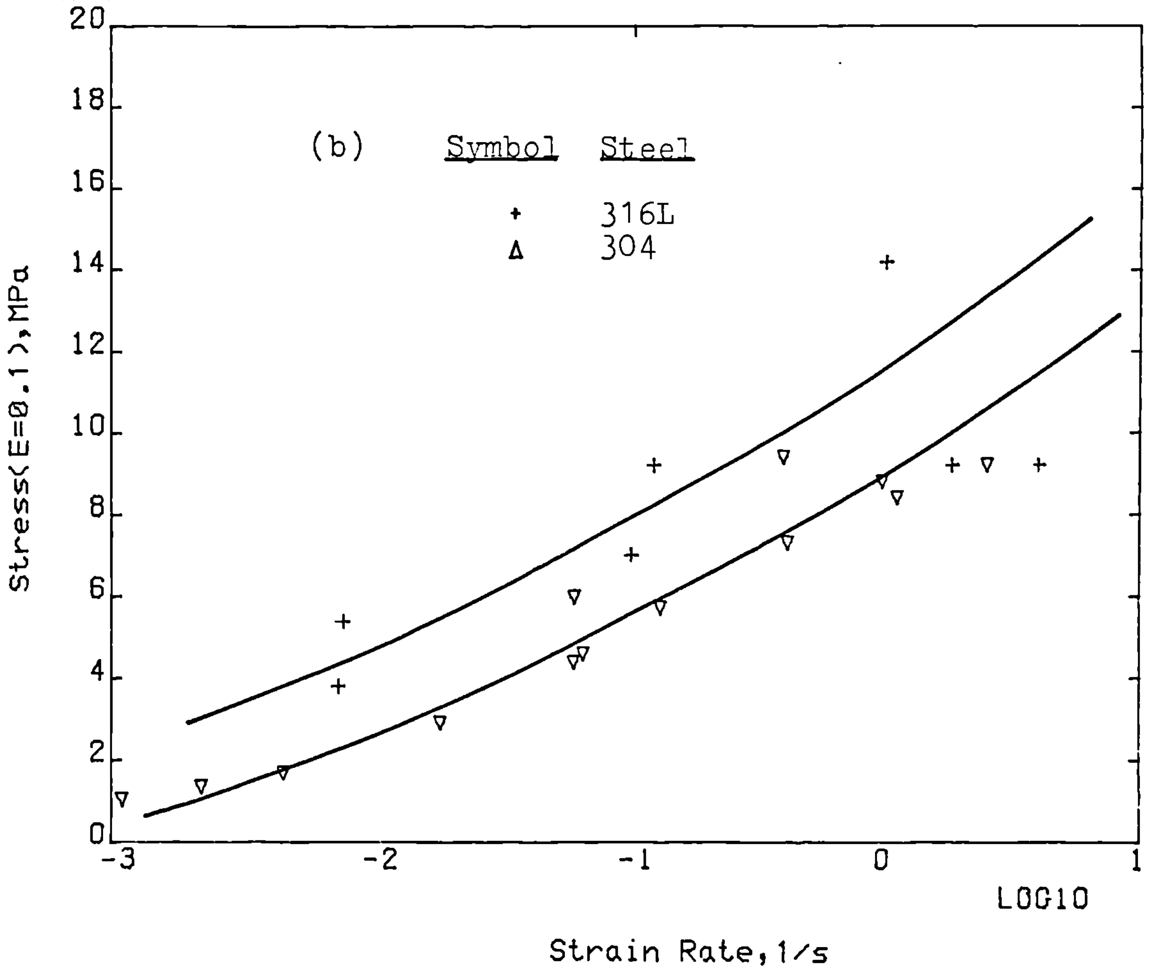
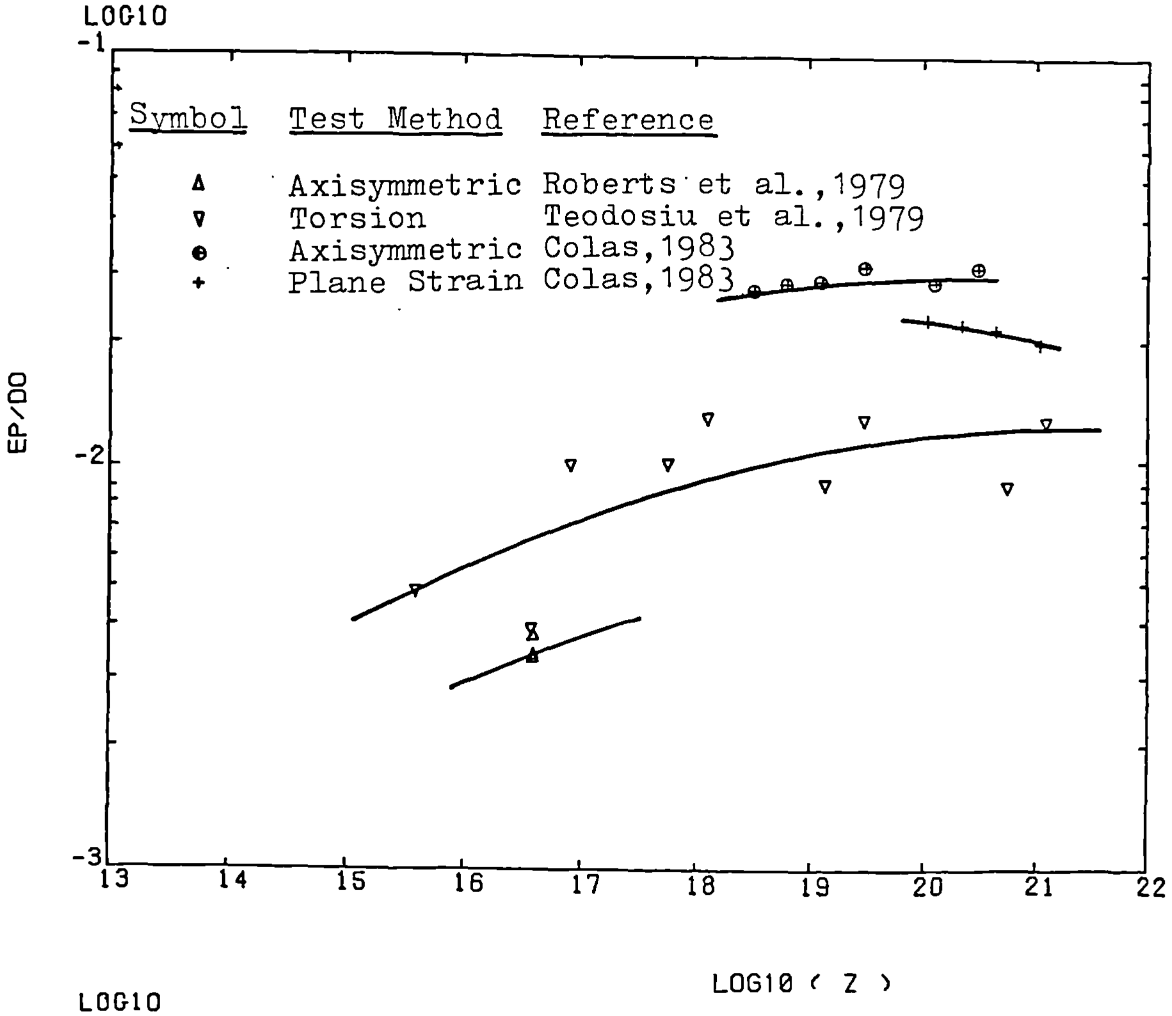
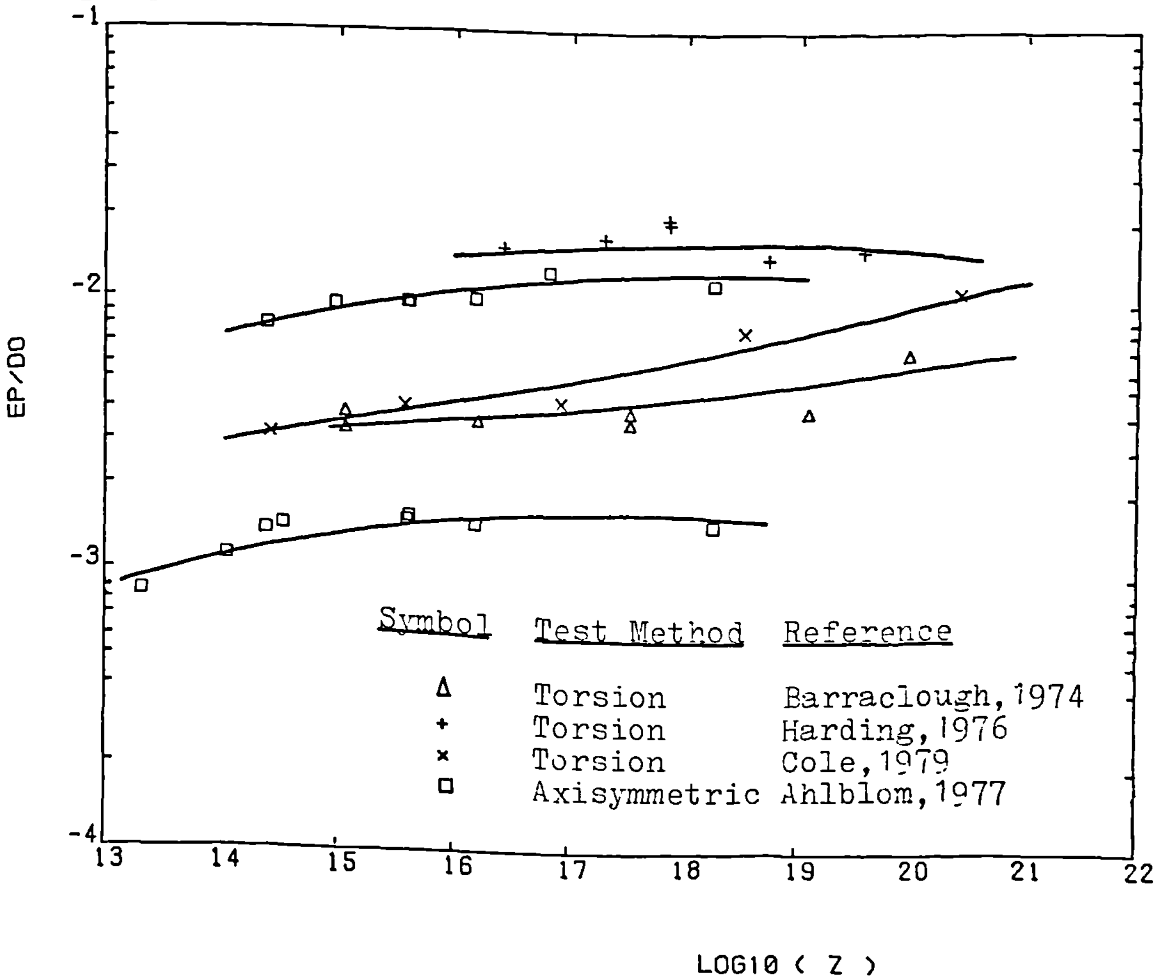

X10^1
20
18
16
14
12
10
8
6
4
2
0
Stress(E=0.1),MPa
(b)
Symbol
Steel
+
316L
Δ
304
-3
-2
-1
0
1
LOG10
Strain Rate,1/s

FIGURE 2.9 : The dependence of the strain to the peak stress on the Zener-Hollomon parameter for AISI316 type steel.

FIGURE 2.10 : The dependence of the strain to peak stress on the Zener-Hollomon parameter for AISI304 steel.


LOG10
-1
-2
-3
EP/DO
13
14
15
16
17
18
19
20
21
22
LOG10 (Z)
Symbol Test Method Reference
▲ Axisymmetric Roberts et al.,1979
▽ Torsion Teodosiu et al.,1979
⊕ Axisymmetric Colas,1983
+ Plane Strain Colas,1983


LOG10
-1
-2
-3
-4
EP/DO
13
14
15
16
17
18
19
20
21
22
LOG10 (Z)
Symbol Test Method Reference
Δ Torsion Barraclough,1974
+ Torsion Harding,1976
× Torsion Cole,1979
□ Axisymmetric Ahlblom,1977

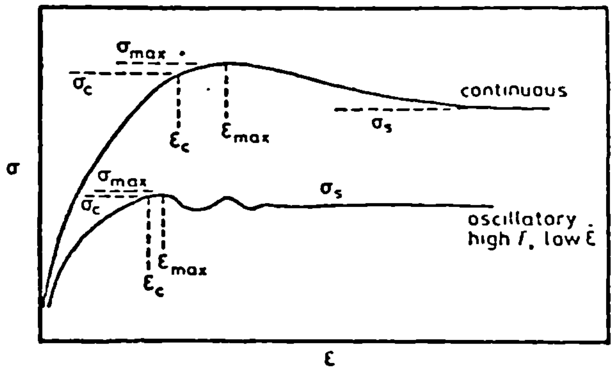


Figure 3.1: High temperature stress-strain curves for materials undergoing dynamic recrystallization (schematic). (After Roberts et al., 1979).

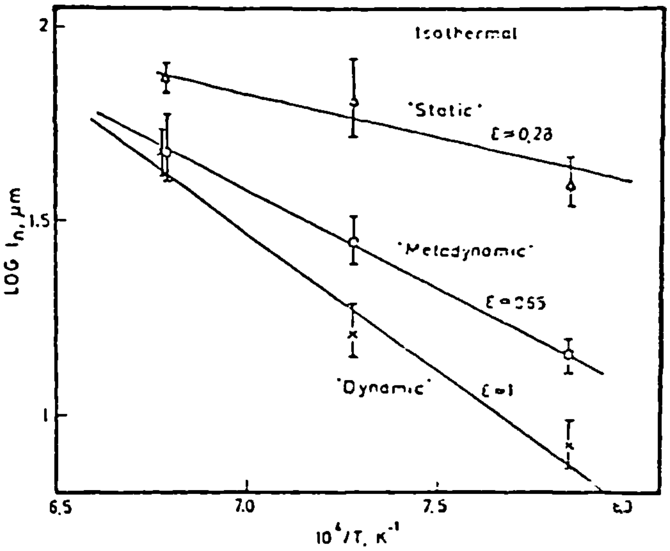


Figure 3.2: Linear intercept grain size in Type 304 steel due to dynamic recrystallization (ε = 1 ± 0.05) compared with that produced by recrystallization after straining to ε = 0.28 ± 0.02 (static) and ε = 0.65 ± 0.03 (metadynamic). (After Ahlblom, 1977. Figure reproduced from Ahlblom and Roberts, 1978).

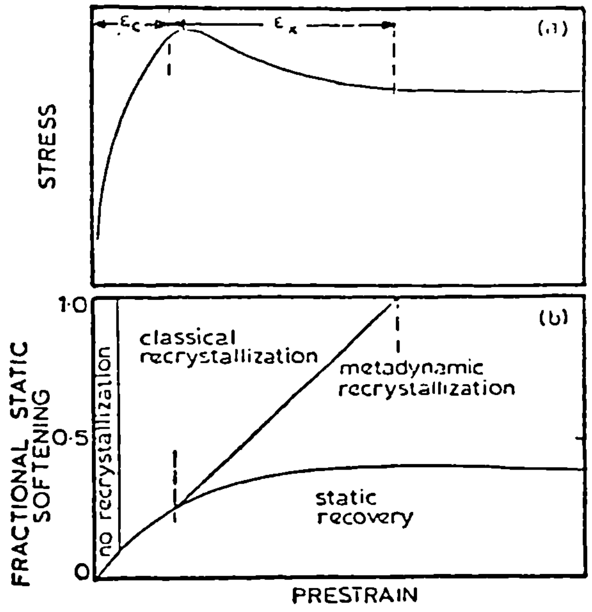


Figure 3.3: Schematic representation of (a) relationship between stress/strain behaviour during deformation and (b) mechanisms of static softening that take place after deformation.
(Reproduced from Sellars and Whiteman, 1979).

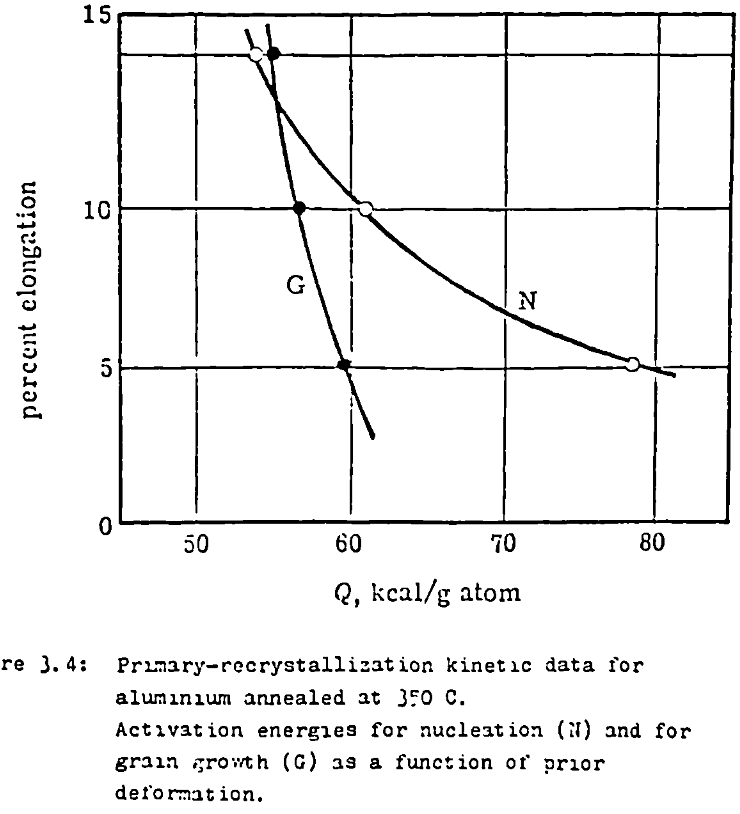


Figure 3.4: Primary-recrystallization kinetic data for aluminium annealed at 350 C.
Activation energies for nucleation (N) and for grain growth (G) as a function of prior deformation.
(After Cotterill and Mould, 1976).

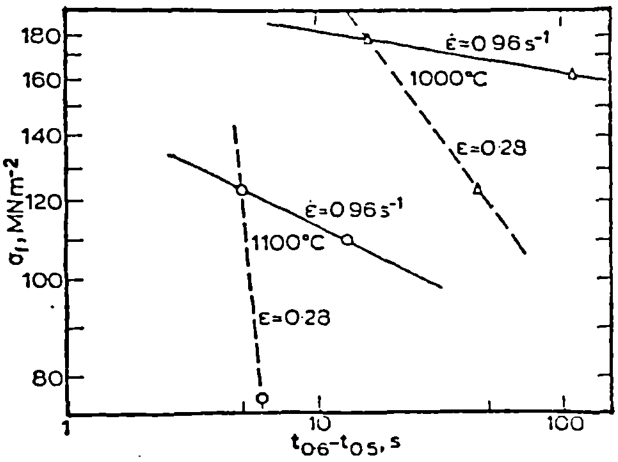


Figure 3.5: Double logarithmic plot showing relationship between finishing stress σ_f and recrystallization rate $(t_{0.6}-t_{0.4})$ for a constant strain rate (solid curve) and for a constant strain (broken curve). (Reproduced from Ahlblom and Sandstrom, 1982).

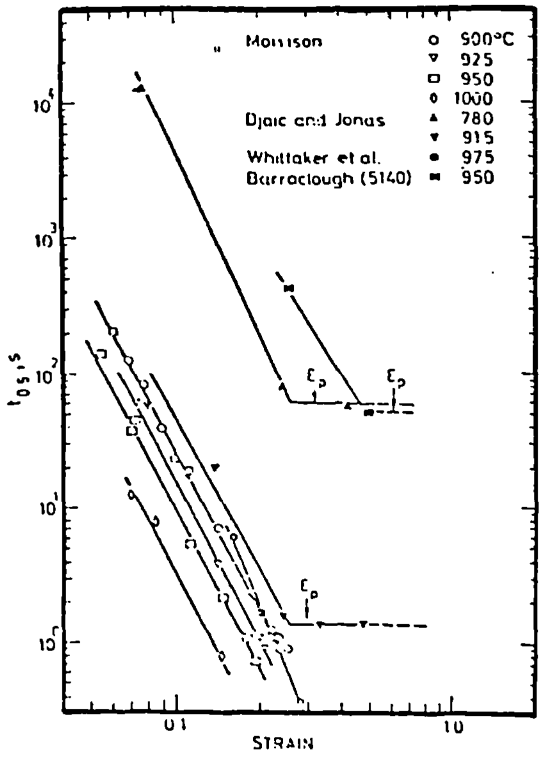
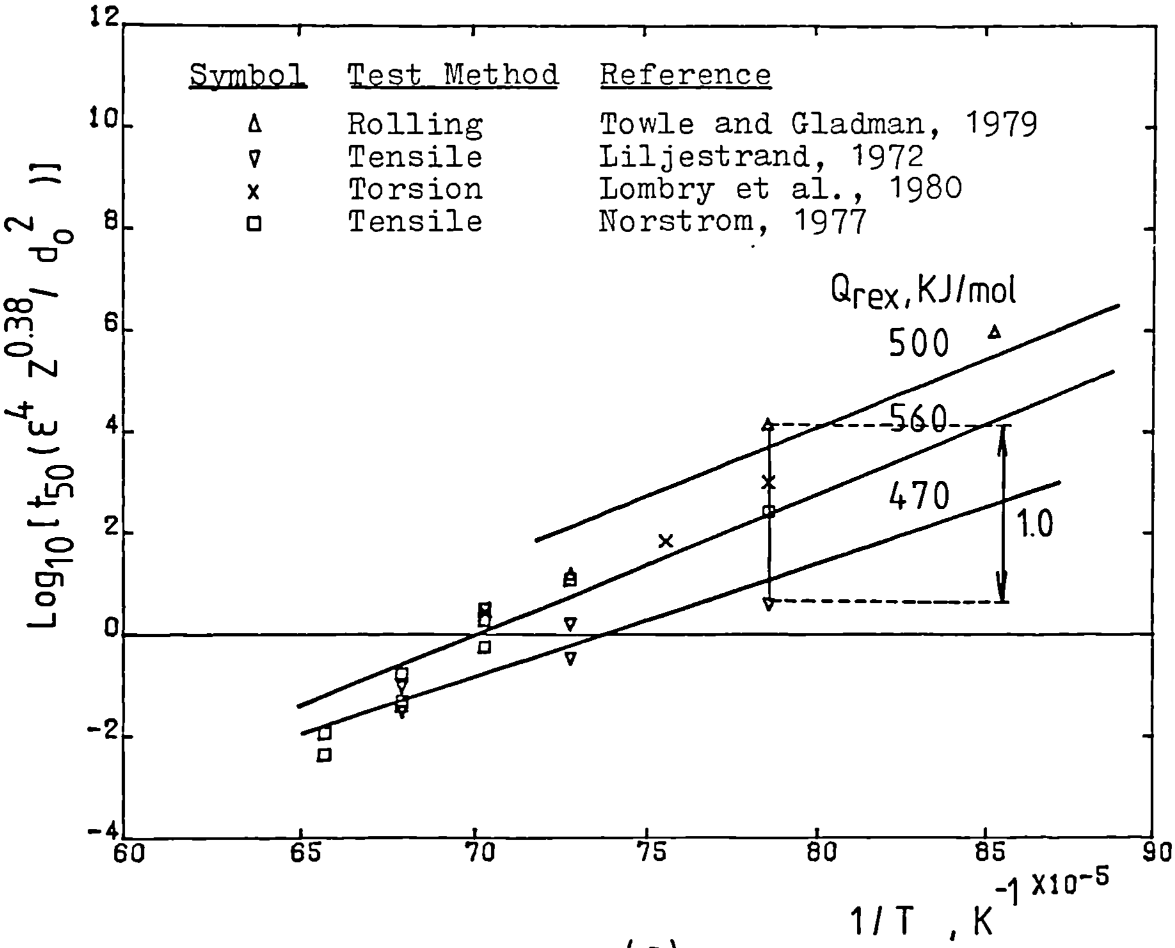
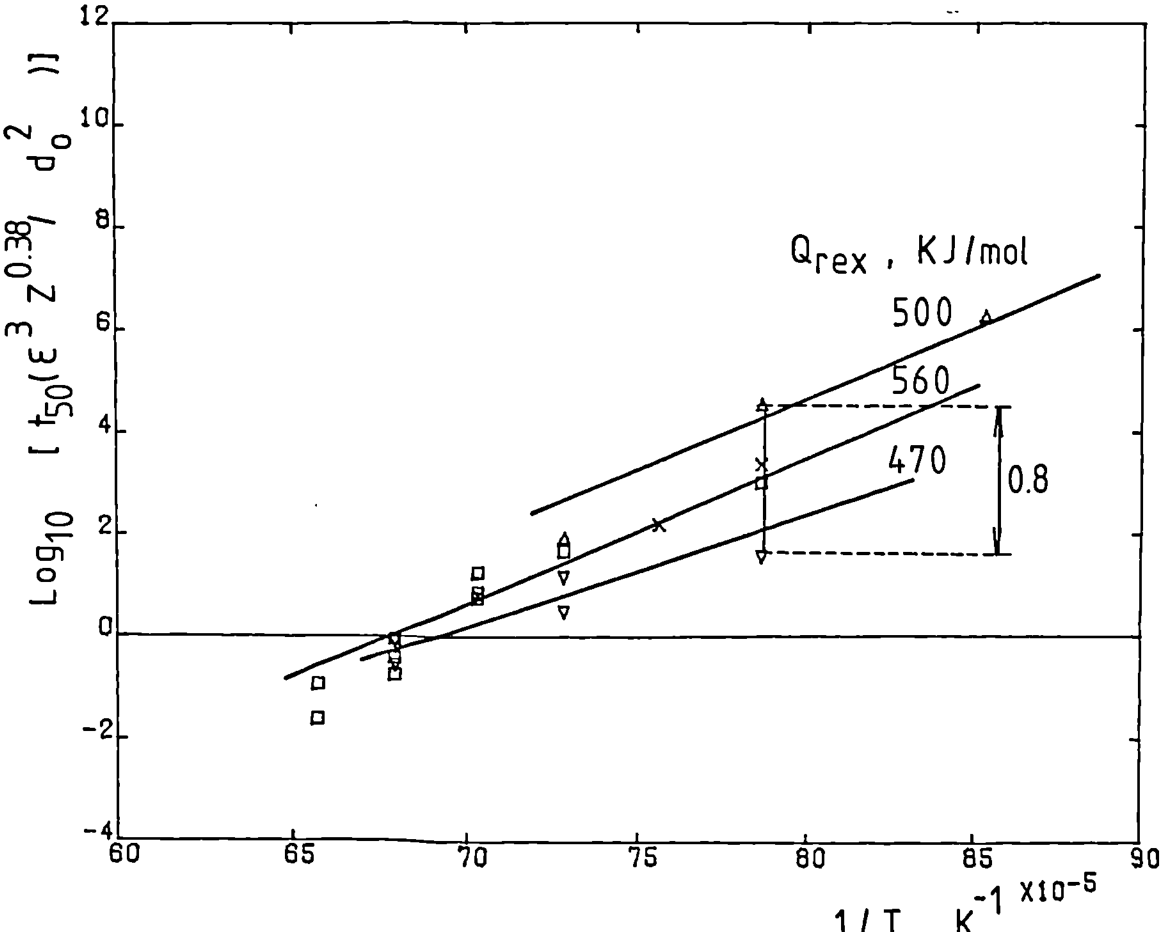


Figure 3.6: Dependence of time for 50% recrystallization or restoration on strain for C-Mn and low alloy steels.
(After Sellars, 1980)

FIGURE 3.7 : Correlation between time for 50% fraction recrystallized and the inverse of absolute temperature for AISI316 steel.

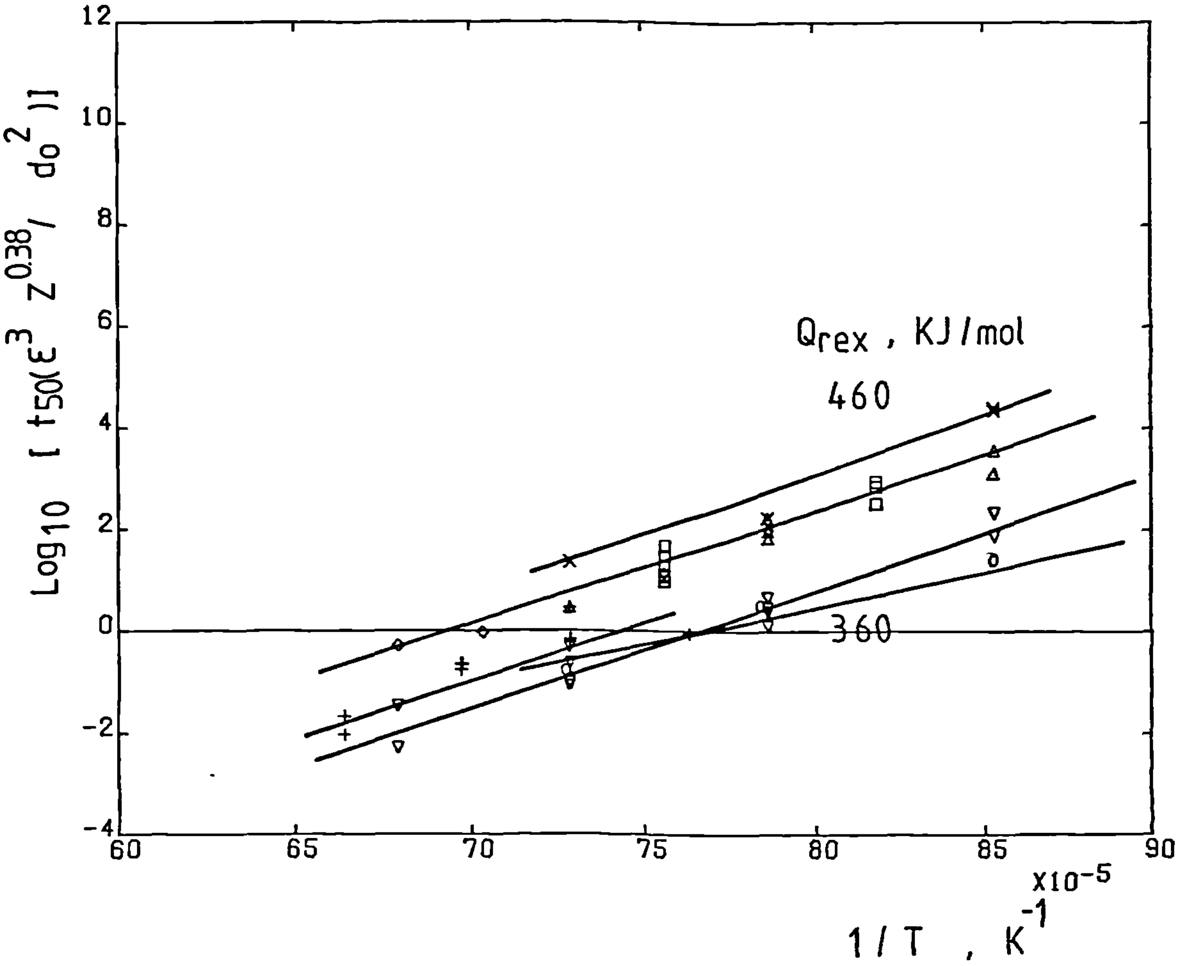

Symbol
Test Method
Reference
Δ Rolling Towle and Gladman, 1979
∇ Tensile Liljestrand, 1972
x Torsion Lombry et al., 1980
□ Tensile Norstrom, 1977
Qrex, KJ/mol
500
560
470
1.0
$\mathrm{Log}_{10}[t_{50}(\varepsilon^4 Z^{0.38}/d_o^2)]$
$1/T$, K^{-1} x10^{-5}
12
10
8
6
4
2
0
-2
-4
60
65
70
75
80
85
90

(a)


Qrex , KJ/mol
500
560
470
0.8
$\mathrm{Log}_{10}[t_{50}(\varepsilon^3 Z^{0.38}/d_o^2)]$
$1/T$, K^{-1} x10^{-5}
12
10
8
6
4
2
0
-2
-4
60
65
70
75
80
85
90

(b)

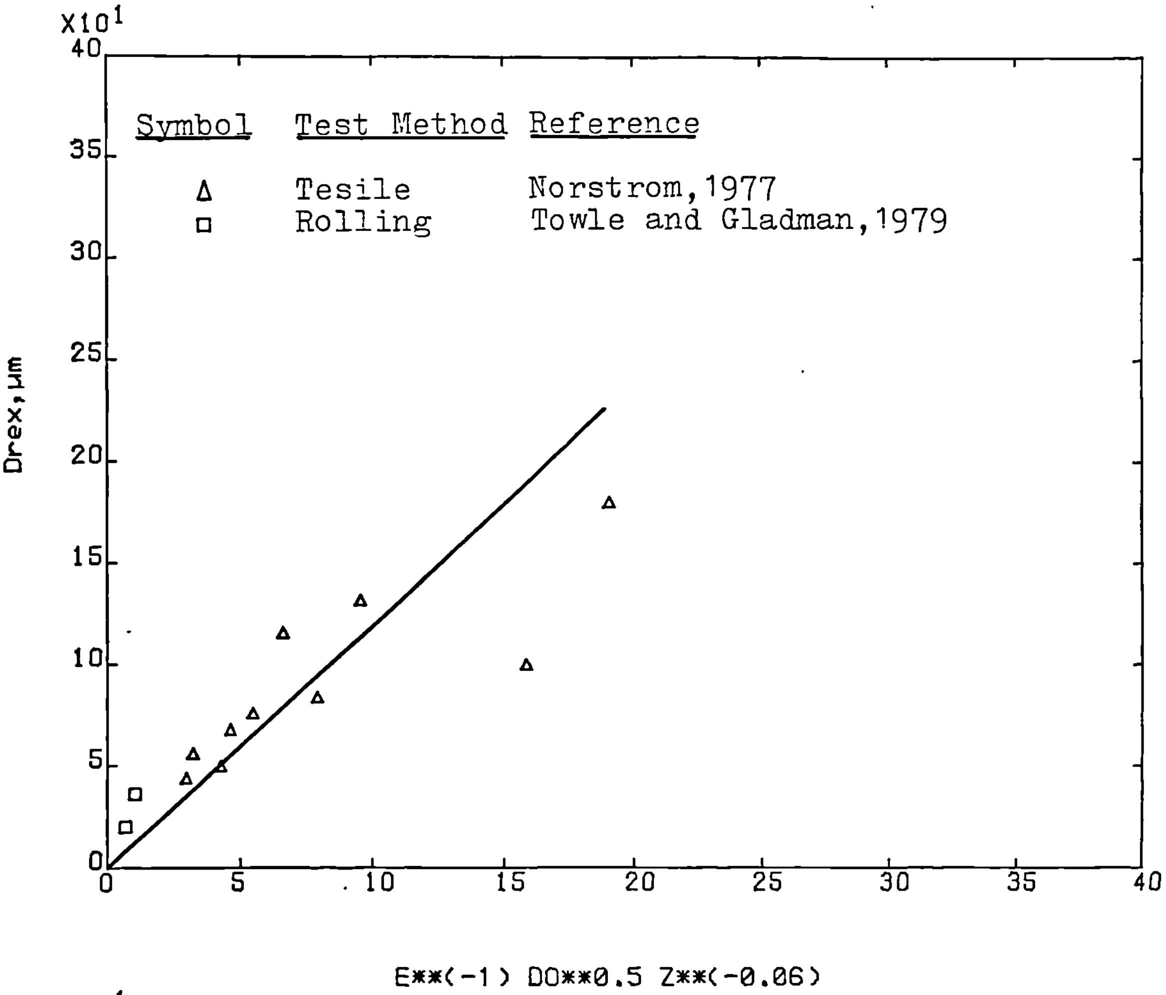
FIGURE 3.8 : Correlation between time for 50% fraction recrystallized and the inverse of absolute temperature for AISI304 steel.



Symbol	Test Method	Reference
Δ	Rolling	Towle and Gladman, 1979
∇	Axisymmetric	Ahlblom, 1977
+	Tensile	Campbell, 1974
✦	Axisymmetric	Campbell, 1974
x	Rolling	Kozasu and Shimizu, 1971
□	Torsion	Barraclough and Sellars, 1979
◇	Torsion	Lombry et al., 1979
o	Torsion	Ryan et al., 1982

FIGURE 3.9 : Correlation between the recrystallized grain size with hot rolling variables for AISI316 steel.

FIGURE 3.10 : Correlation between recrystallized grain size with function of deformation variables and original grain size for AISI304 steel.


X10^1
Drex,μm
0
5
10
15
20
25
30
35
40
Symbol Test Method Reference
Δ Tesile Norstrom,1977
□ Rolling Towle and Gladman,1979
E**(-1) DO**0.5 Z**(-0.06)

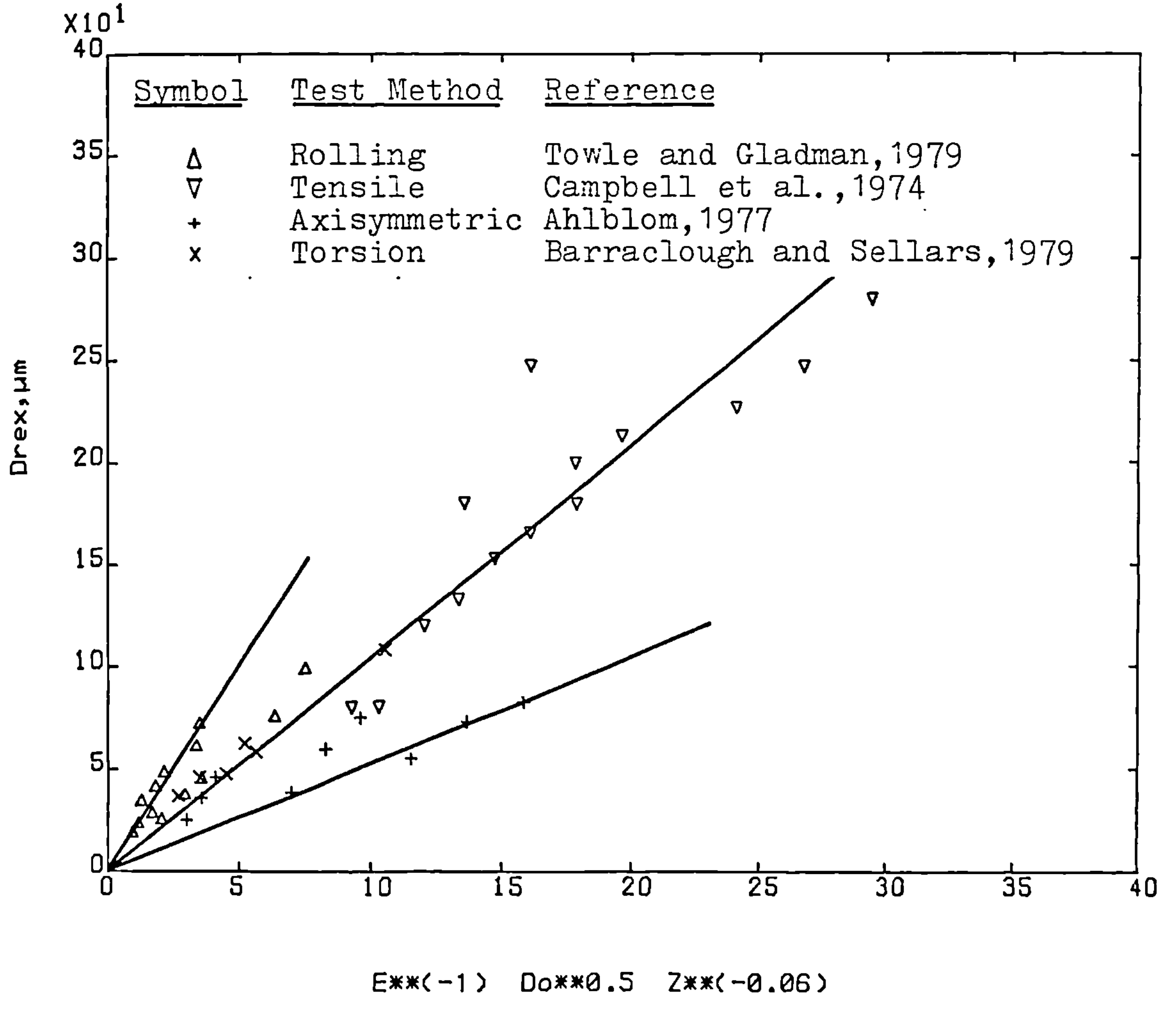
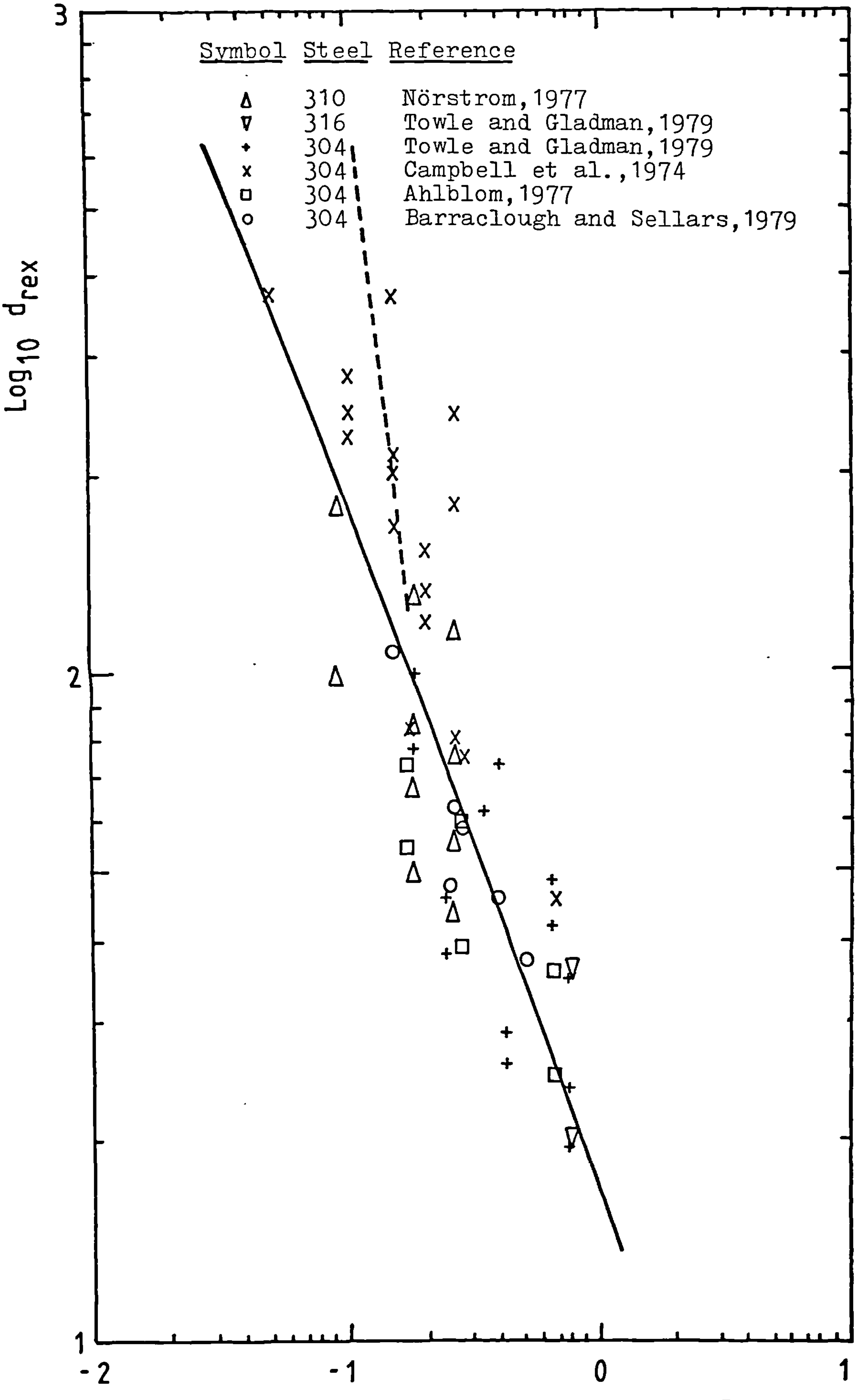

X10^1
Drex,μm
0
5
10
15
20
25
30
35
40
Symbol Test Method Reference
Δ Rolling Towle and Gladman,1979
∇ Tensile Campbell et al.,1974
+ Axisymmetric Ahlblom,1977
x Torsion Barraclough and Sellars,1979
E**(-1) Do**0.5 Z**(-0.06)

FIGURE 3.11 : Dependence of the recrystallized grain size on the equivalent strain for 316 and 304 type steels.


Symbol Steel Reference
Δ 310 Nörstrom,1977
∇ 316 Towle and Gladman,1979
+ 304 Towle and Gladman,1979
x 304 Campbell et al.,1974
□ 304 Ahlblom,1977
o 304 Barraclough and Sellars,1979
3
2
1
-2
-1
0
1
$\mathrm{Log}_{10}\ d_{rex}$
$\mathrm{Log}_{10}\ \varepsilon$

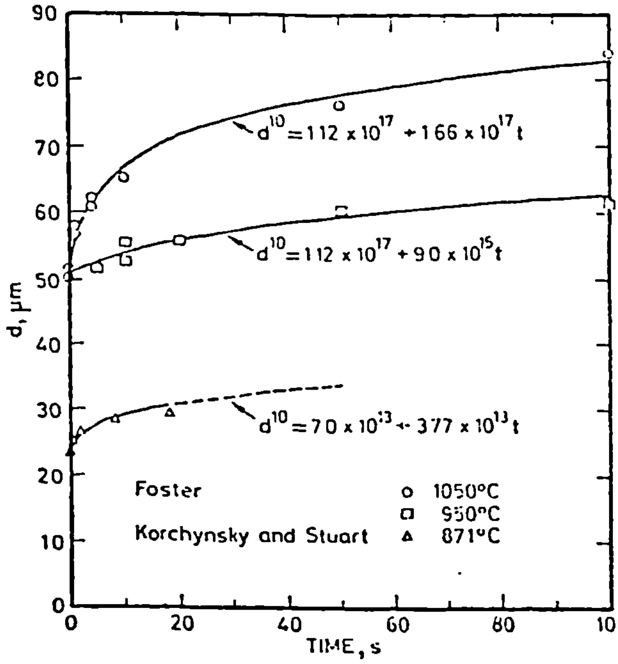


Figure 3.12: Grain growth as function of time after complete static recrystallization in C-Mn steels. (After Sellars, 1980).

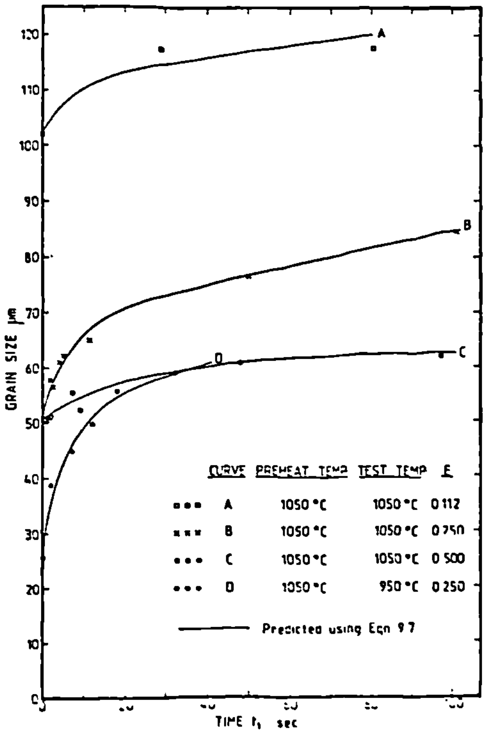


Figure 3.13: Grain size as a function of the time after static recrystallization for a mild steel (After Foster, 1981).

FIGURE 3.14 : Dependence of d^2 on the annealing time for isothermal grain growth.

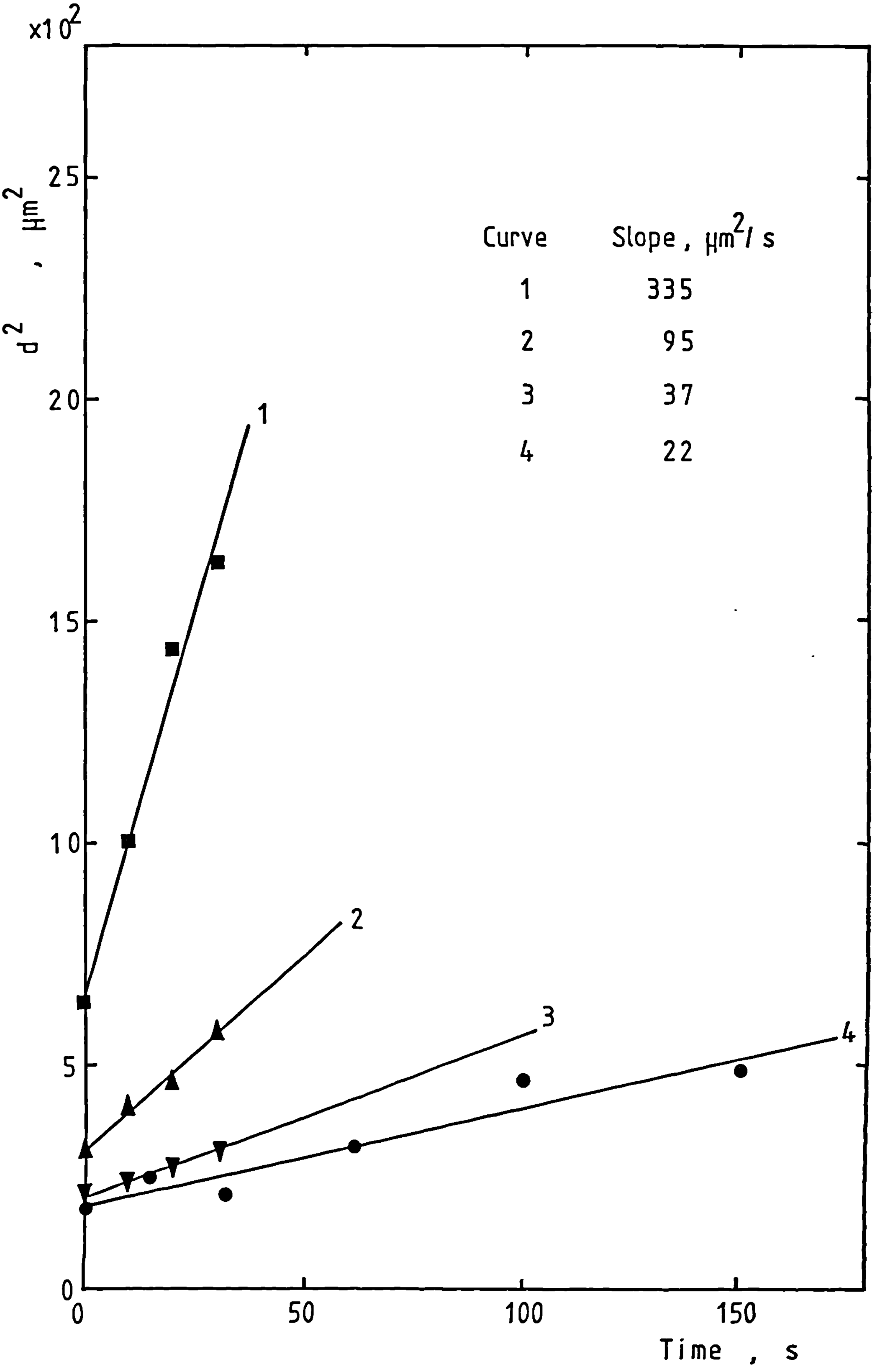
x10²
d², μm²
0
5
10
15
20
25
0
50
100
150
Time, s
1
2
3
4
Curve
Slope, μm²/s
1 335
2 95
3 37
4 22

FIGURE 3.15 : Comparison between experimental and theoretical results for isothermal grain growth of AISI316.

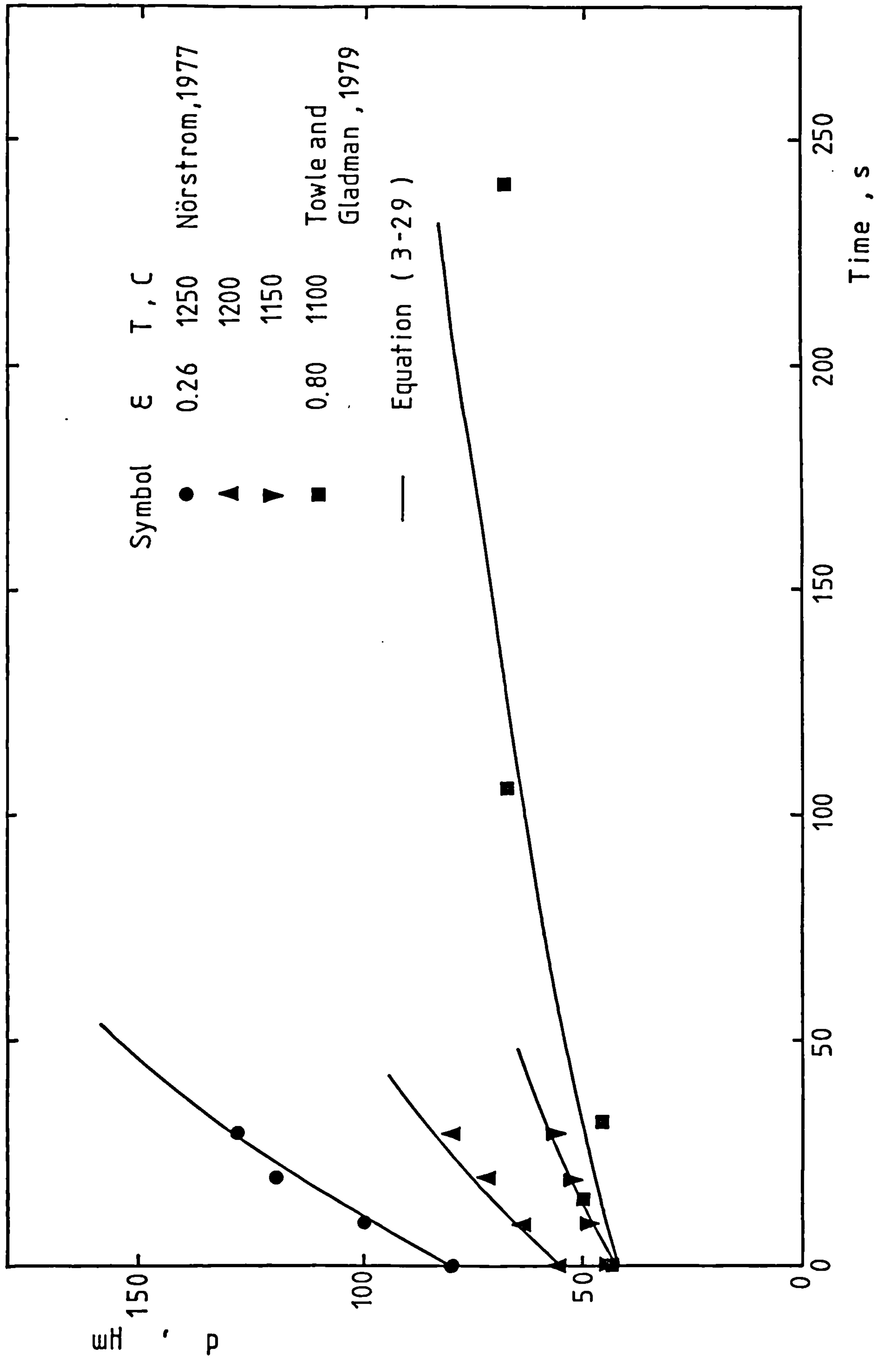

d , μm
0
50
100
150
Time , s
0
50
100
150
200
250
Symbol ε T , C
● 0.26 1250 Nörstrom,1977
▲ 1200
▼ 1150
■ 0.80 1100 Towle and Gladman , 1979
— Equation (3-29)

FIGURE 5.1 : Diagram showing the main stages executed during the present research.

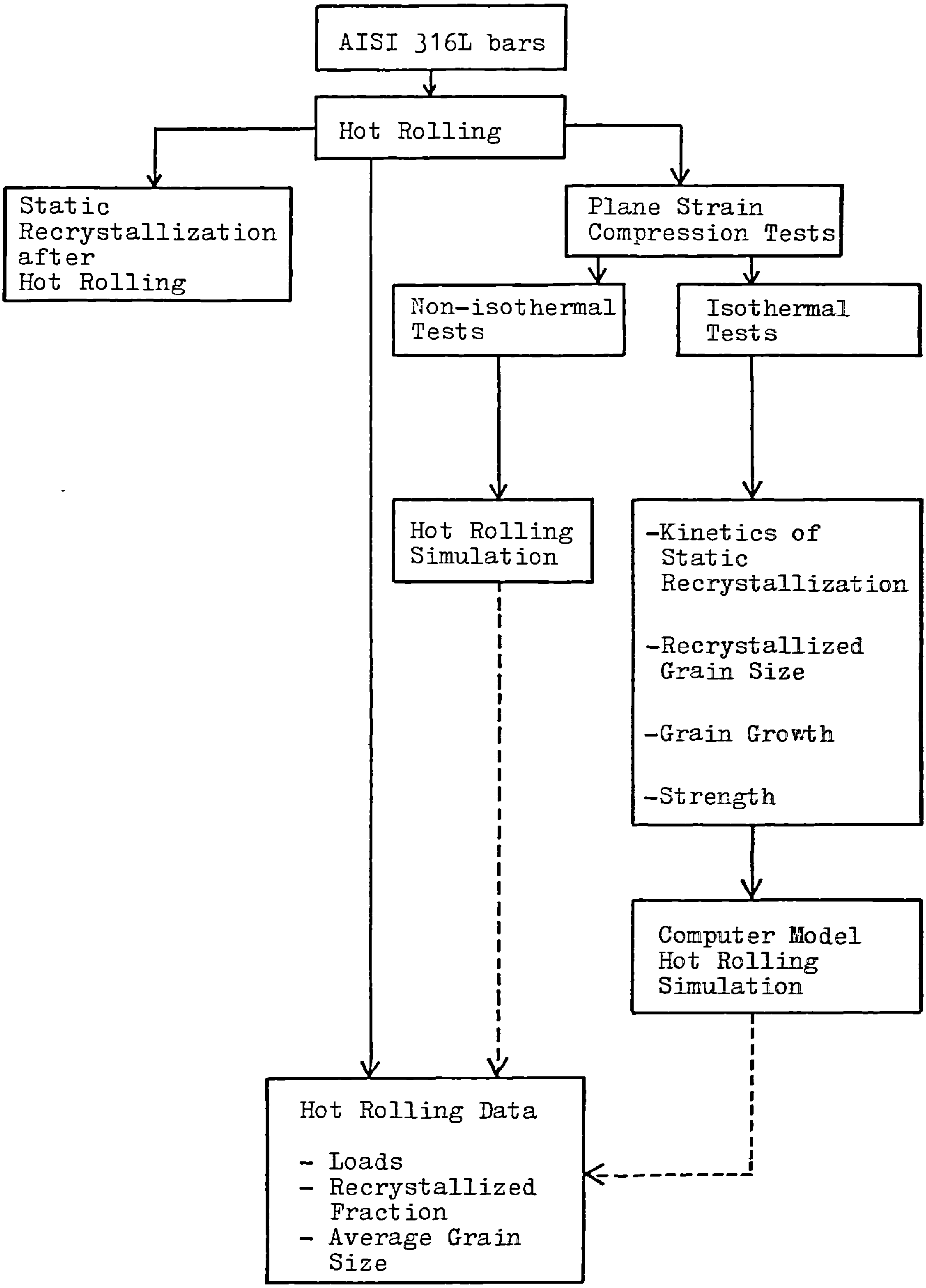

AISI 316L bars
Hot Rolling
Static Recrystallization after Hot Rolling
Plane Strain Compression Tests
Non-isothermal Tests
Isothermal Tests
Hot Rolling Simulation
-Kinetics of Static Recrystallization
-Recrystallized Grain Size
-Grain Growth
-Strength
Computer Model Hot Rolling Simulation
Hot Rolling Data
- Loads
- Recrystallized Fraction
- Average Grain Size

FIGURE 5.2 : Rolling specimen.

FIGURE 5.3 : Samples for metallographic observation

a- kinetics of static recrystallization

b- material for hot rolling simulation.

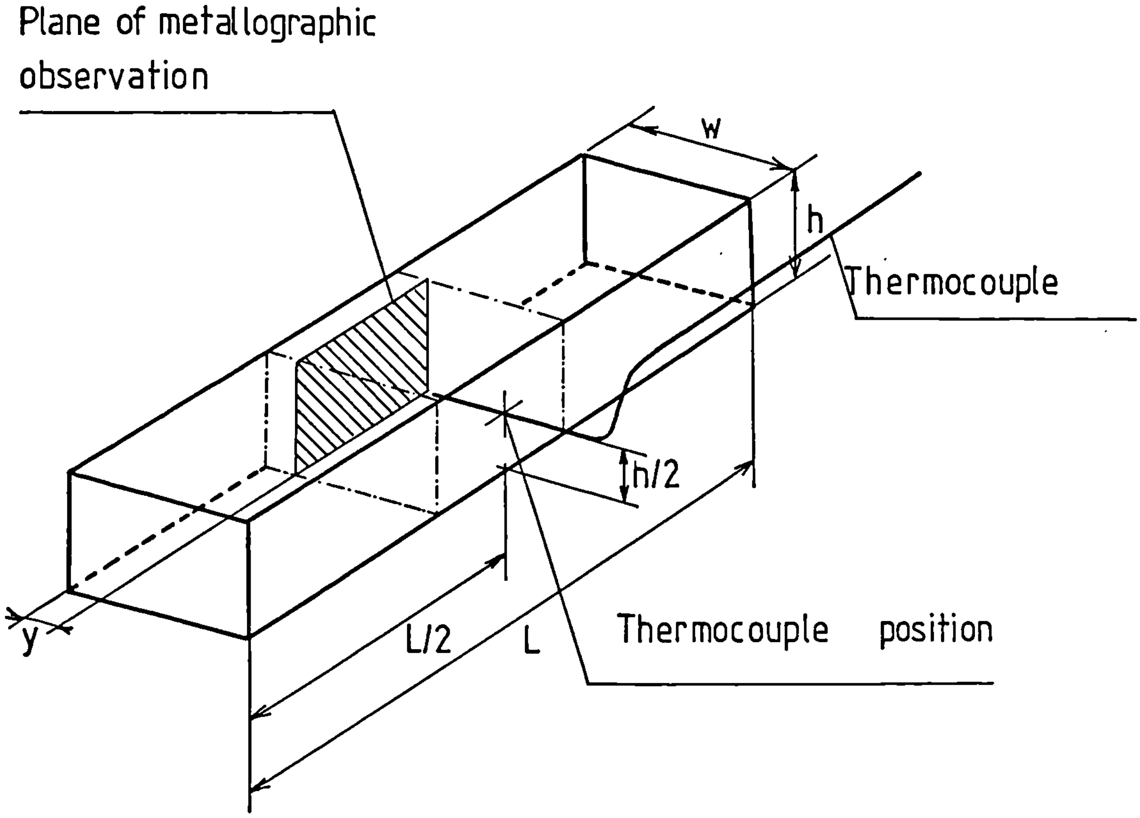


Figure 5.2

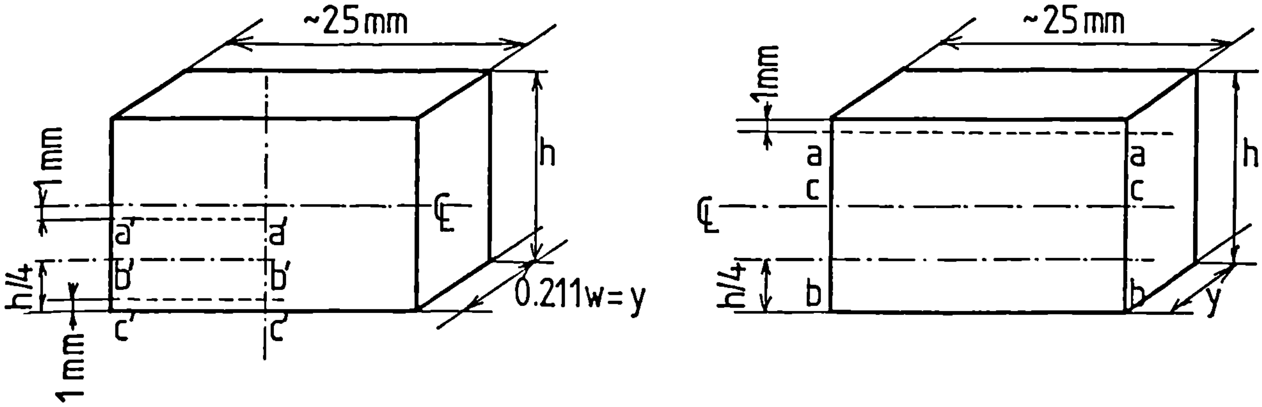
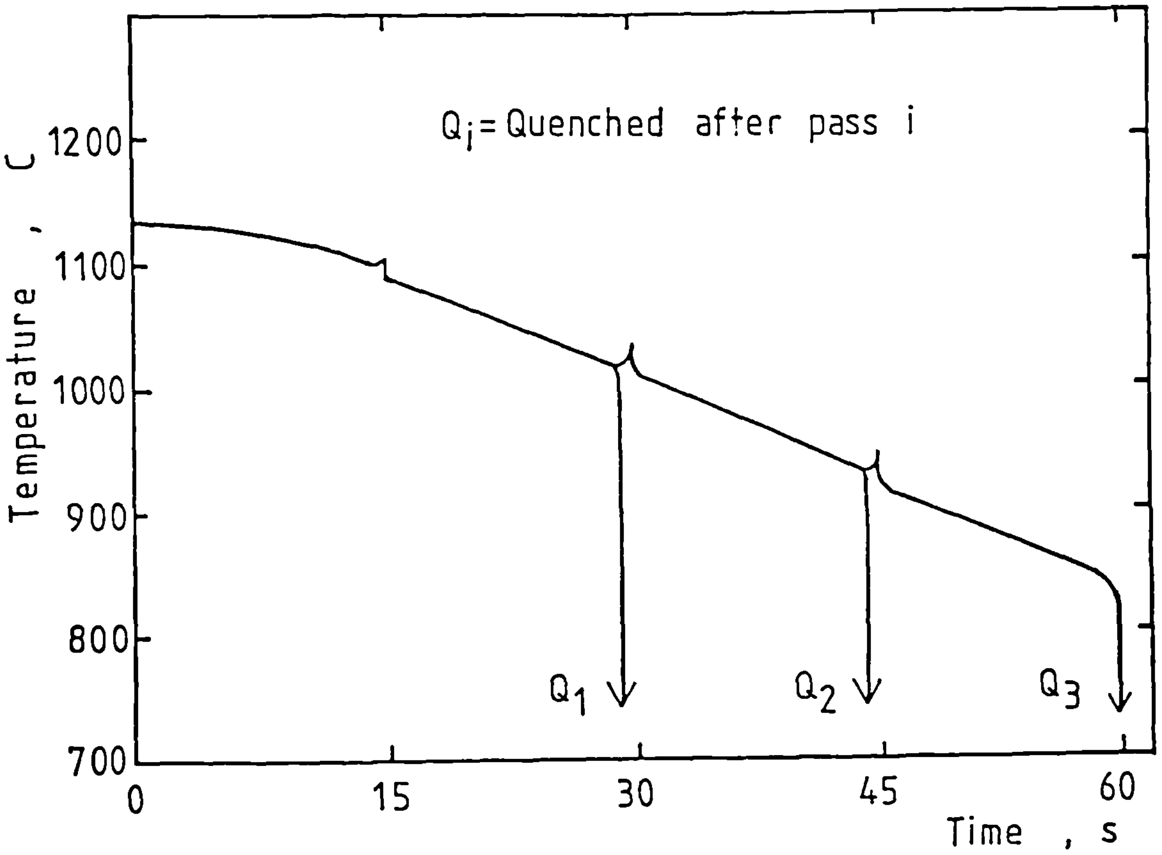


Figure 5.3

FIGURE 5.4 : Hot rolling experiment with samples quenched in between passes and after the last pass.

FIGURE 5.5 : Changes in mean linear intercept after torsion, during recrystallization. Experimental points after Barraclough(1974). Figure reproduced from Leduc(1980).


Qi = Quenched after pass i
Temperature , C
1200
1100
1000
900
800
700
Q1
Q2
Q3
0
15
30
45
60
Time , s

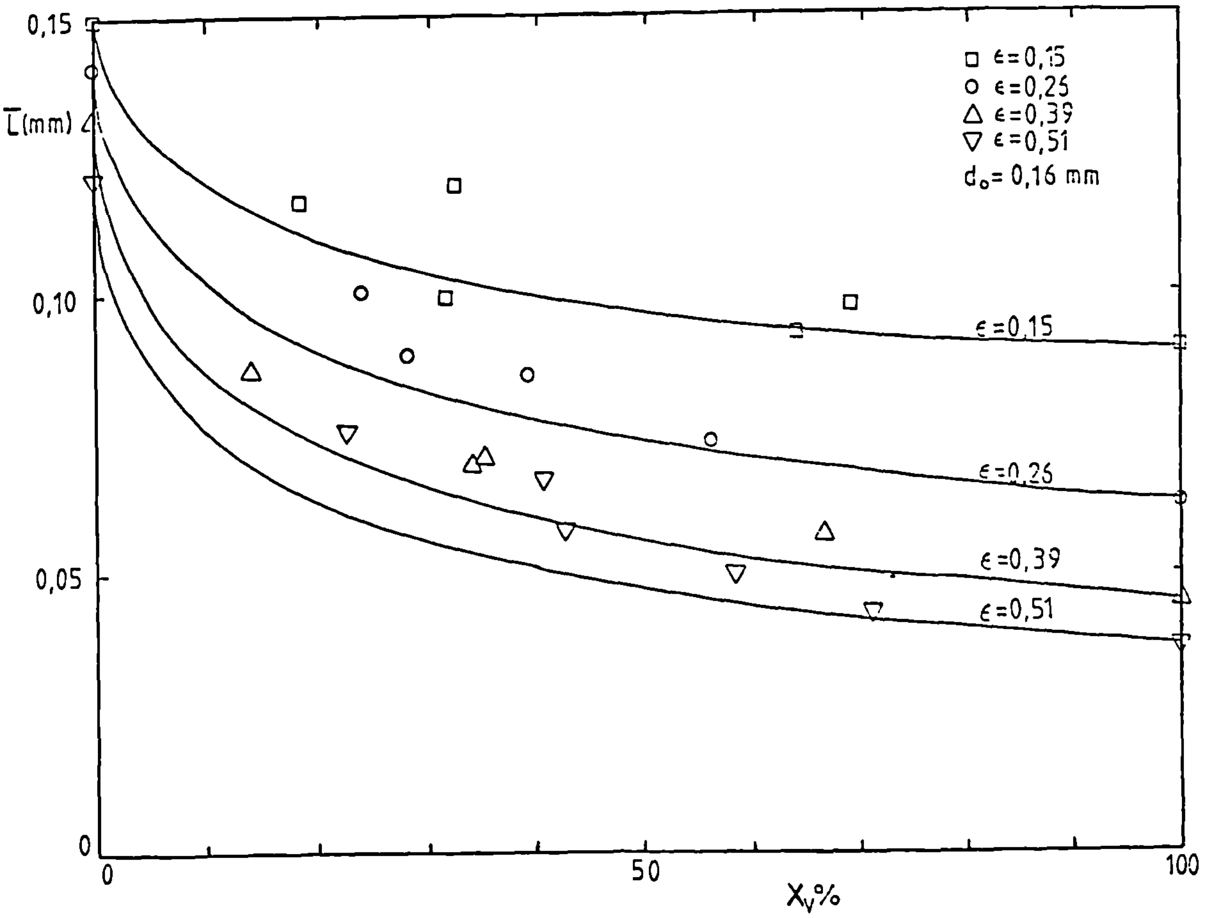
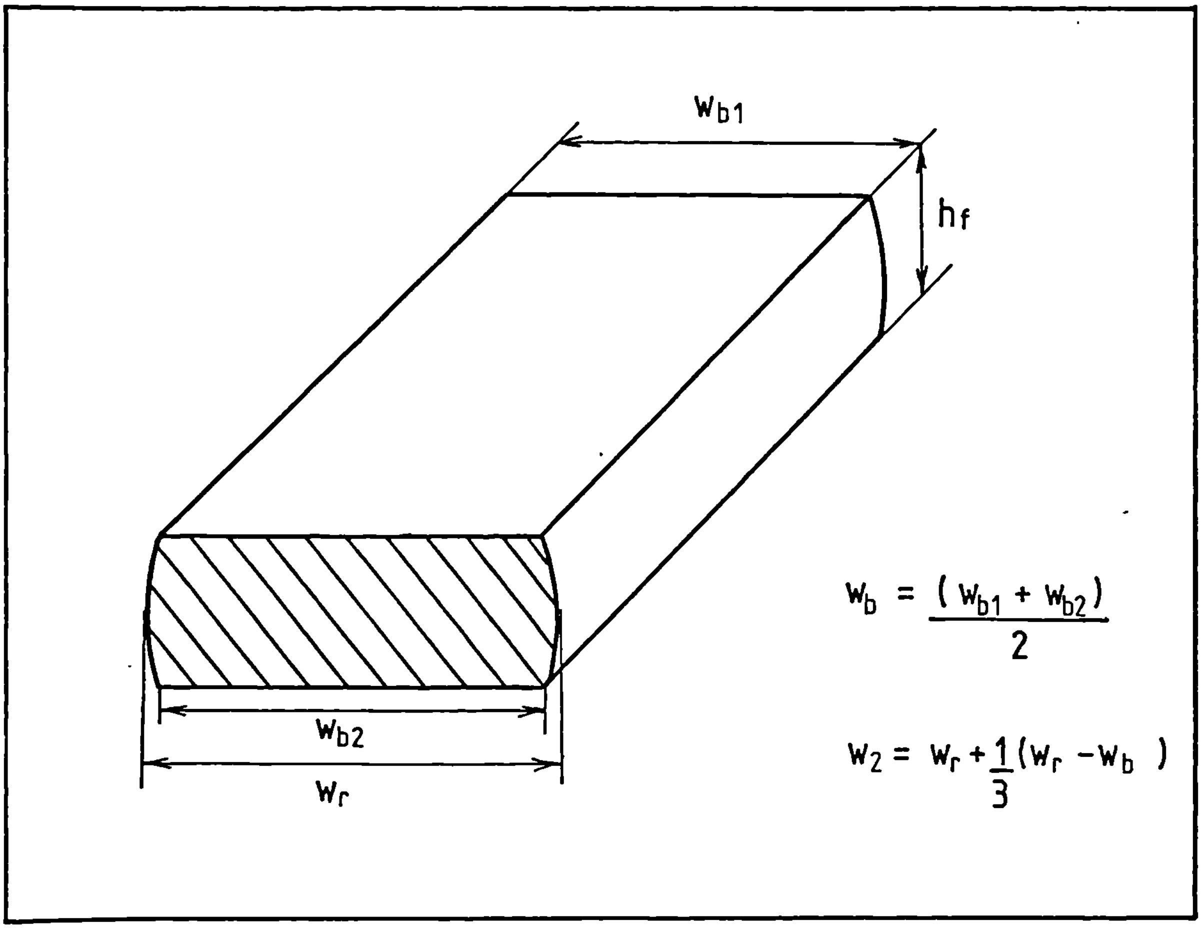
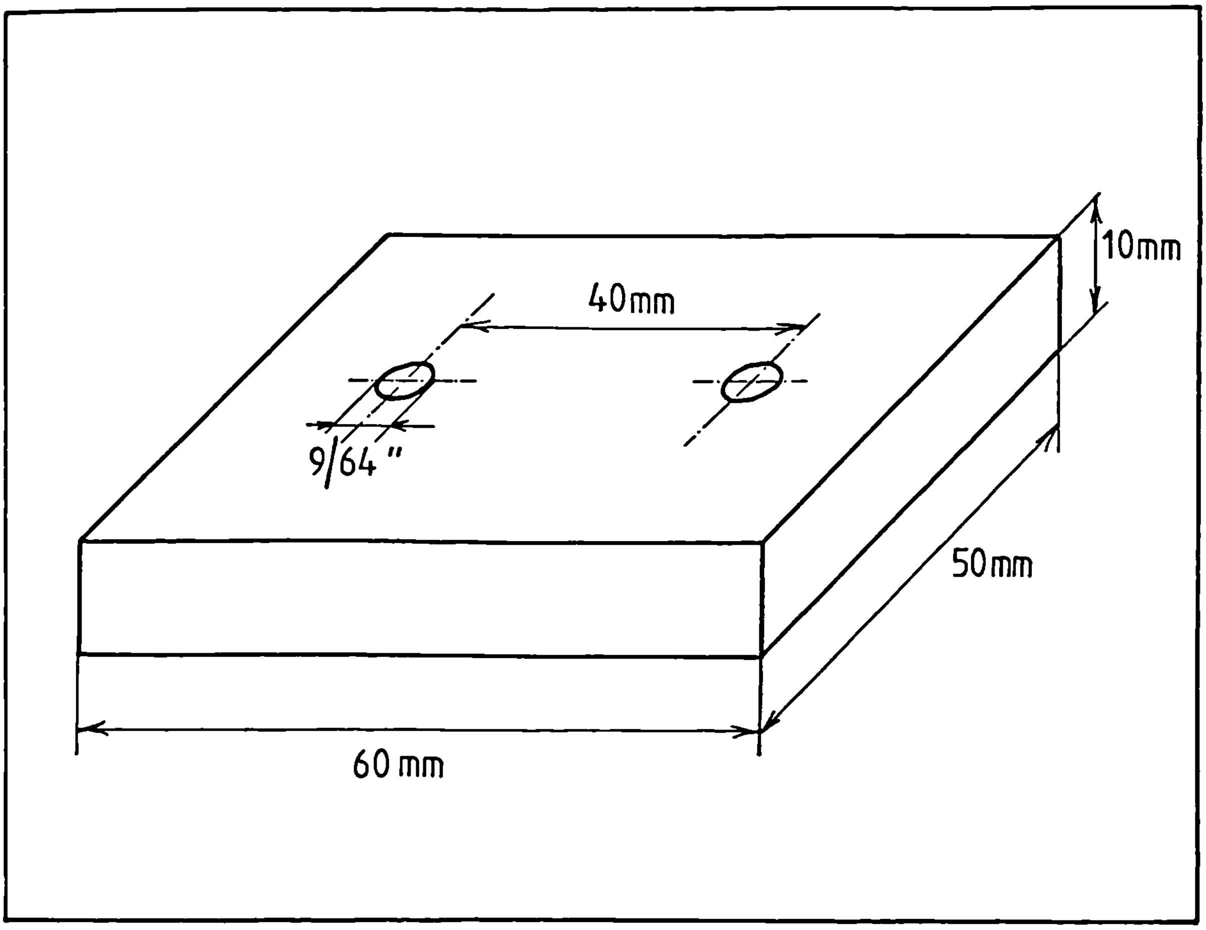

□ ε=0,15
○ ε=0,25
△ ε=0,39
▽ ε=0,51
d₀= 0,16 mm
L̄(mm)
0,15
0,10
0,05
0
ε=0,15
ε=0,26
ε=0,39
ε=0,51
0
50
100
Xv%

FIGURE 5.6 : Deformed hot rolling sample.

FIGURE 5.7 : Original geometry of a plane strain compression specimen.

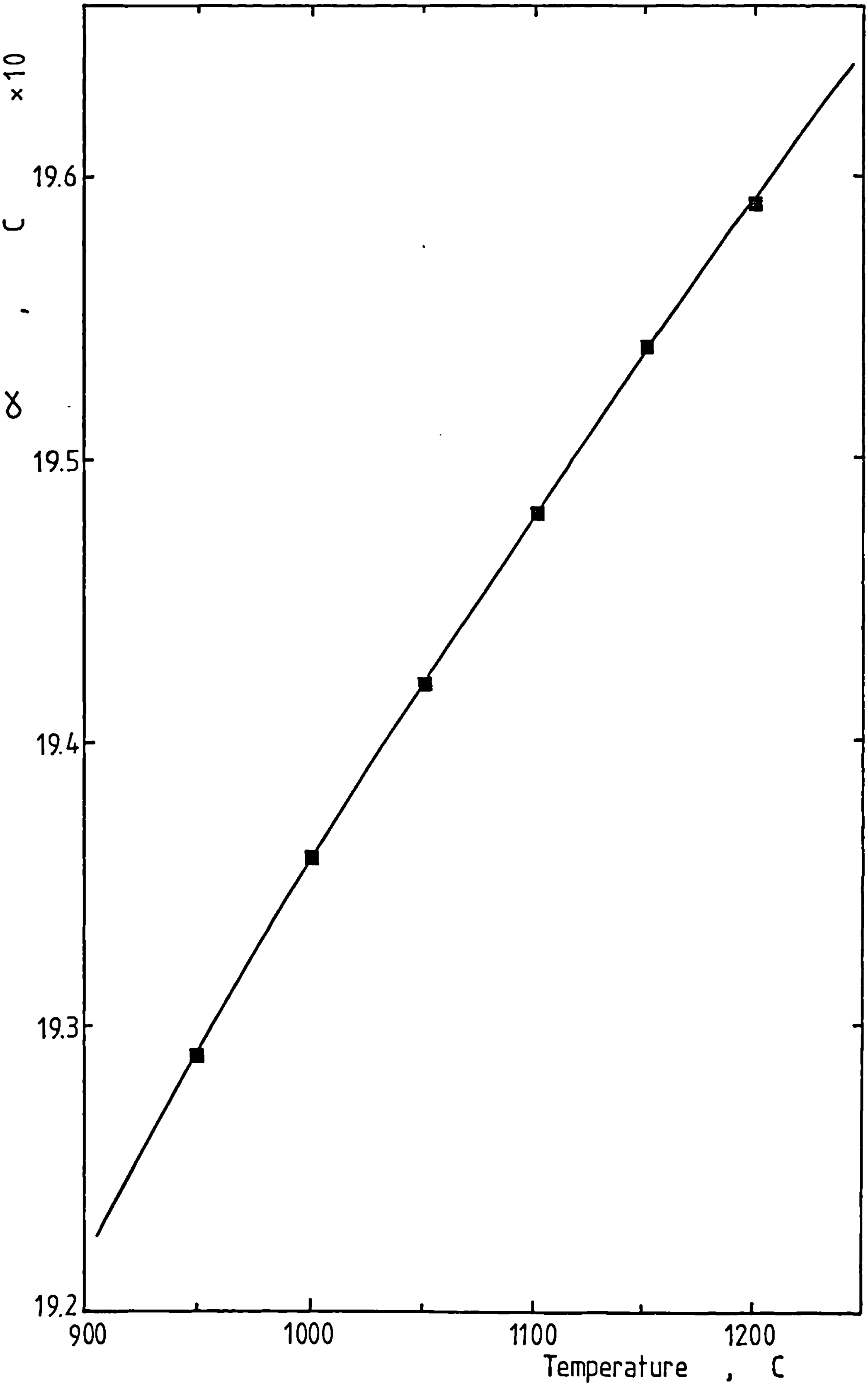


W_{b1}
h_f
W_{b2}
W_r
$W_b = \frac{(W_{b1} + W_{b2})}{2}$
$W_2 = W_r + \frac{1}{3}(W_r - W_b)$



40mm
10mm
9/64"
50mm
60 mm

FIGURE 5.8 : Dependence of the average linear coefficient of thermal expansion between room and test temperature as a function of the test temperature. Data after 'Physical Constants of Some Steels at Elevated Temperatures'



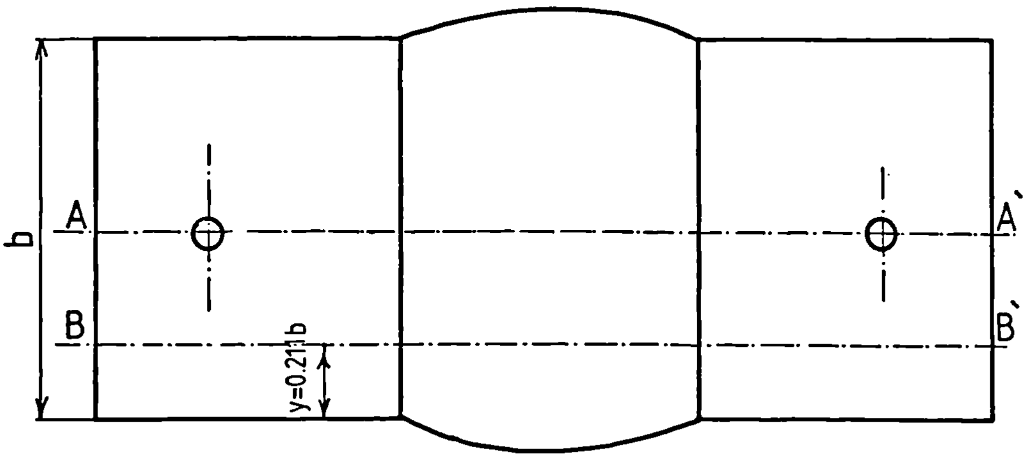
α , C^{-1} $\times 10^{-6}$
19.6
19.5
19.4
19.3
19.2
900
1000
1100
1200
Temperature , C

FIGURE 5.9 : Geometry of a deformed plane strain compression test.

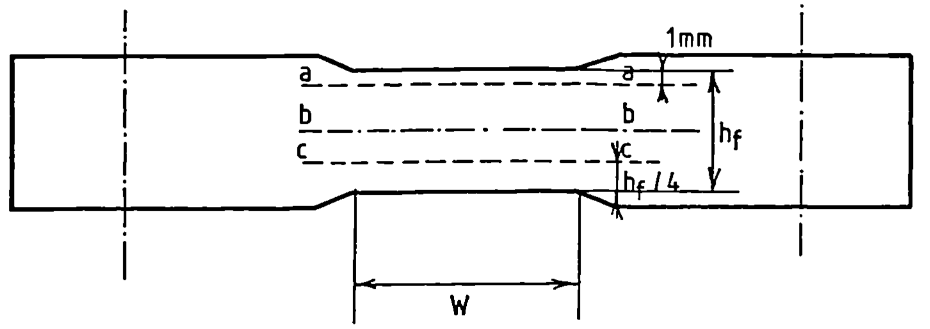
a- Section for metallographic studies(y)

b- Lines a, b and c on which fraction recrystallized measurements were undertaken.

FIGURE 5.10 : Cross section of a deformed plane strain compression test. Shaded area (~4x2mm) was used for measurements of average recrystallized grain size.



(a)



(b)

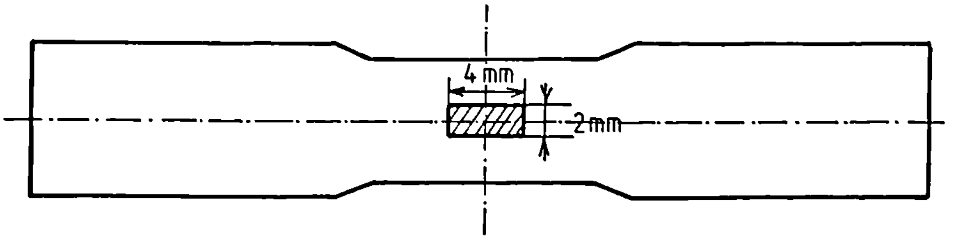


FIGURE 5.11 : Determination of the spread coefficient for isothermal and non-isothermal tests performed on AISI316 over a range of temperatures using glass lubricant DAG2626.

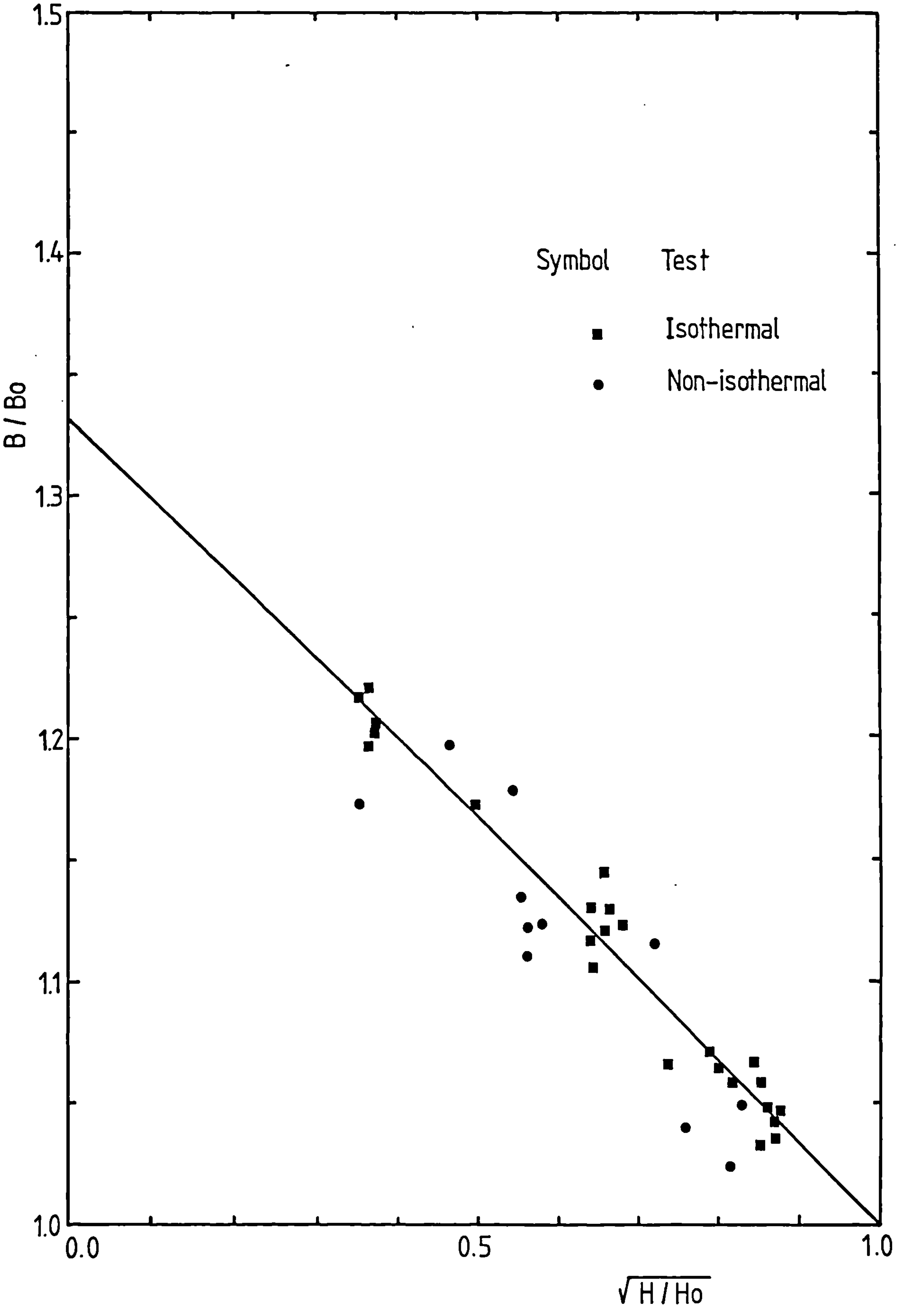

B / Bo
1.5
1.4
1.3
1.2
1.1
1.0
0.0
0.5
1.0
√H / Ho
Symbol Test
■ Isothermal
● Non-isothermal

FIGURE 5.12 : Schematic representation of the interpolation carried out in the early stages of a load vs. displacement curve in order to perform an origin correction.

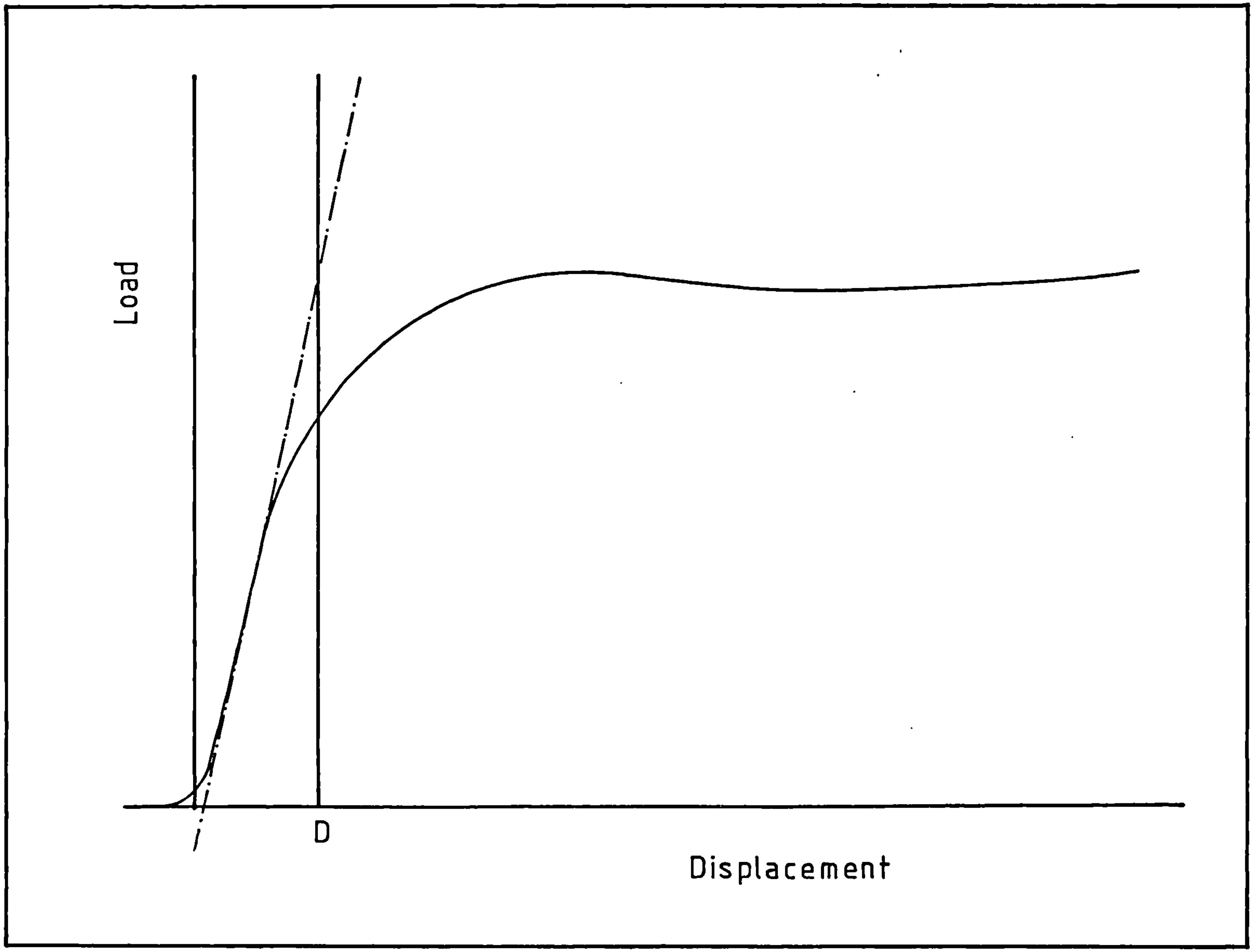

Load
D
Displacement

FIGURE 5.13 : Cooling curve of a hot rolling sample in air compared with the one obtained for plane strain compression sample cooled inside the test furnace at 230C.

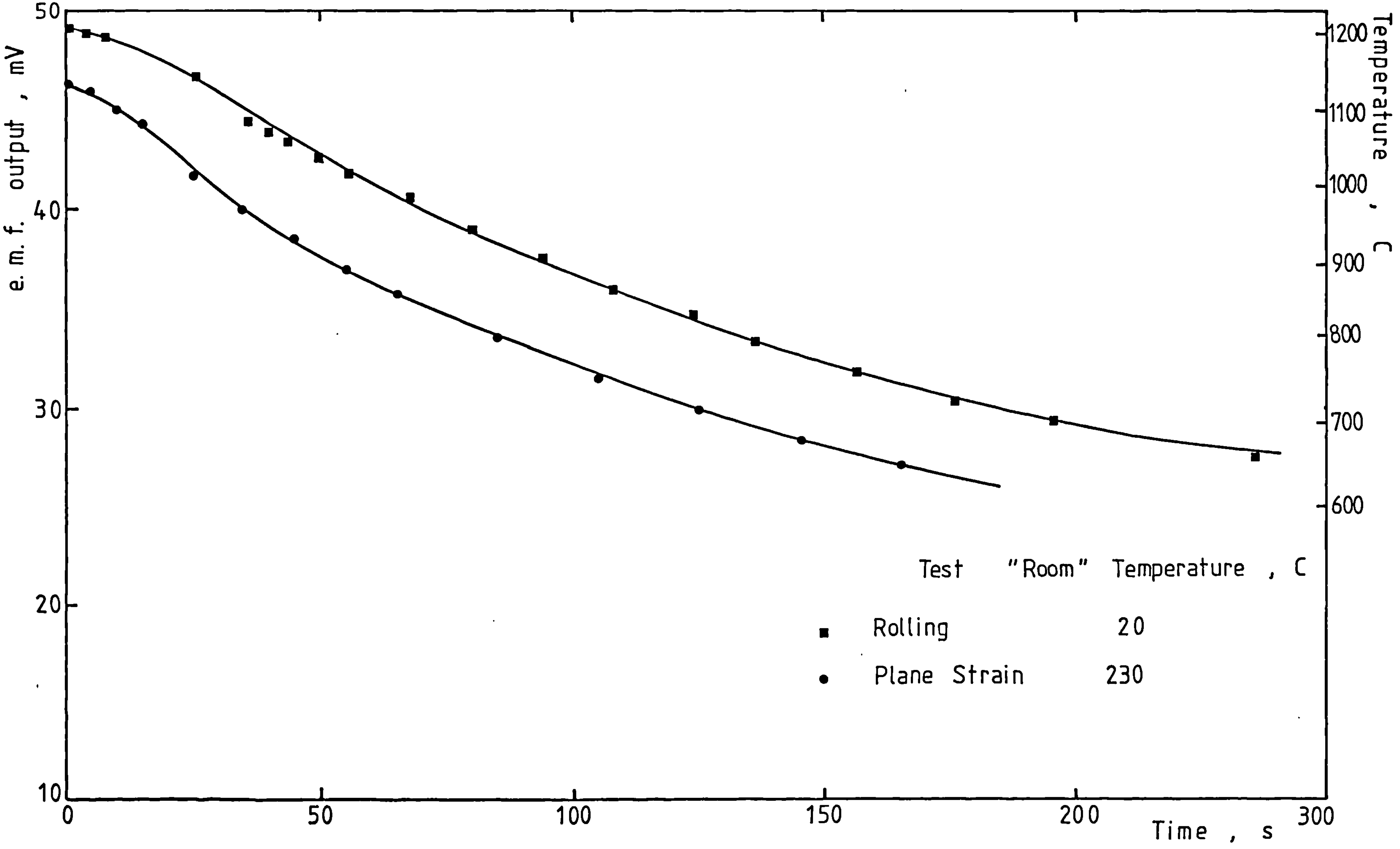
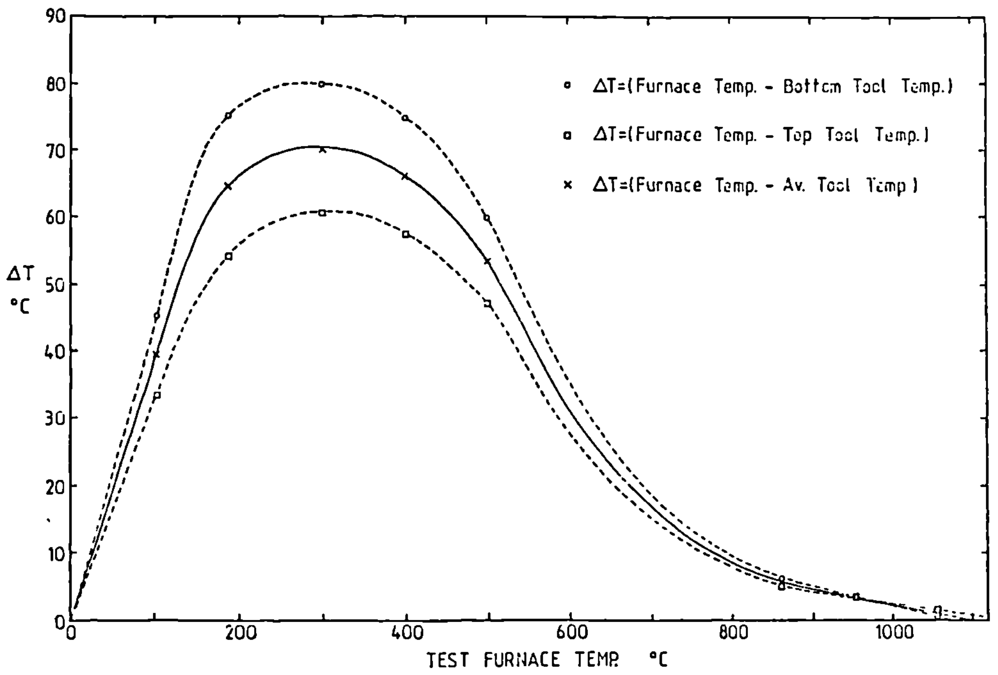
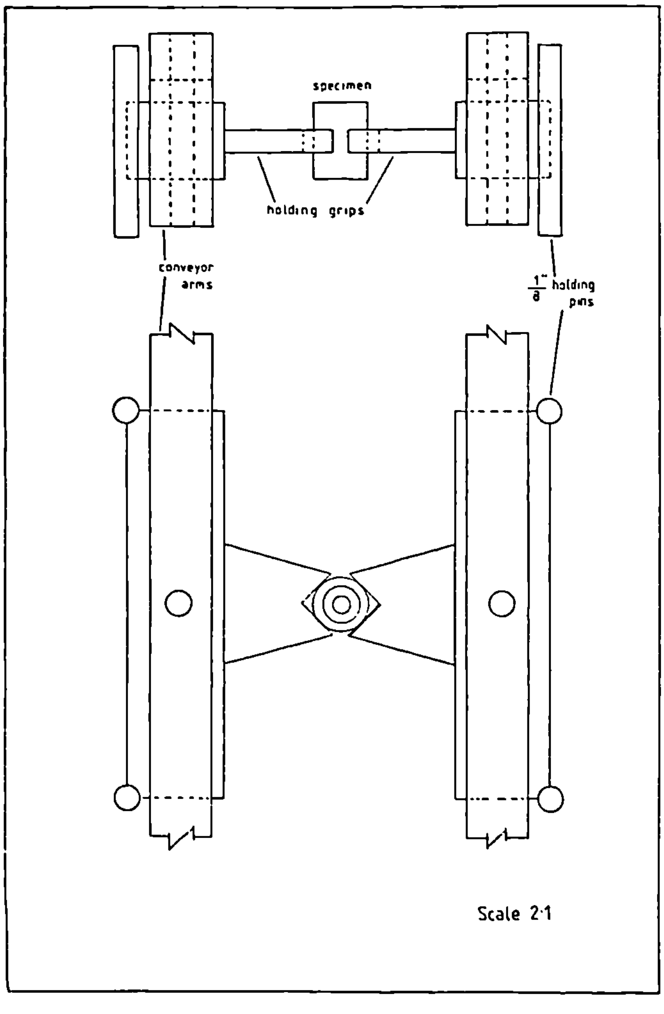

e. m. f. output , mV
50
40
30
20
10
Temperature , C
1200
1100
1000
900
800
700
600
0
50
100
150
200
300
Time , s
Test "Room" Temperature , C
■ Rolling 20
● Plane Strain 230

FIGURE 5.14 : Plot of the difference between the top and bottom tool and test furnace temperatures as a function of the furnace temperature. (After Foster,1981).

FIGURE 5.15 : Handling device used in the transportation of an axisymmetric compression sample from the pre-heating furnace to the test furnace. (After Colás,1983).



ΔT=(Furnace Temp. - Bottom Tool Temp.)
ΔT=(Furnace Temp. - Top Tool Temp.)
ΔT=(Furnace Temp. - Av. Tool Temp.)
ΔT °C
0
10
20
30
40
50
60
70
80
90
0
200
400
600
800
1000
TEST FURNACE TEMP. °C



specimen
holding grips
conveyor arms
1/8" holding pins
Scale 2·1

FIGURE 5.16 : Stages involved in the convertion of the raw data from a plane strain compression test into stress, strain, strain rate and temperature.

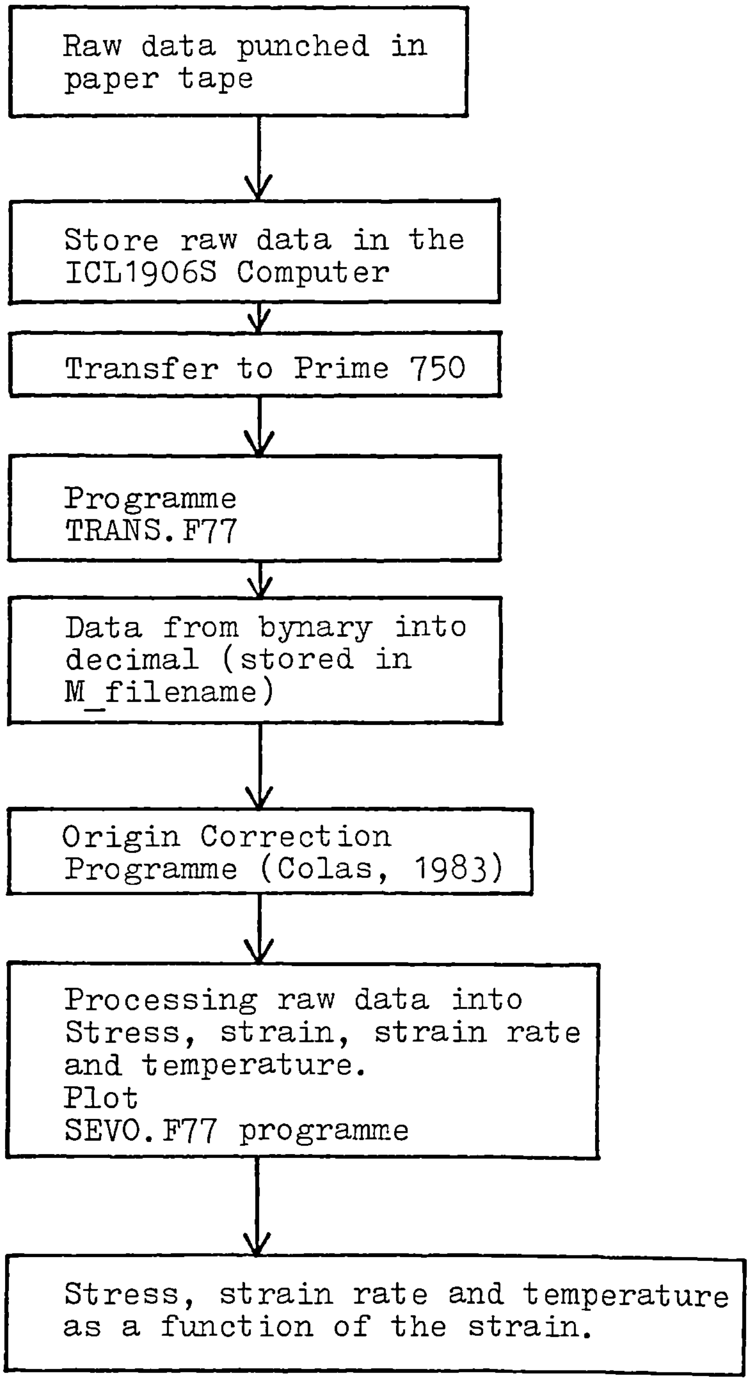

Raw data punched in paper tape
Store raw data in the ICL1906S Computer
Transfer to Prime 750
Programme TRANS.F77
Data from bynary into decimal (stored in M_filename)
Origin Correction Programme (Colas, 1983)
Processing raw data into Stress, strain, strain rate and temperature. Plot SEVO.F77 programme
Stress, strain rate and temperature as a function of the strain.

FIGURE 5.16 : Stages involved in the convertion of the raw data from a plane strain compression test into stress, strain, strain rate and temperature.

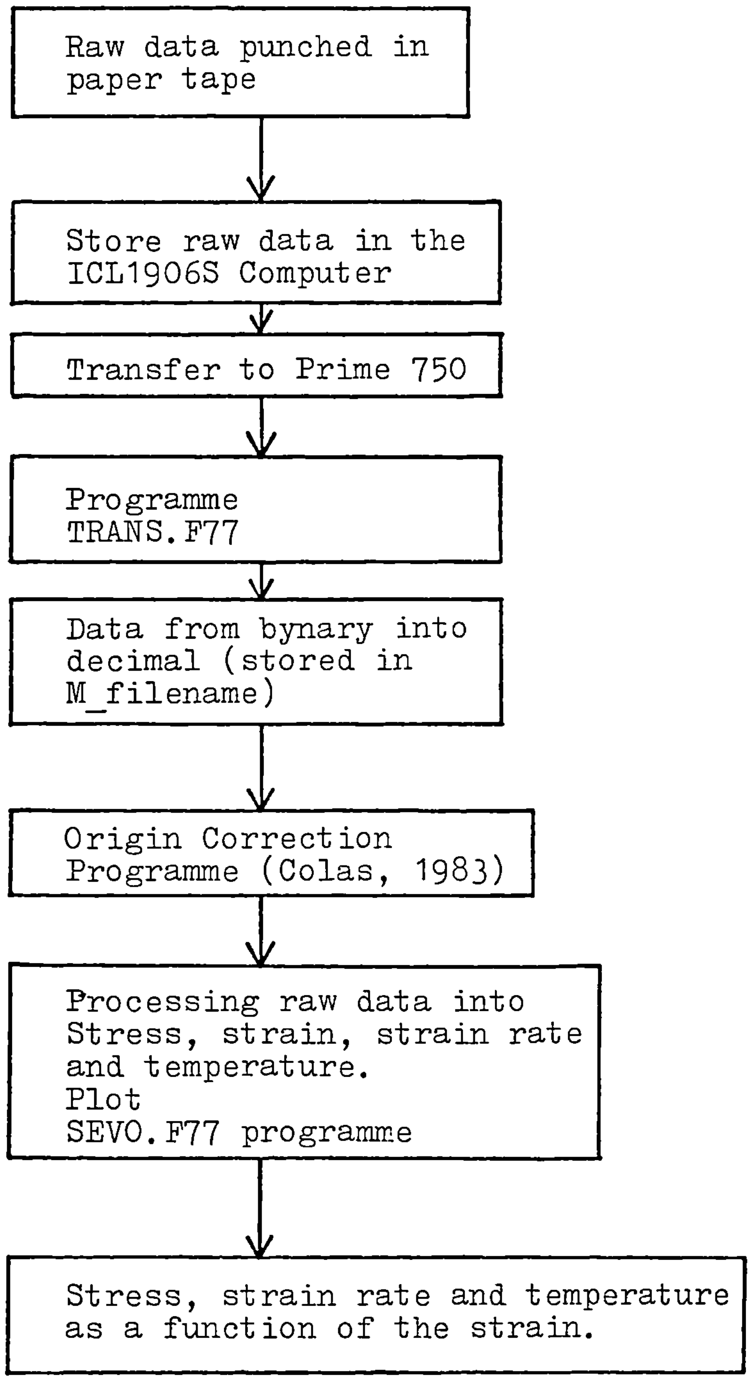

Raw data punched in paper tape
Store raw data in the ICL1906S Computer
Transfer to Prime 750
Programme TRANS.F77
Data from bynary into decimal (stored in M_filename)
Origin Correction Programme (Colas, 1983)
Processing raw data into Stress, strain, strain rate and temperature. Plot SEVO.F77 programme
Stress, strain rate and temperature as a function of the strain.

FIGURE 6.1 : Stress-strain curves for AISI316 with original grain size 100μm.

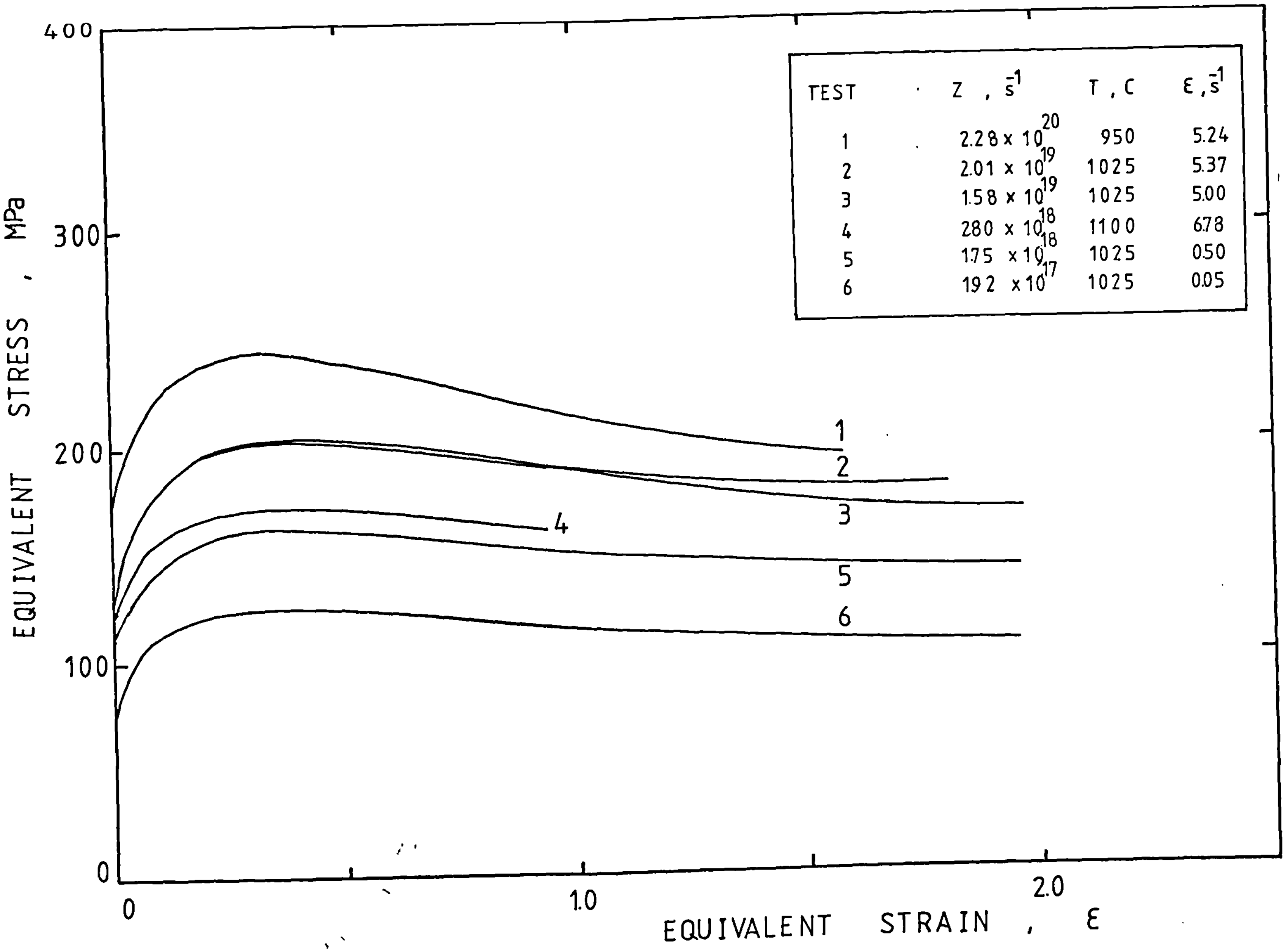

TEST Z , $\bar{s}^1$ T , C ε , $\bar{s}^1$
1 2.28×10^{20} 950 5.24
2 2.01×10^{19} 1025 5.37
3 1.58×10^{19} 1025 5.00
4 2.80×10^{18} 1100 6.78
5 1.75×10^{18} 1025 0.50
6 1.92×10^{17} 1025 0.05
1
2
3
4
5
6
400
300
200
100
0
EQUIVALENT STRESS , MPa
0
1.0
2.0
EQUIVALENT STRAIN , ε

FIGURE 6.2 : Correlation between the strain rate of test with the maximum stress for samples with original grain size of 100μm. Figures near symbols mean number of coincident points.

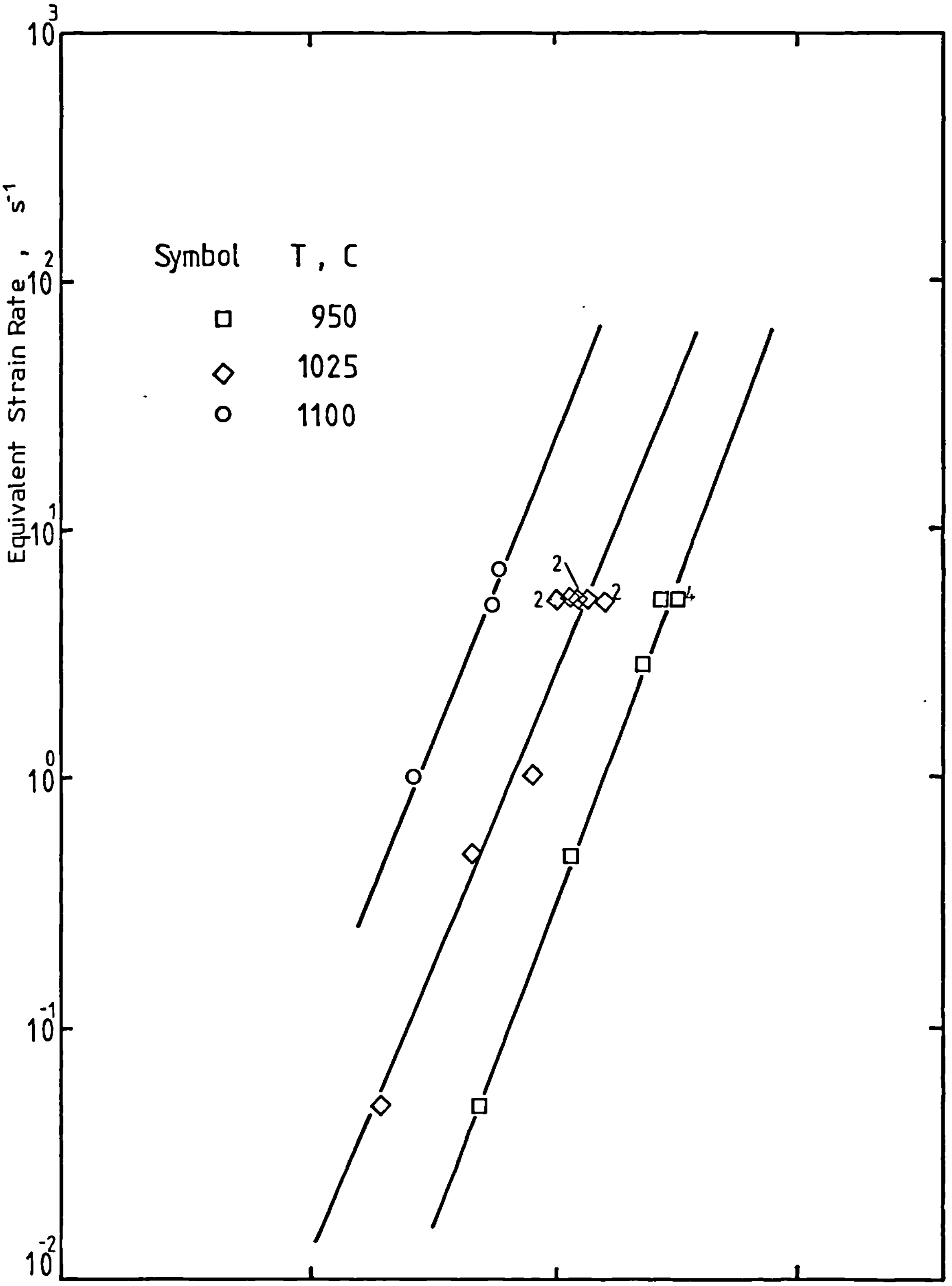

Equivalent Strain Rate , s^{-1}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
100
200
300
Maximum Equivalent Stress , MPa
Symbol T , C
□ 950
◇ 1025
○ 1100
2
2
2
4

FIGURE 6.3 : Strain rate at a constant stress as a function of the inverse of the absolute testing temperature.

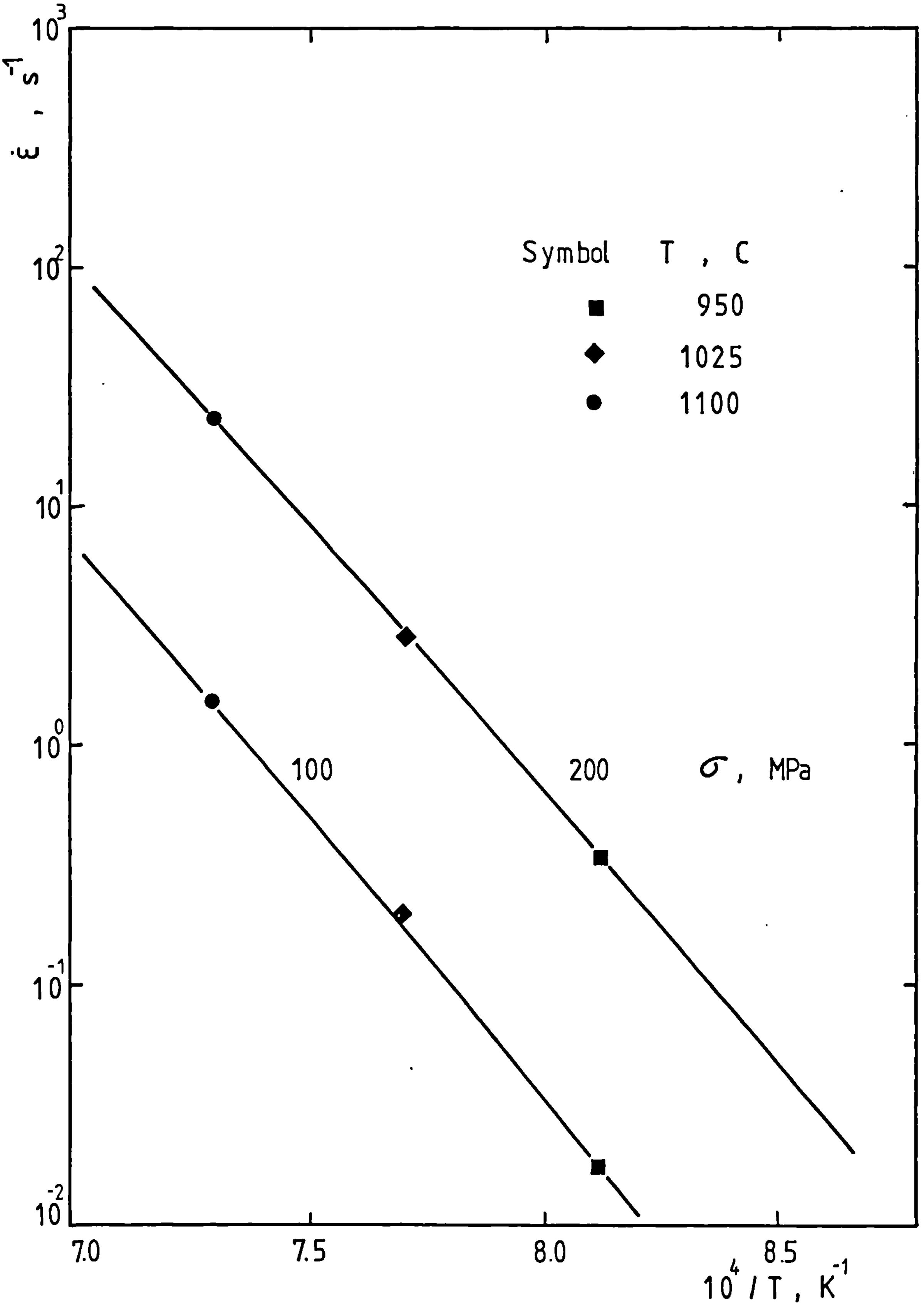

$\dot{\varepsilon}$, s^{-1}
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
7.0
7.5
8.0
8.5
10^4 / T , K^{-1}
Symbol T , C
■ 950
◆ 1025
● 1100
100
200
σ , MPa

FIGURE 6.4 : Dependence of the maximum stress on the original grain size.

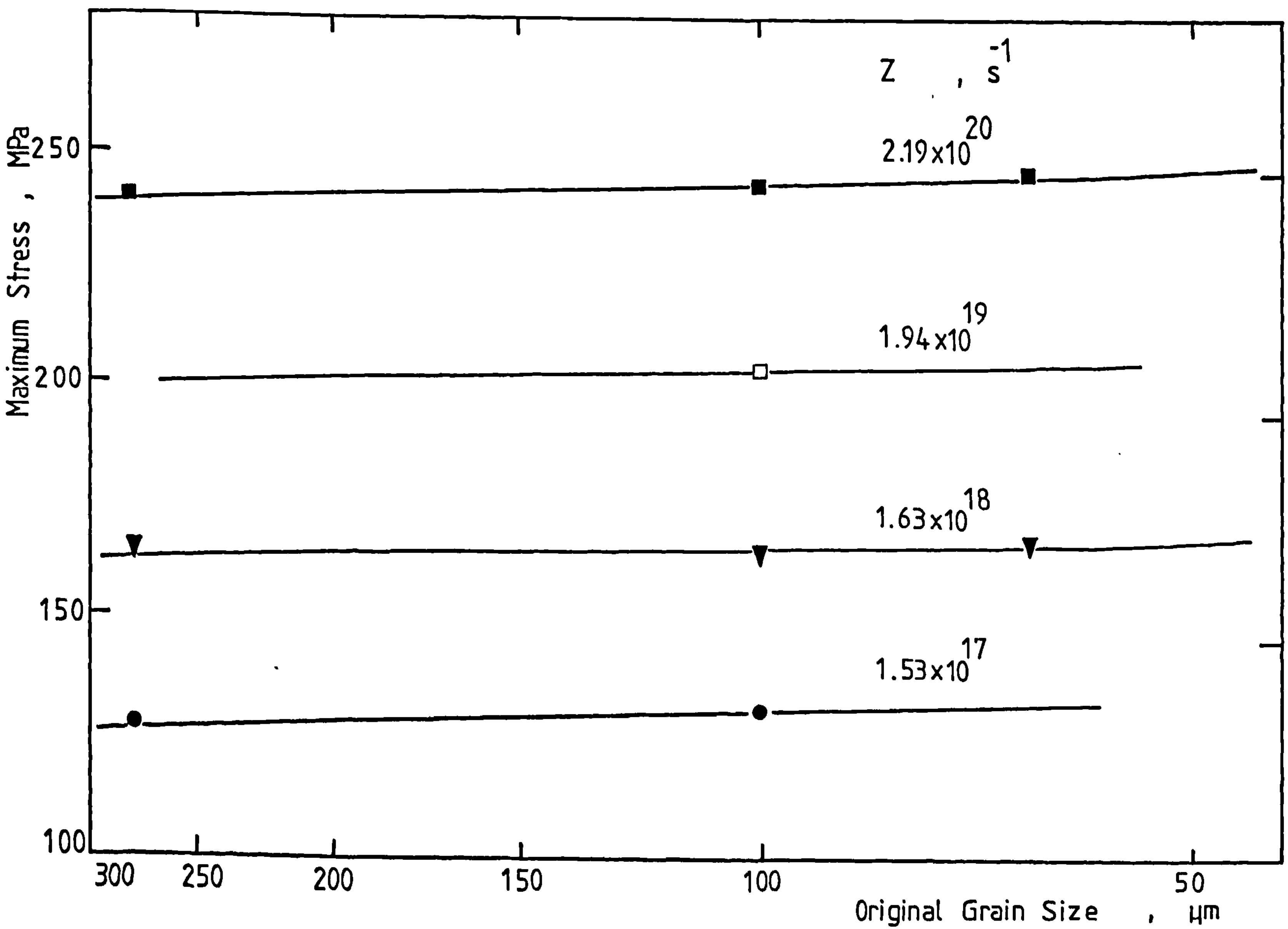
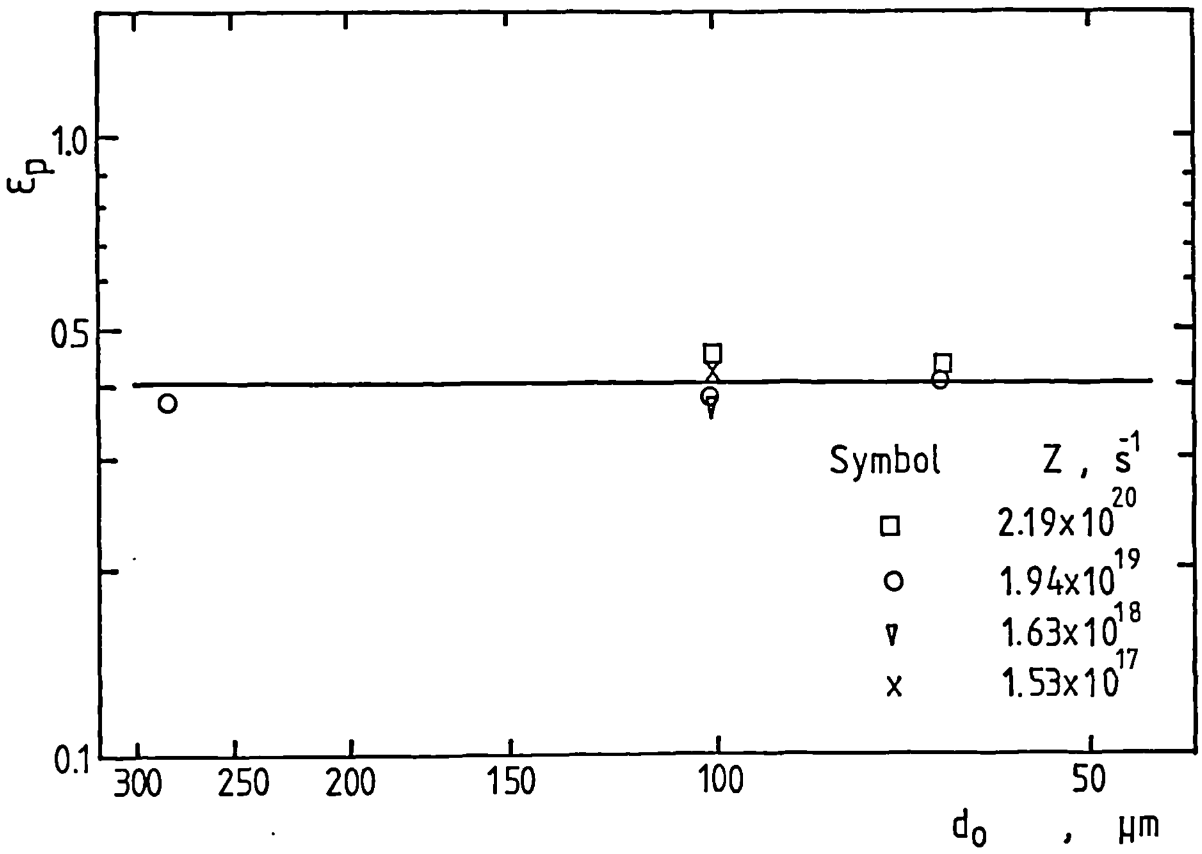
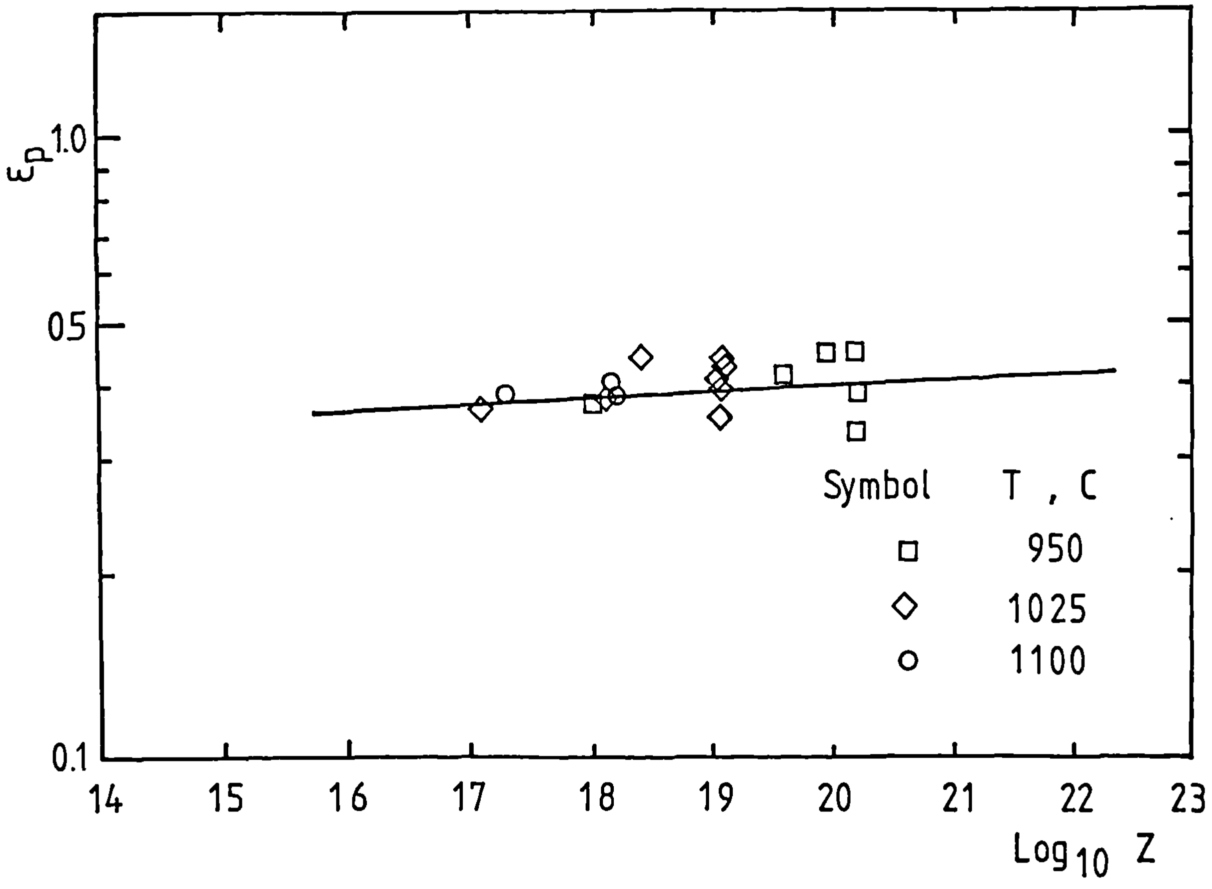

Z , s^{-1}
2.19×10^{20}
1.94×10^{19}
1.63×10^{18}
1.53×10^{17}
Maximum Stress , MPa
250
200
150
100
300
250
200
150
100
50
Original Grain Size , μm

FIGURE 6.5 : Dependence of the strain to peak stress on the original grain size of samples tested under plane strain compression.

FIGURE 6.6 : Dependence of the strain to peak stress on the Zener-Hollomon paramenter for samples of original grain size 100μm tested under plane strain compression.



ε_p
1.0
0.5
0.1
300
250
200
150
100
50
d_0 , μm
Symbol
Z , s^{-1}
□ 2.19×10^{20}
○ 1.94×10^{19}
▿ 1.63×10^{18}
x 1.53×10^{17}



ε_p
1.0
0.5
0.1
14
15
16
17
18
19
20
21
22
23
$\mathrm{Log}_{10}\ Z$
Symbol
T , C
□ 950
◇ 1025
○ 1100

FIGURE 6.7 : Dependence of the stress at an equivalent strain of 0.02, σ_0, and the maximum stress, σ_p, on the Zener-Hollomon parameter. Numbers near symbols mean coincident points.

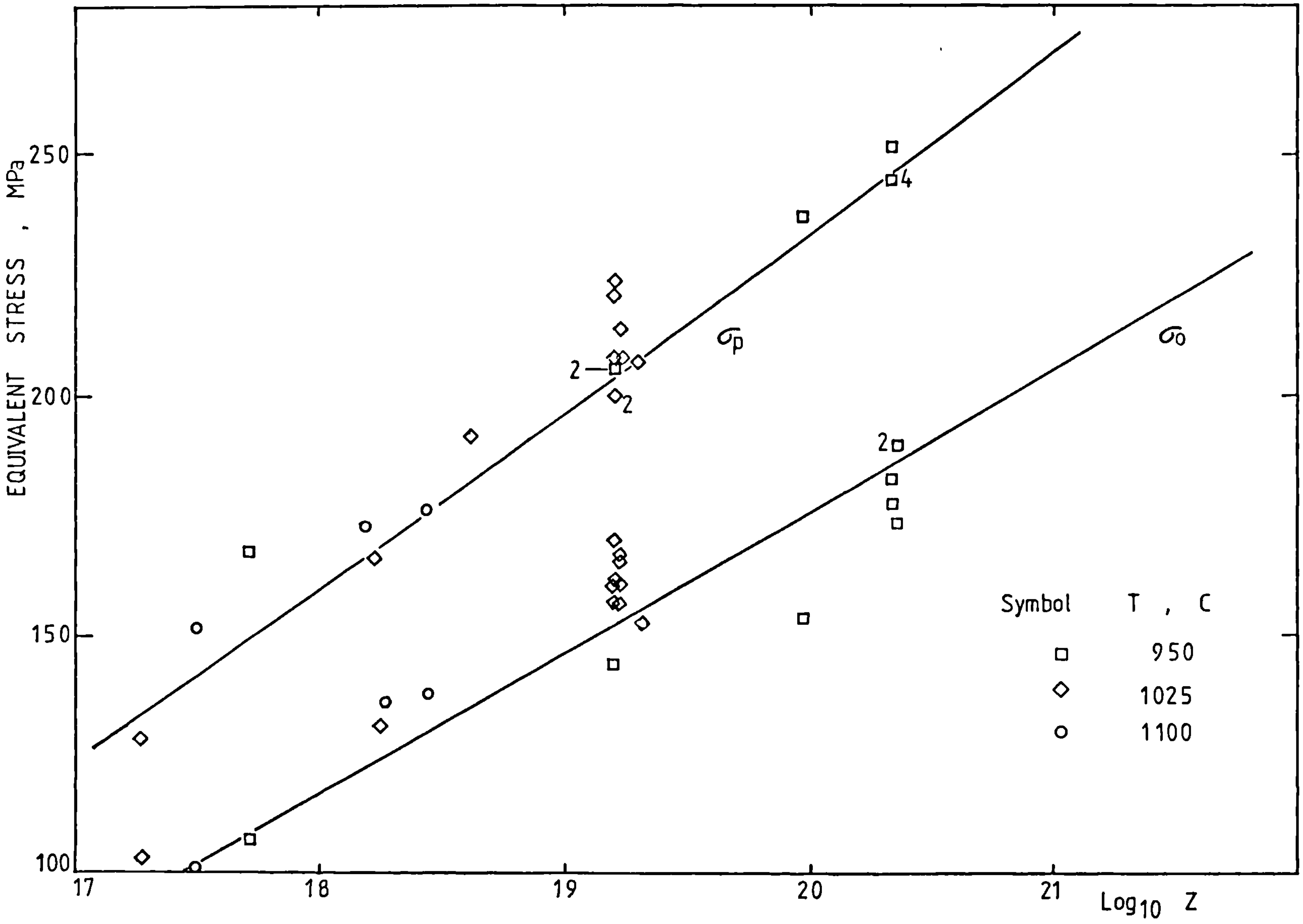

EQUIVALENT STRESS , MPa
250
200
150
100
17
18
19
20
21
Log10 Z
σp
σo
2
4
2
2
Symbol T , C
□ 950
◇ 1025
○ 1100

FIGURE 6.8 : Dependence of the stress at an equivalent strain of 0.1, $\sigma_{0.1}$, on the Zener-Hollomon parameter. Numbers near symbols have the same meaning as in figure(6.7).

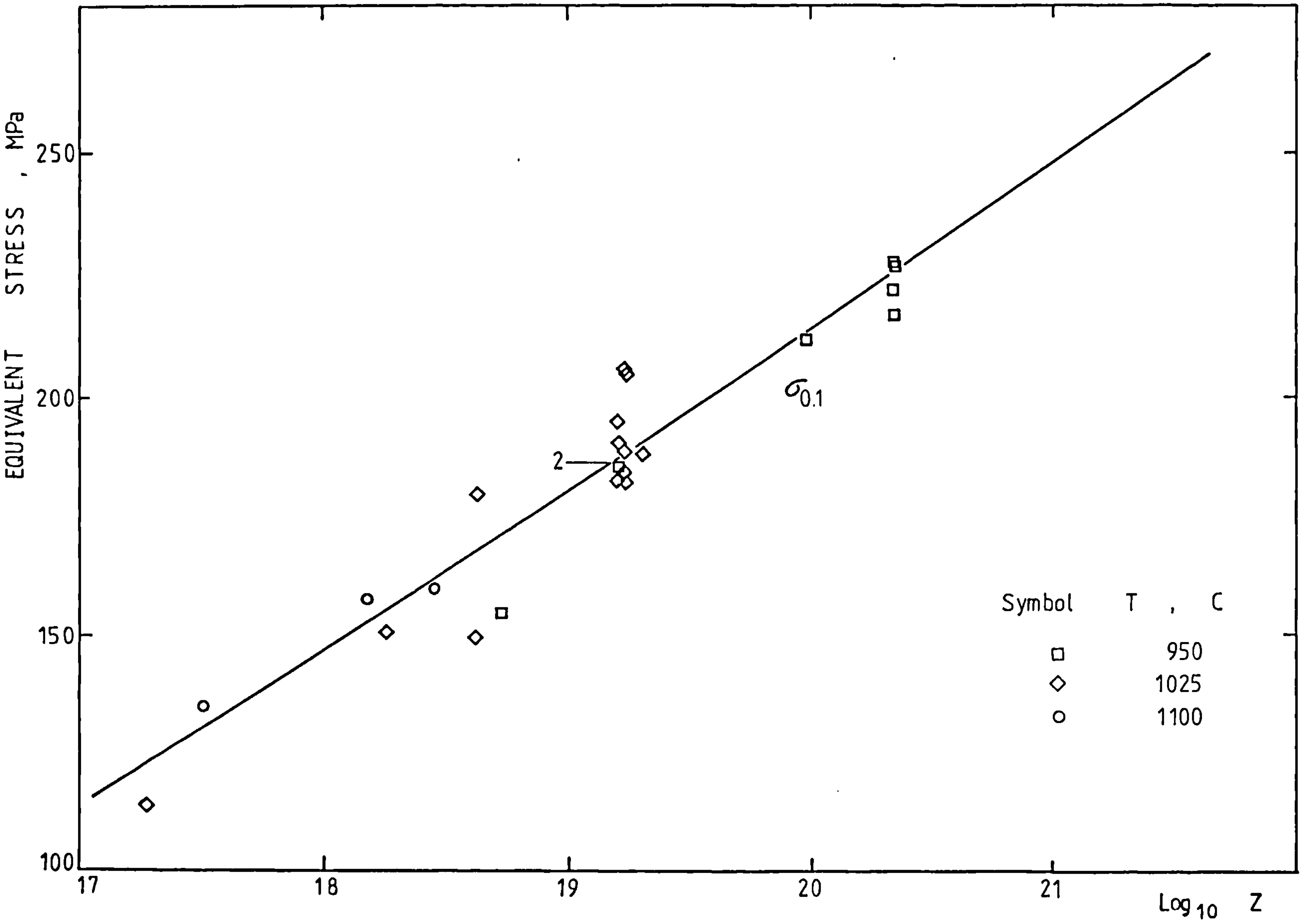

EQUIVALENT STRESS , MPa
250
200
150
100
17
18
19
20
21
Log$_{10}$ Z
$\sigma_{0.1}$
2
Symbol T , C
□ 950
◇ 1025
○ 1100

FIGURE 6.9 : Dependence of the stress at steady state, σ_{ss}, on the Zener-Hollomon paramenter. Numbers near symbols are as in figure(6.7).

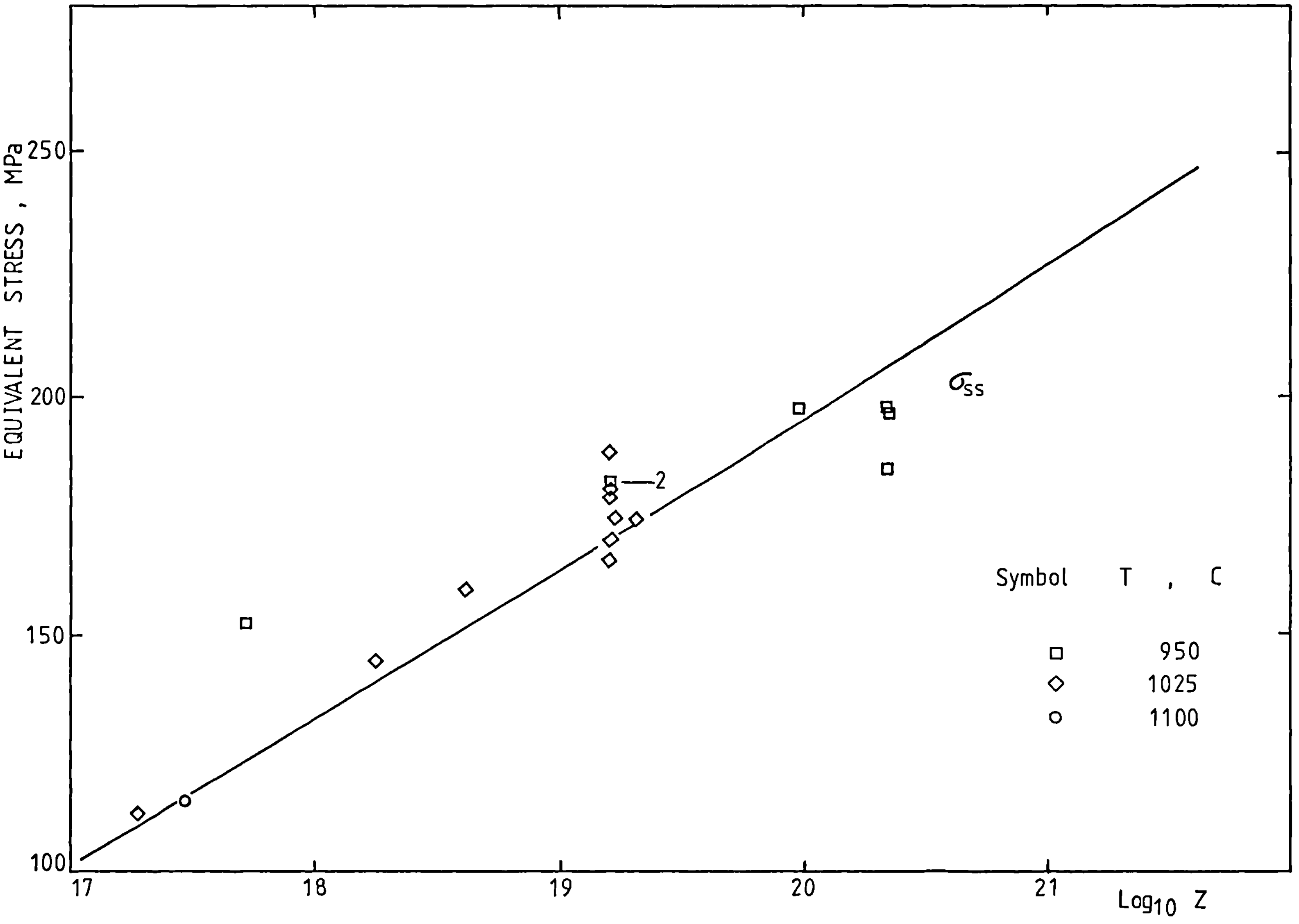

EQUIVALENT STRESS , MPa
250
200
150
100
17
18
19
20
21
Log$_{10}$ Z
σ_{ss}
2
Symbol T , C
□ 950
◇ 1025
○ 1100

FIGURE 6.10 : Stress strain curves for AISI316 samples tested under plane strain compression. The samples' original grain size 100μm.

solid line- Theoretical curve

dotted line- Experimental one.

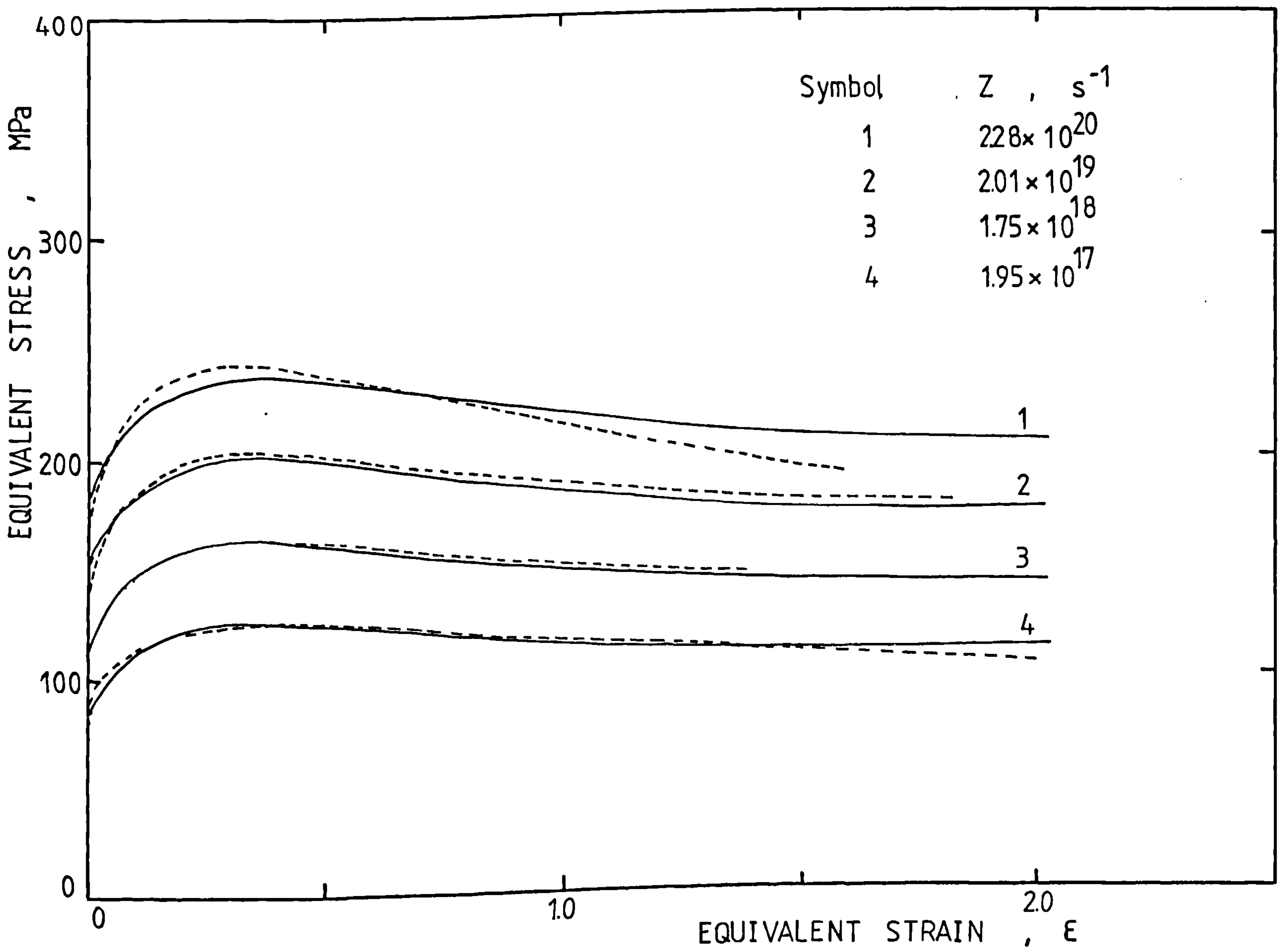

Symbol
Z , s^{-1}
1 2.28×10^{20}
2 2.01×10^{19}
3 1.75×10^{18}
4 1.95×10^{17}
1
2
3
4
400
300
200
100
0
EQUIVALENT STRESS , MPa
0
1.0
2.0
EQUIVALENT STRAIN , ε

FIGURE 6.11 : Static recrystallization kinetics of AISI316 with original grain size 260 μm deformed at 950C under plane strain compression.

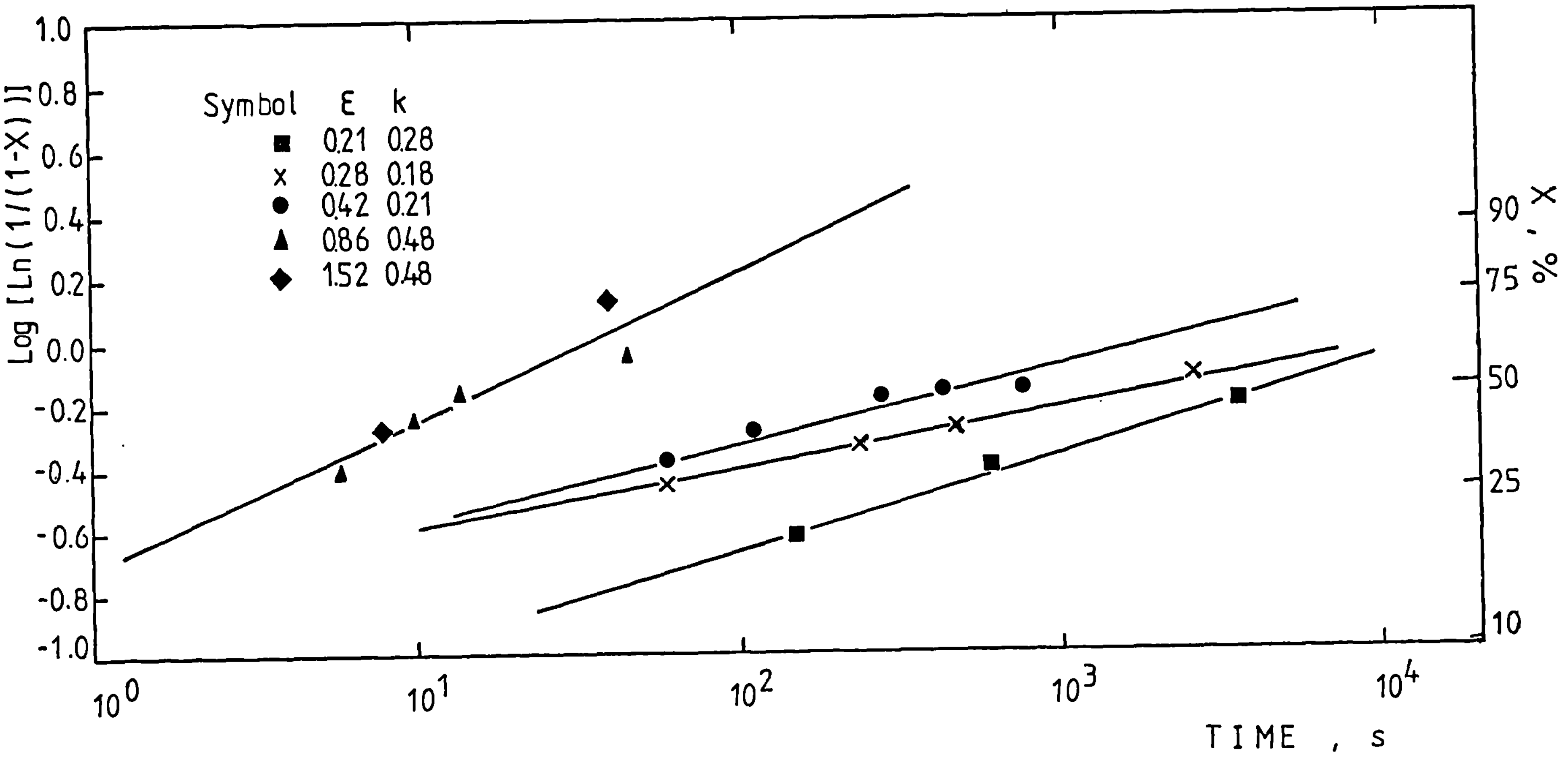

Symbol ε k
■ 0.21 0.28
x 0.28 0.18
● 0.42 0.21
▲ 0.86 0.48
◆ 1.52 0.48
Log [Ln(1/(1-X))]
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
X, %
90
75
50
25
10
10^0
10^1
10^2
10^3
10^4
TIME, s

FIGURE 6.12 : Static recrystallization kinetics of AISI316 with original grain size 260 μm deformed at 1025C under plane strain compression.

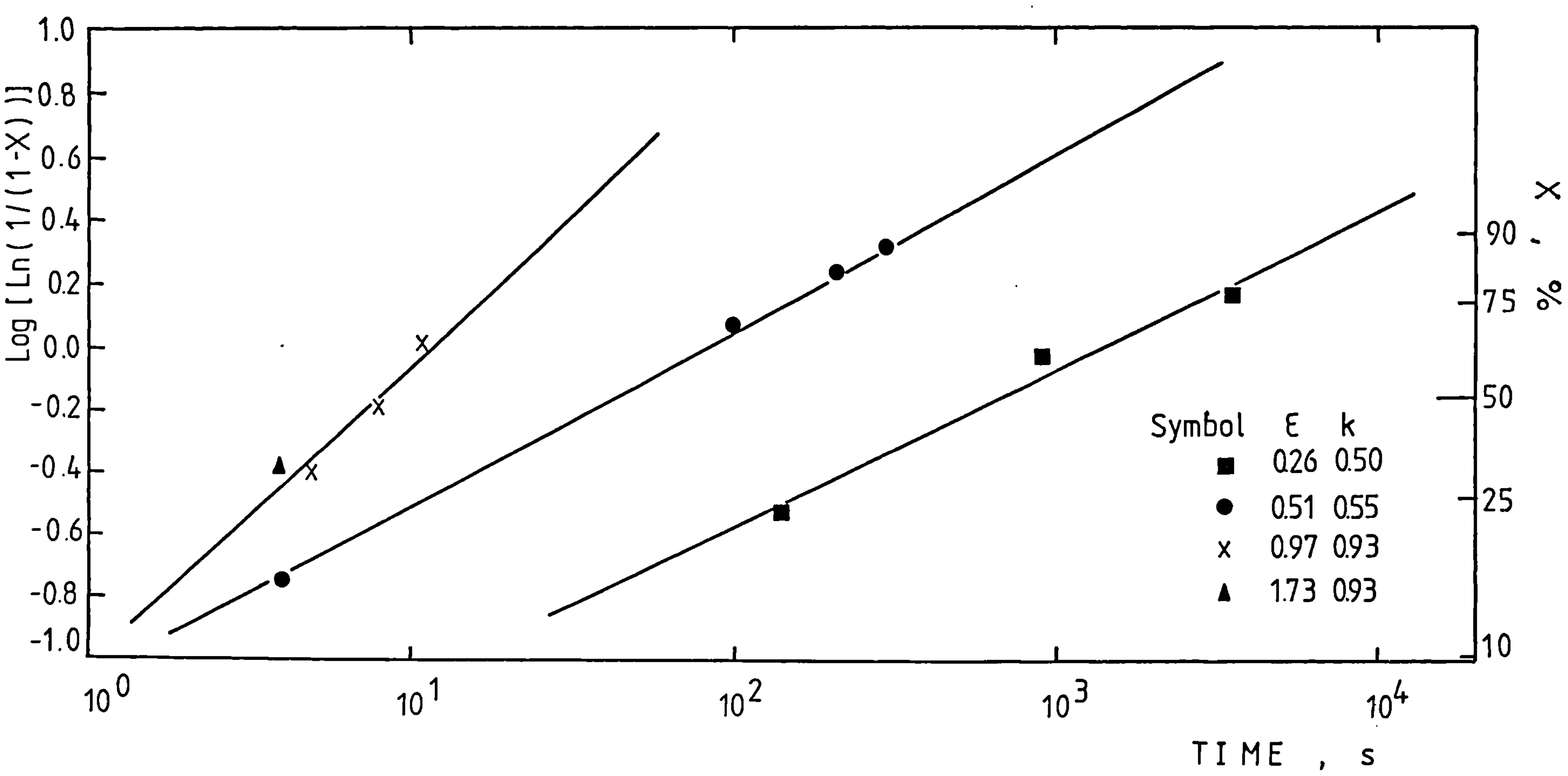
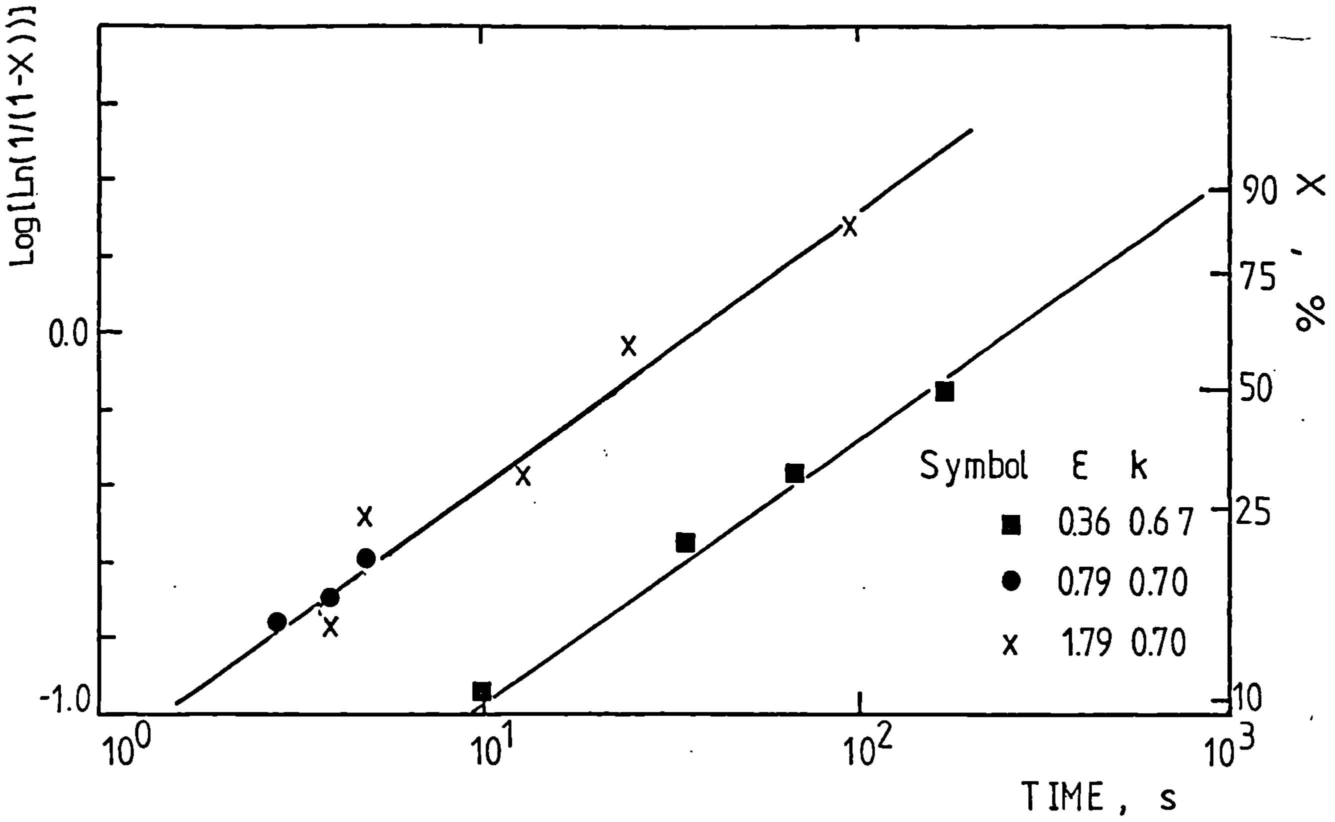

Log [Ln (1/ (1-X))]
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
10^0
10^1
10^2
10^3
10^4
TIME , s
X , %
90
75
50
25
10
Symbol ε k
■ 0.26 0.50
● 0.51 0.55
x 0.97 0.93
▲ 1.73 0.93

FIGURE 6.13 : Static recrystallization kinetics of AISI316 with original grain size 100 μm deformed at 950C under plane strain compression.

FIGURE 6.14 : Static recrystallization kinetics of AISI316 with original grain size 100 μm deformed at 1025C under plane strain compression.


Log[Ln(1/(1-X))]
0.0
-1.0
10^0
10^1
10^2
10^3
TIME, s
90
75
50
25
10
X, %
Symbol ε k
■ 0.36 0.67
● 0.79 0.70
x 1.79 0.70

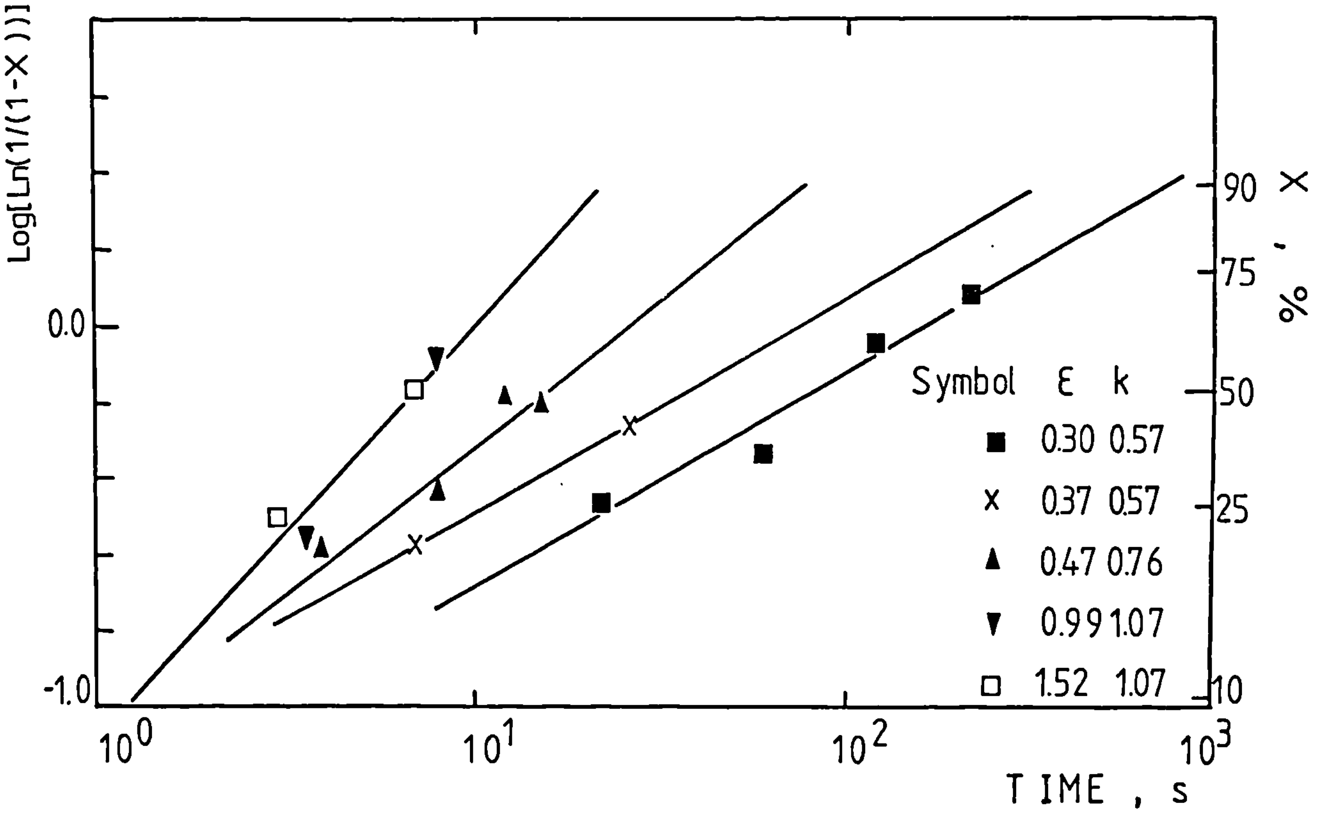
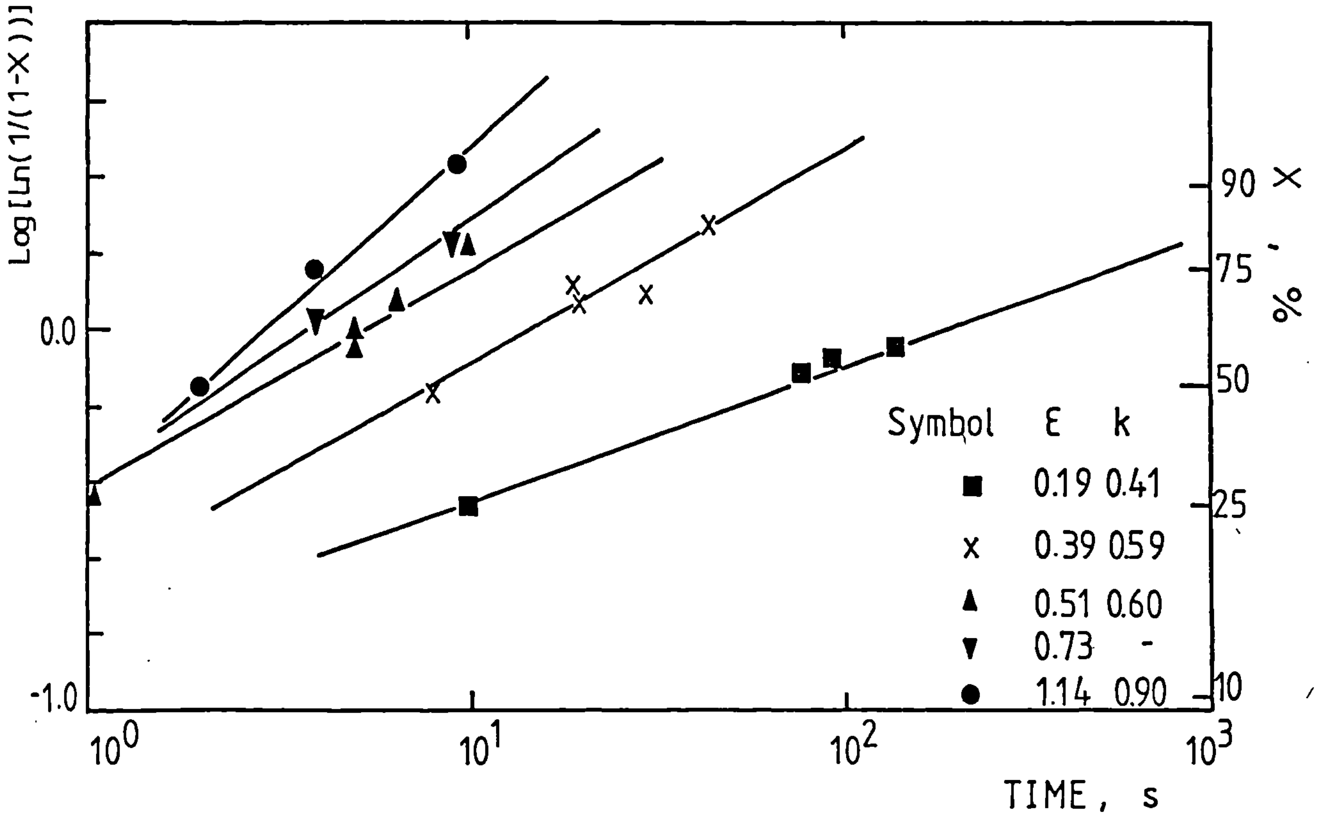

Log[Ln(1/(1-X))]
0.0
-1.0
10^0
10^1
10^2
10^3
TIME, s
90
75
50
25
10
X, %
Symbol ε k
■ 0.30 0.57
x 0.37 0.57
▲ 0.47 0.76
▼ 0.99 1.07
□ 1.52 1.07

FIGURE 6.15 : Static recrystallization kinetics of AISI316 with original grain size 100 μm deformed at 1100C under plane strain compression.

FIGURE 6.16 : Static recrystallization kinetics of AISI316 with original grain size 191 μm hot rolled at 950C (temperature measured at the centre of the slab at the entry of the rolling gap).


Log[Ln(1/(1-X))]
0.0
-1.0
10^0
10^1
10^2
10^3
TIME, s
90
75
50
25
10
X %
Symbol ε k
■ 0.19 0.41
x 0.39 0.59
▲ 0.51 0.60
▼ 0.73 -
● 1.14 0.90

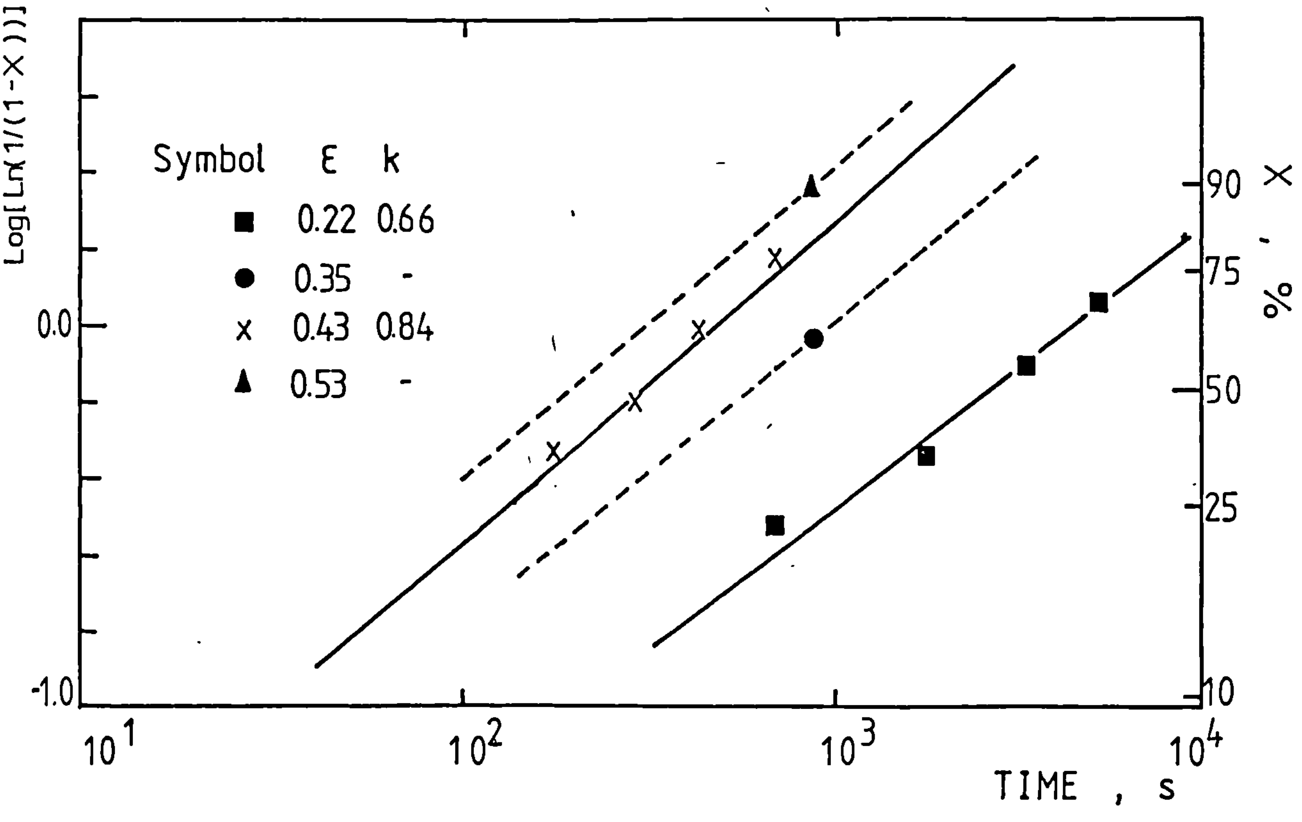

Log[Ln(1/(1-X))]
0.0
-1.0
10^1
10^2
10^3
10^4
TIME , s
90
75
50
25
10
X %
Symbol ε k
■ 0.22 0.66
● 0.35 -
x 0.43 0.84
▲ 0.53 -

FIGURE 6.17 : Static recrystallization kinetics of AISI316 with original grain size 100 μm deformed at 1025C under axisymmetric compression.

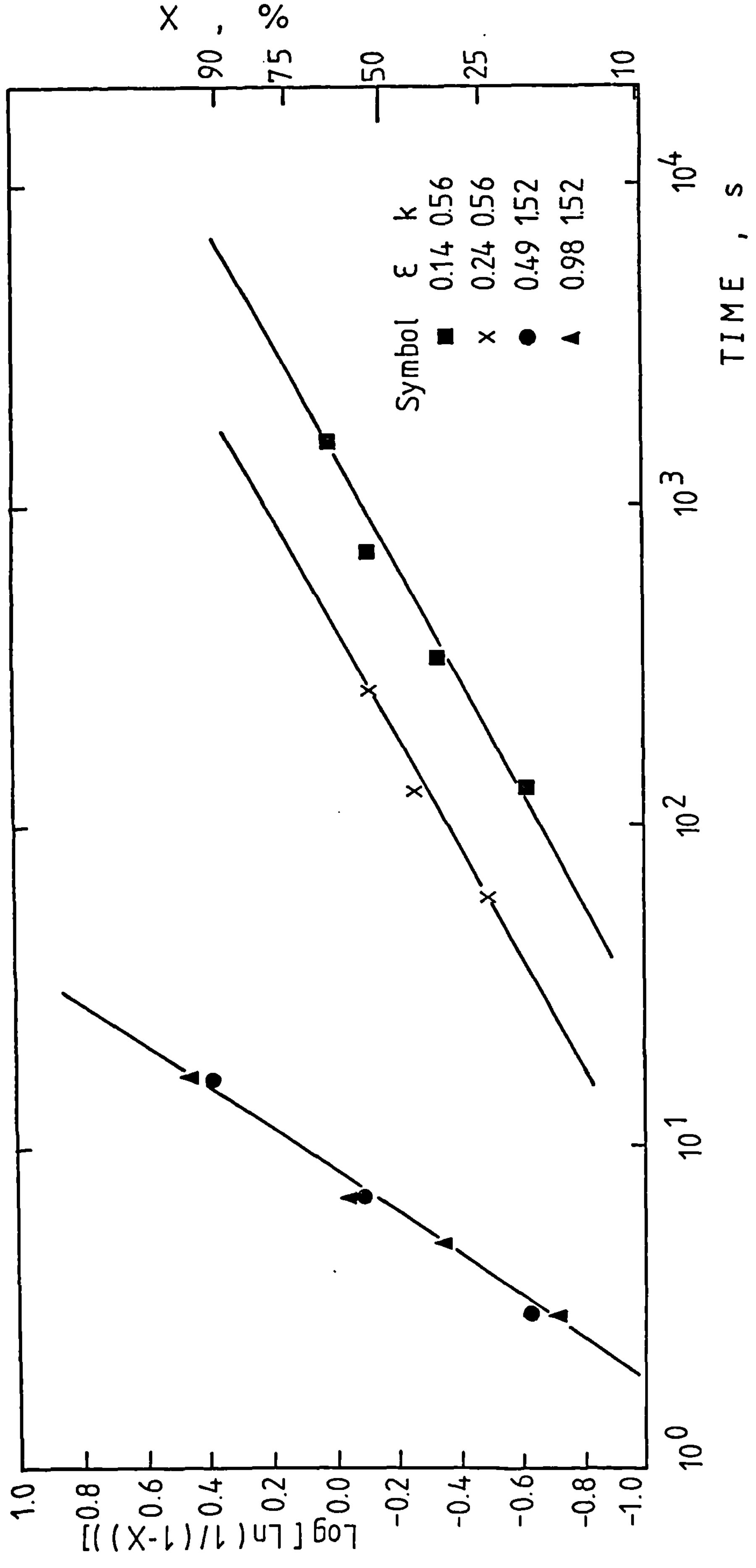

X , %
90
75
50
25
10
Symbol ε k
■ 0.14 0.56
× 0.24 0.56
● 0.49 1.52
▲ 0.98 1.52
10^0
10^1
10^2
10^3
10^4
TIME , s
Log [Ln (1/ (1-X))]
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0

FIGURE 6.18 : Time for 50% of material to recrystallize statically as a function of the applied equivalent strain for samples tested under plane strain compression.

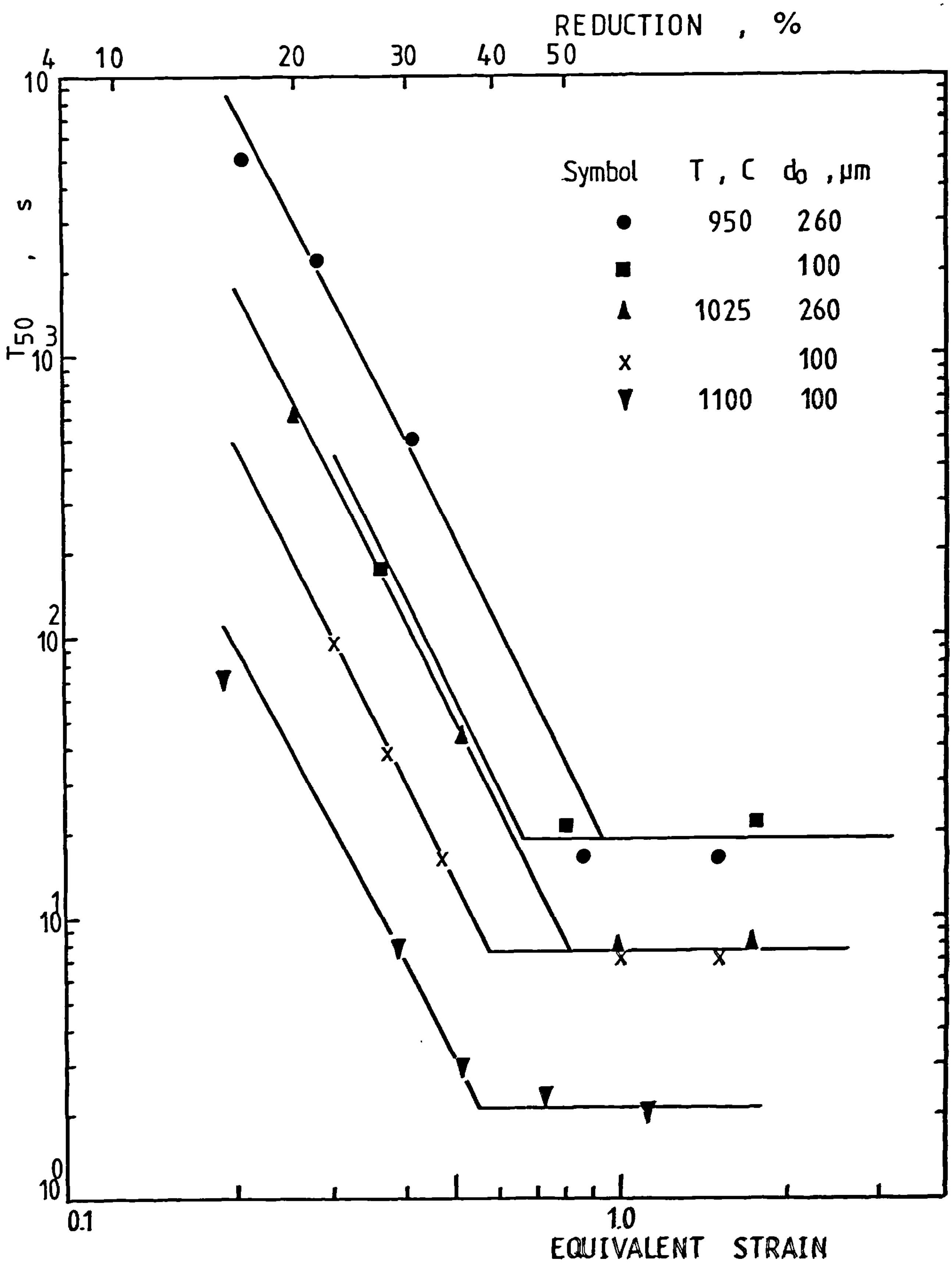

REDUCTION , %
10
20
30
40
50
10^4
10^3
10^2
10^1
10^0
T_{50} , s
0.1
1.0
EQUIVALENT STRAIN
Symbol T , C d_0 , μm
● 950 260
■ 100
▲ 1025 260
x 100
▼ 1100 100

FIGURE 6.19 : Time for 50% of material to recrystallize statically as a function of the applied equivalent strain for samples tested under axisymmetric compression and hot rolled.

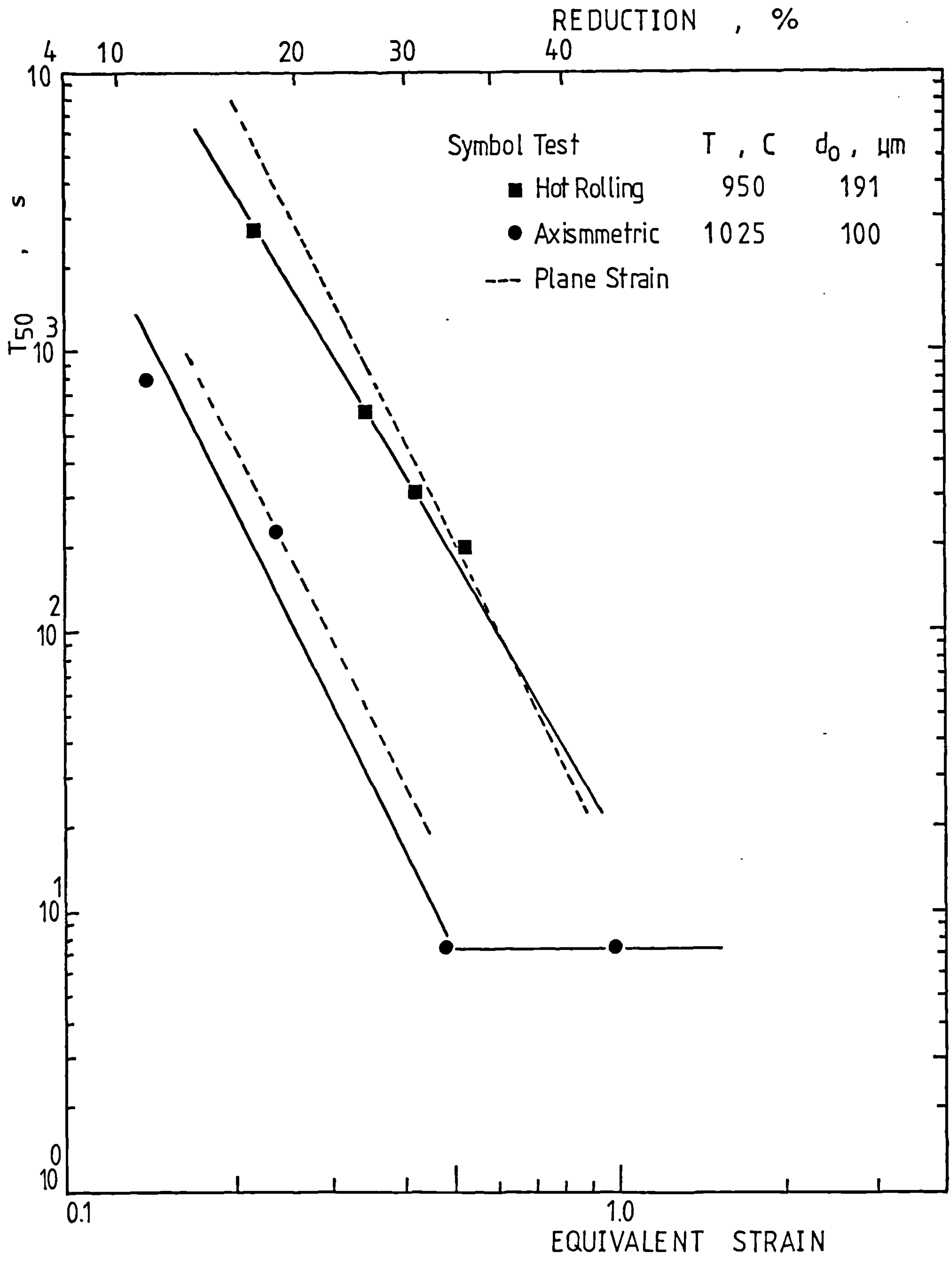
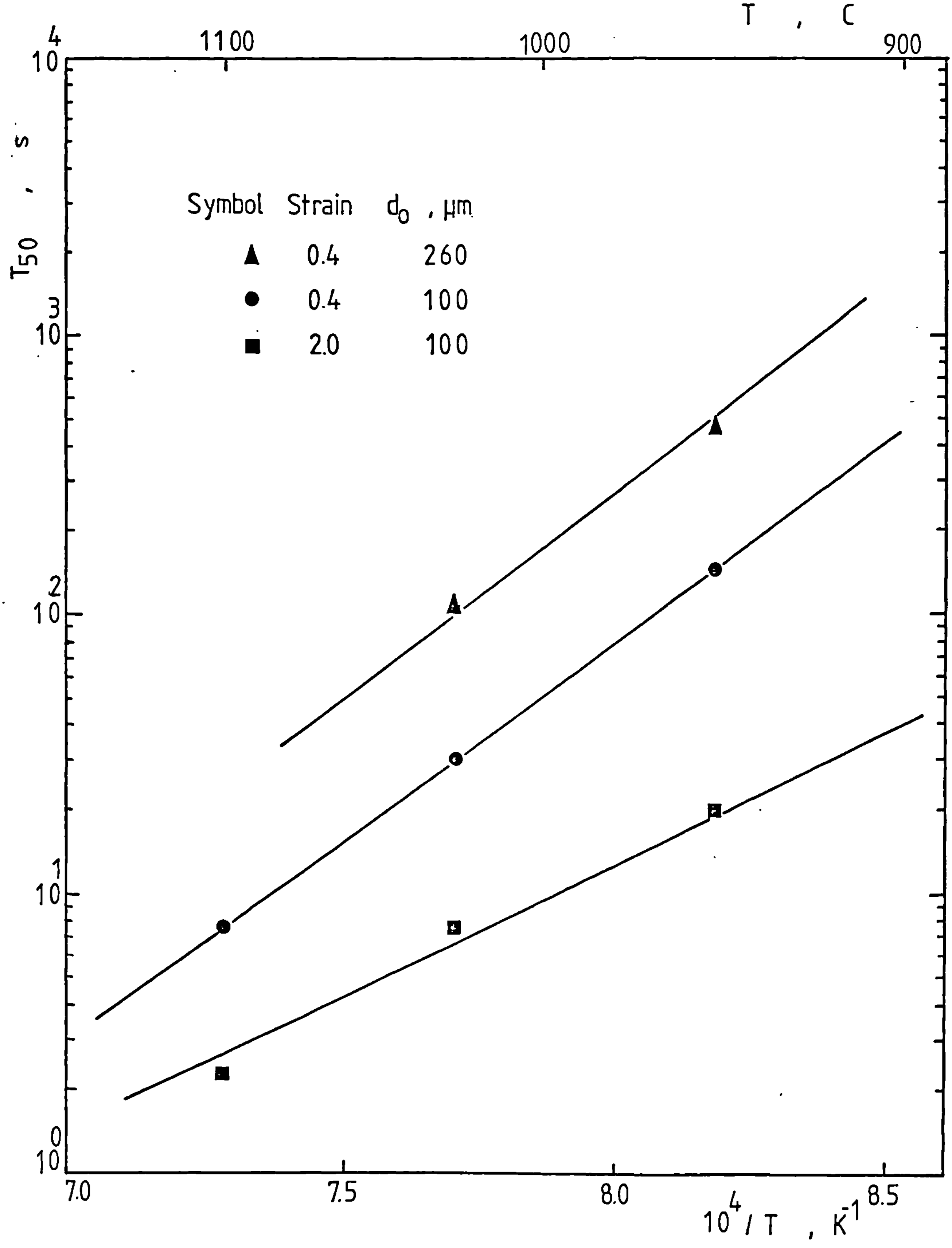

REDUCTION , %
4
10
20
30
40
T_{50} , s
10^4
10^3
10^2
10^1
10^0
0.1
1.0
EQUIVALENT STRAIN
Symbol Test T , C d_0 , μm
■ Hot Rolling 950 191
● Axismmetric 1025 100
--- Plane Strain

FIGURE 6.20 : Effect of the test temperature on the time for 50% recrystallization. Samples were tested under plane strain compression at a strain rate of $5s^{-1}$.



T , C
1100
1000
900
T_{50} , s
10^4
10^3
10^2
10^1
10^0
Symbol Strain d_0 , µm
▲ 0.4 260
● 0.4 100
■ 2.0 100
7.0
7.5
8.0
8.5
10^4 / T , K^{-1}

FIGURE 6.21 : The time for 50% recrystallization dependence on the original grain size.

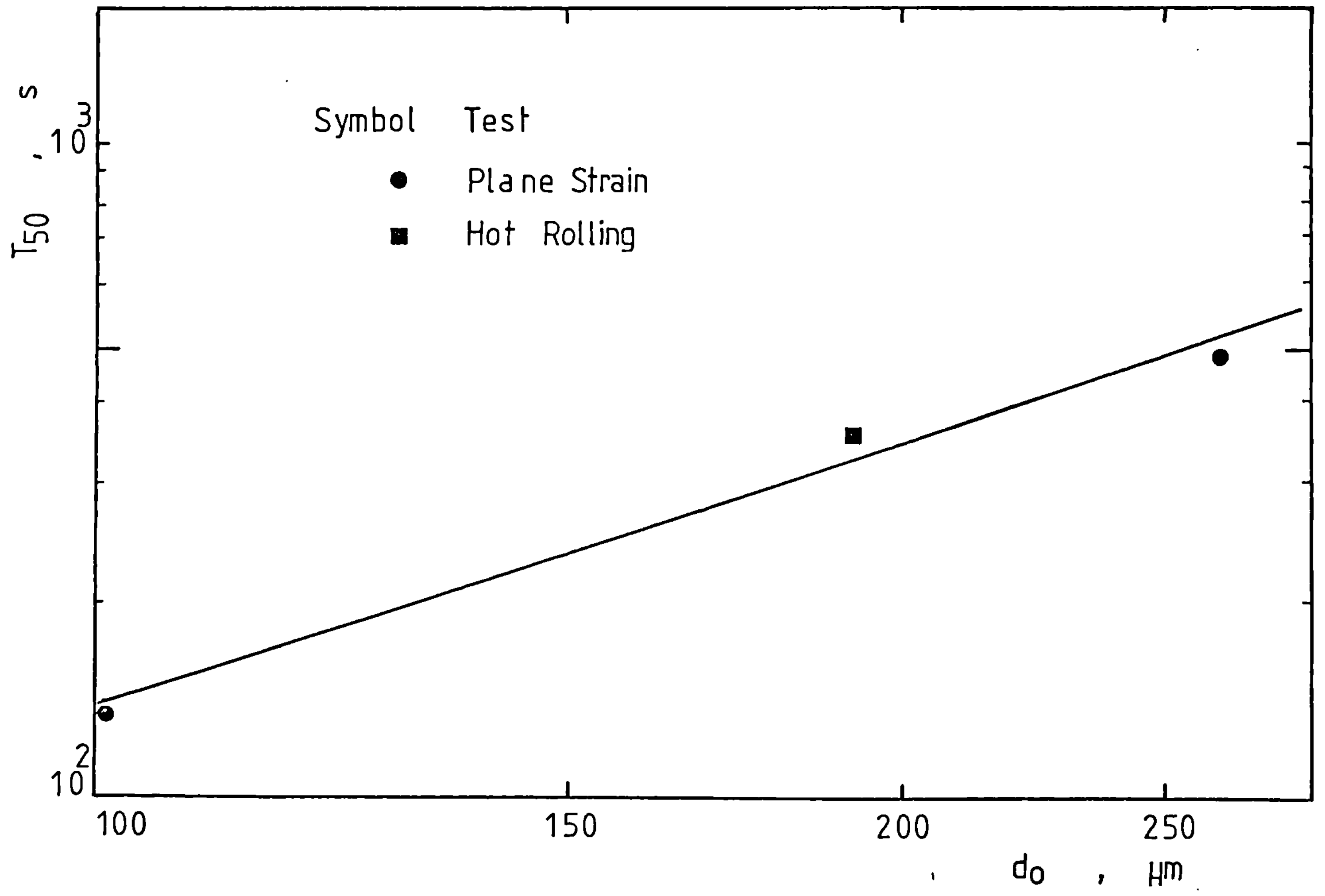

T_{50} , s
10^3
10^2
Symbol Test
● Plane Strain
■ Hot Rolling
100
150
200
250
d_o , μm

FIGURE 6.22 : Correlation of the time for 50% of the material to recrystallize with hot working variables and the original grain size.

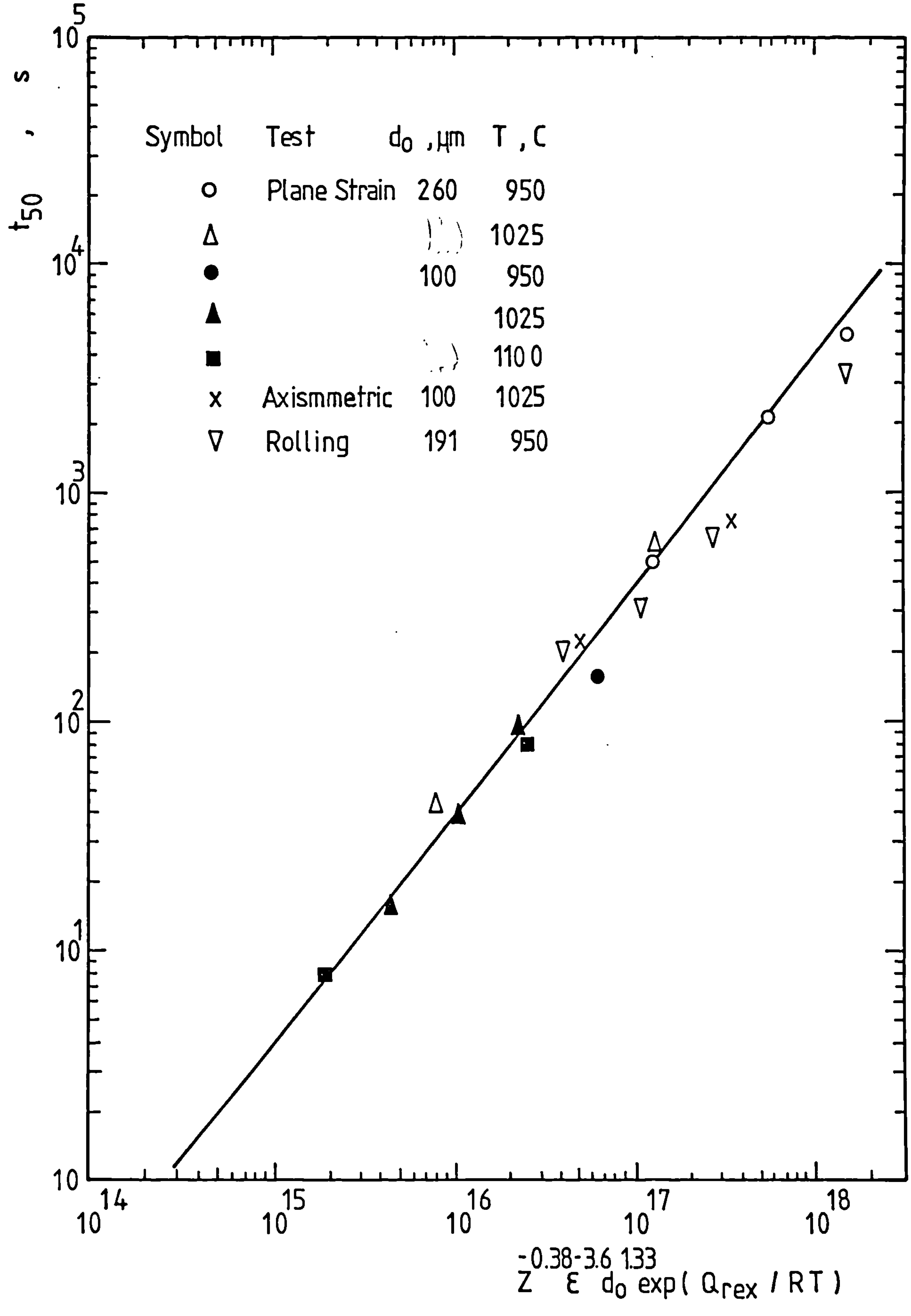

t_{50} , s
10^5
10^4
10^3
10^2
10^1
10
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
$Z^{-0.38} \varepsilon^{-3.6} d_0^{1.33} \exp(Q_{rex}/RT)$
Symbol Test d_0 ,μm T , C
○ Plane Strain 260 950
Δ " " 1025
● 100 950
▲ 1025
■ " 1100
x Axismmetric 100 1025
∇ Rolling 191 950

FIGURE 6.23 : Correlation of the time for 50% of material to recrystallize with the expression $Z^{-0.38} \exp Q_{rex}/R\,T$.

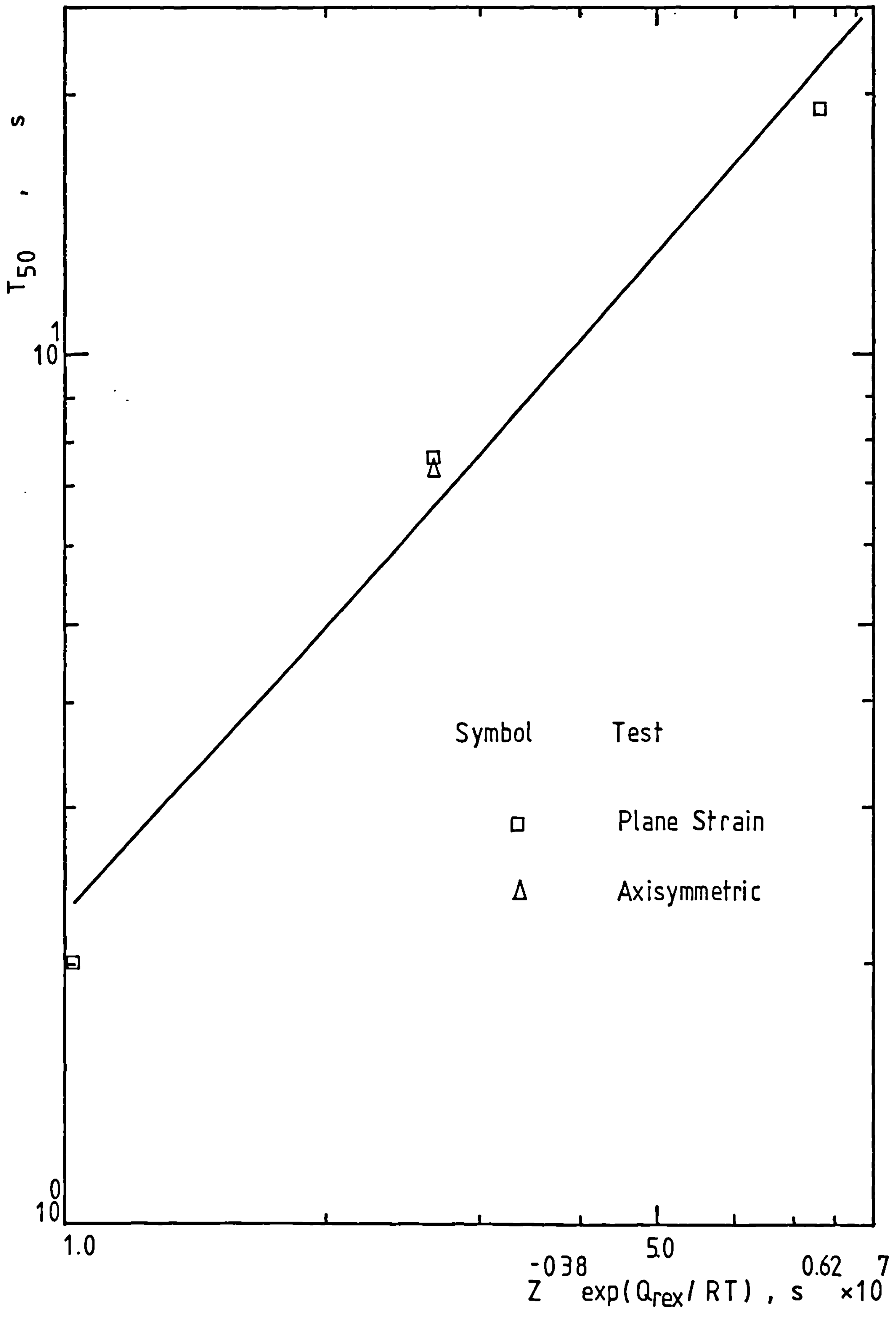
T_{50} , s
10^1
10^0
1.0
5.0
$Z^{-0.38} \exp(Q_{rex}/RT)$, $s^{0.62}$ $\times 10^7$
Symbol
Test
□
Plane Strain
Δ
Axisymmetric

FIGURE 6.24 : Dependence of the static recrystallized grain size on the equivalent strain for samples with original grain size 100μm, tested under plane strain compression at a strain rate of $5s^{-1}$.

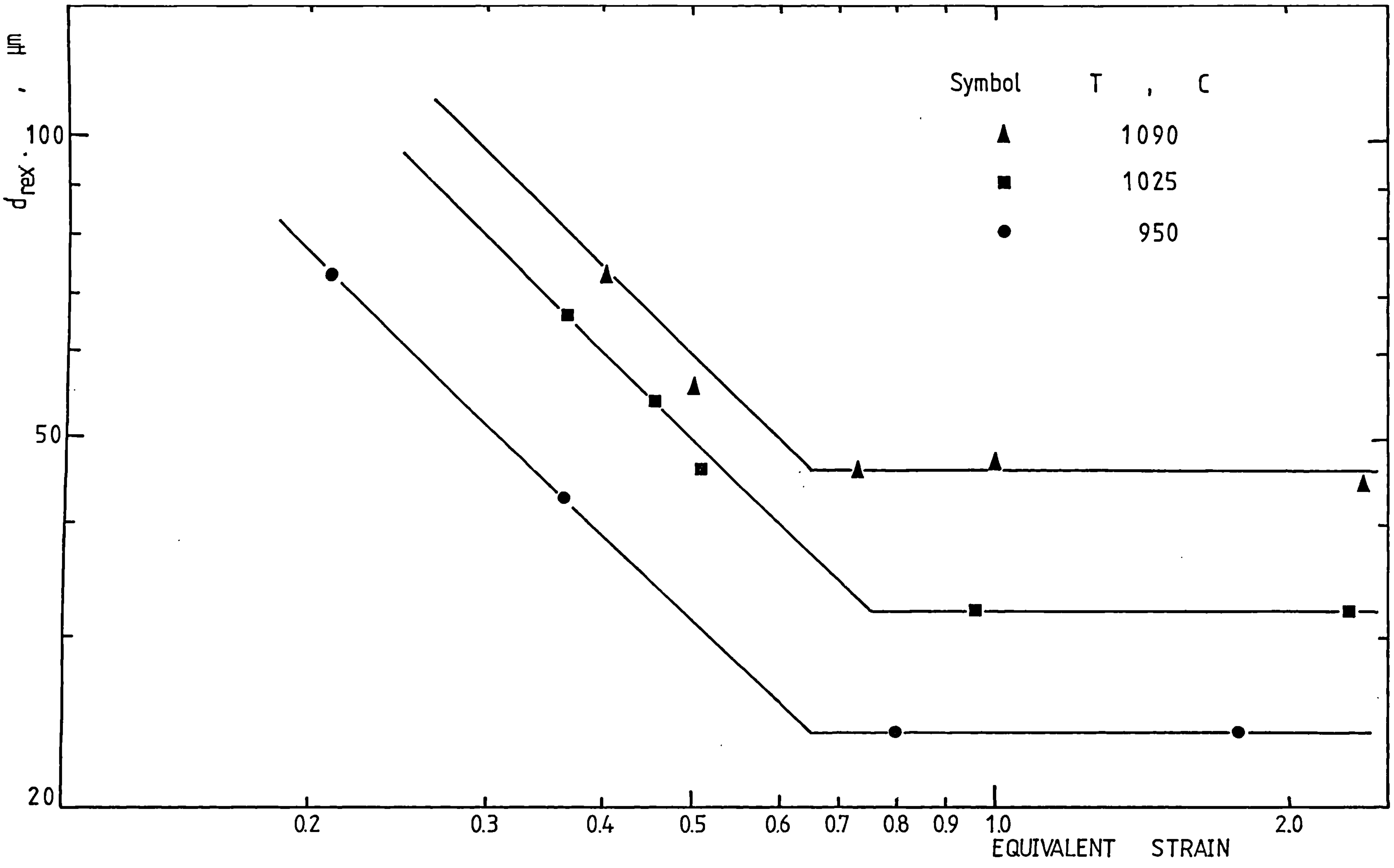
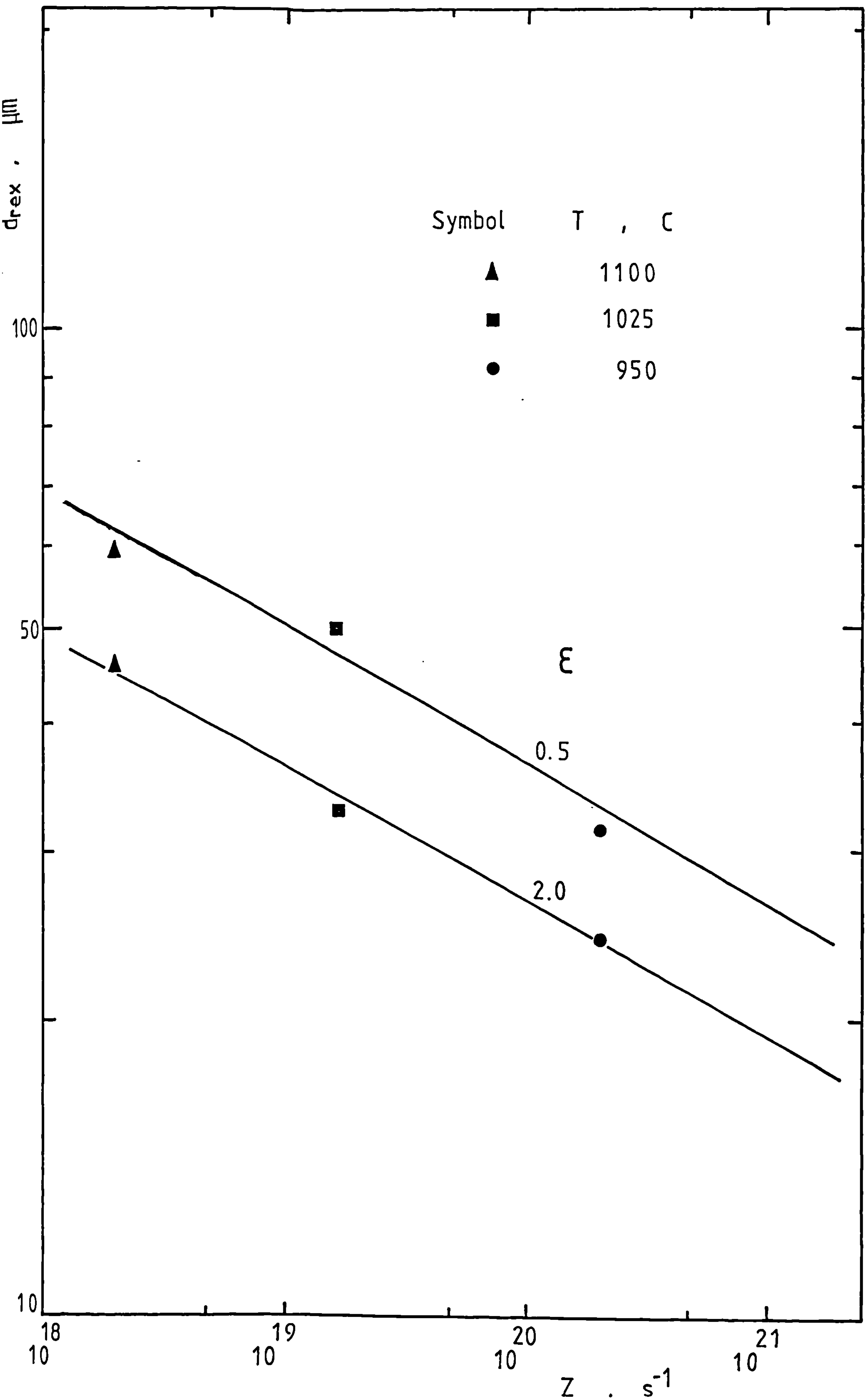
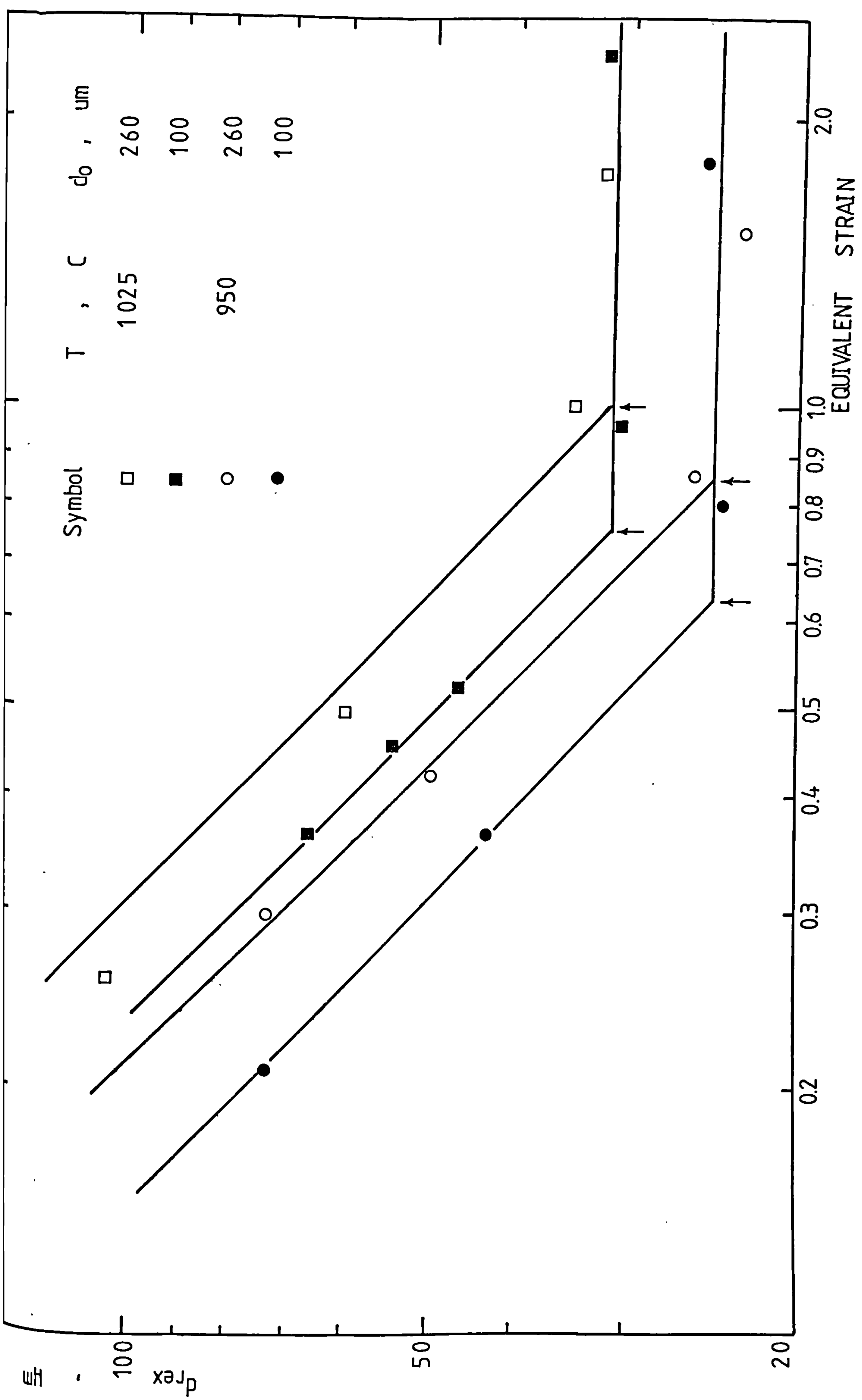

d_{rex} , µm
100
50
20
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2.0
EQUIVALENT STRAIN
Symbol T , C
▲ 1090
■ 1025
● 950

FIGURE 6.25 : Effect of the temperature-compensated strain rate parameter on the recrystallized grain size for samples of original grain size 100μm tested at $5s^{-1}$ under plane strain compression.



d_{rex} , μm
100
50
10
Symbol T , C
▲ 1100
■ 1025
● 950
ε
0.5
2.0
10^{18}
10^{19}
10^{20}
10^{21}
Z , s^{-1}

FIGURE 6.26 : Effect of the original grain size on the recrystallized grain size for samples tested at strains higher and lower than ε_*, critical strain (indicated by arrows).



Symbol
T, C
d_o, um
□ 1025 260
■ 100
○ 950 260
● 100
d_{rex}, μm
100
50
20
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2.0
EQUIVALENT STRAIN

FIGURE 6.27 : Effect of the original grain size on the recrystallized grain size for specimens deformed at 950C and $5s^{-1}$.

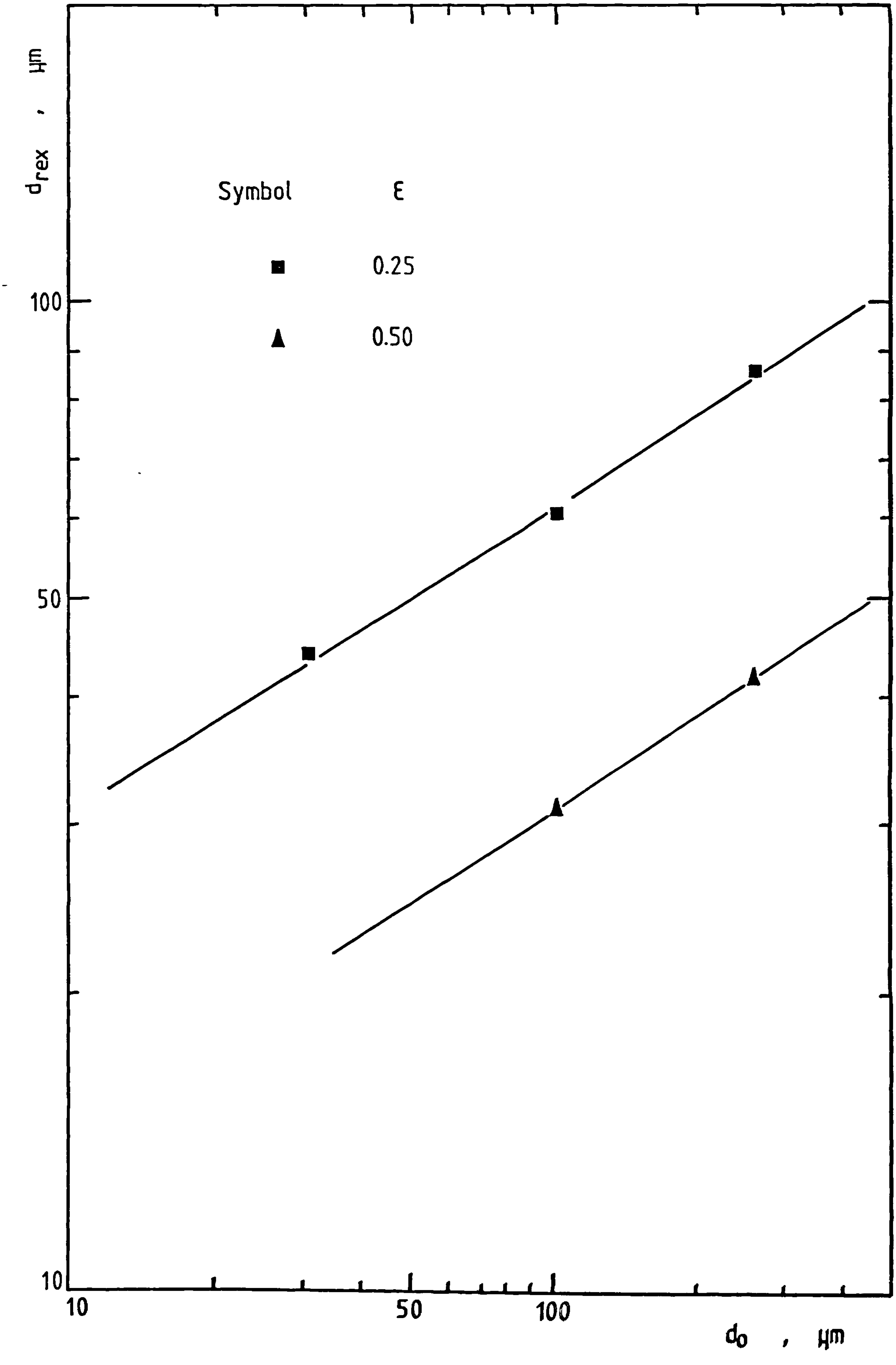
d_{rex} , μm
Symbol
ε
■ 0.25
▲ 0.50
100
50
10
10
50
100
d_0 , μm

FIGURE 6.28 : Correlation of recrystallized grain size with a function of deformation variables and original grain size.

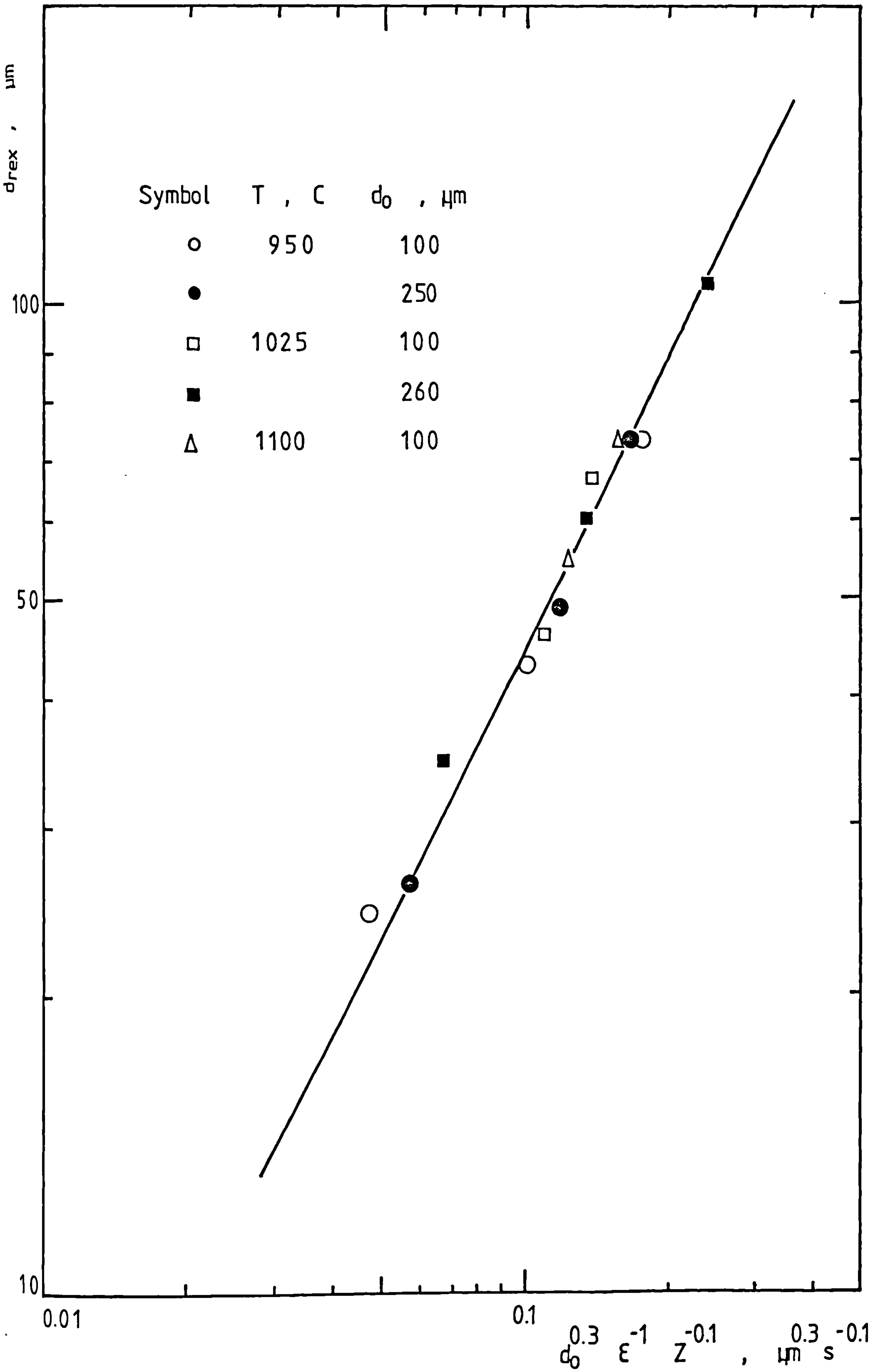
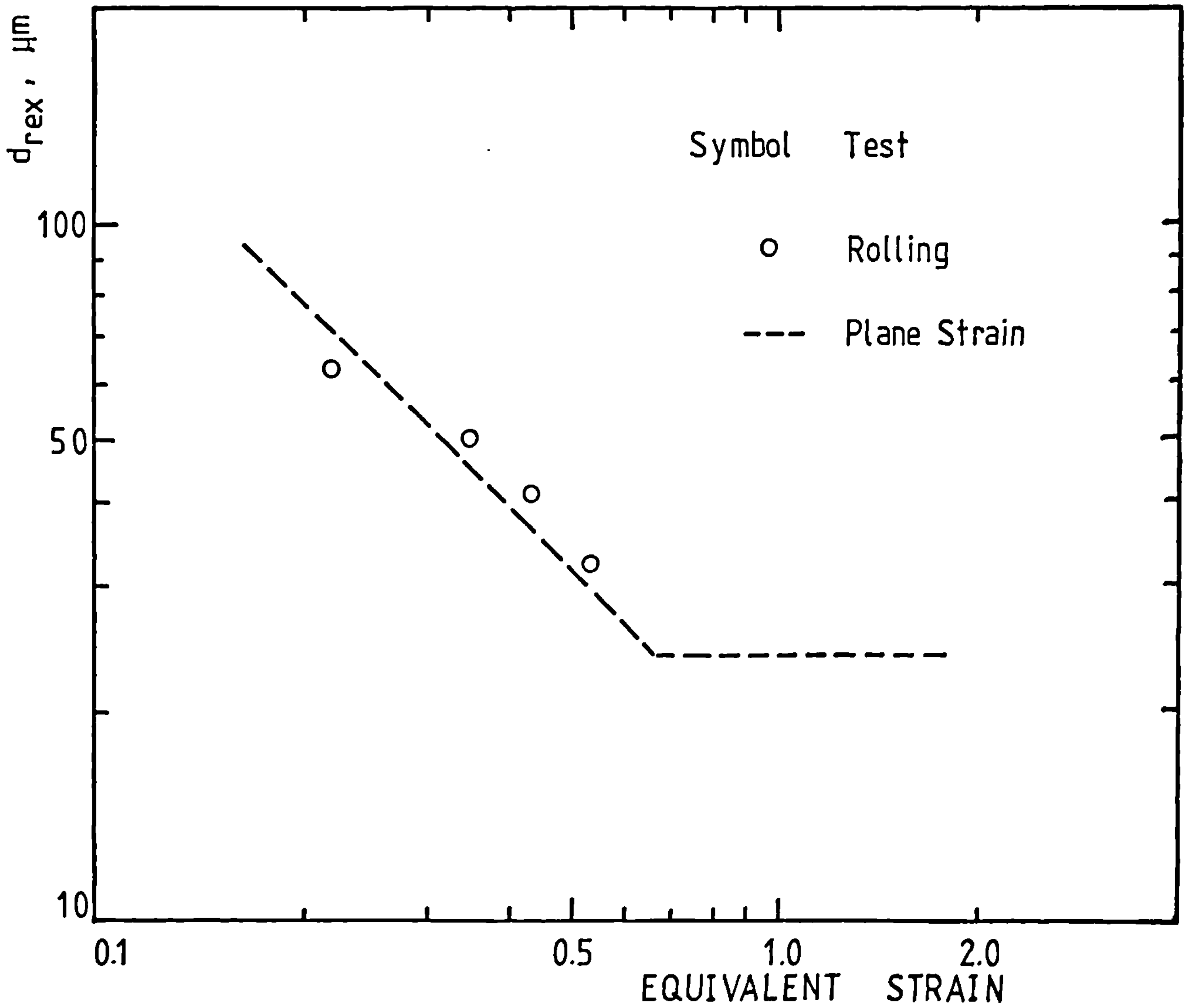

d_{rex} , µm
Symbol T , C d_0 , µm
○ 950 100
● 250
□ 1025 100
■ 260
Δ 1100 100
100
50
10
0.01
0.1
$d_0^{0.3}$ ε^{-1} $Z^{-0.1}$, $\mu m^{0.3}$ $s^{-0.1}$

FIGURE 6.29 : Recrystallized grain size dependence on the strain for samples deformed by hot rolling. Dotted line represents similar dependence found for samples tested under plane strain compression.



d_{rex}, μm
100
50
10
0.1
0.5
1.0
2.0
EQUIVALENT STRAIN
Symbol Test
○ Rolling
--- Plane Strain

FIGURE 6.30 : Grain growth evolution of AISI316 during isothermal annealing. Full line represents values predicted by the use of equation(3.29).

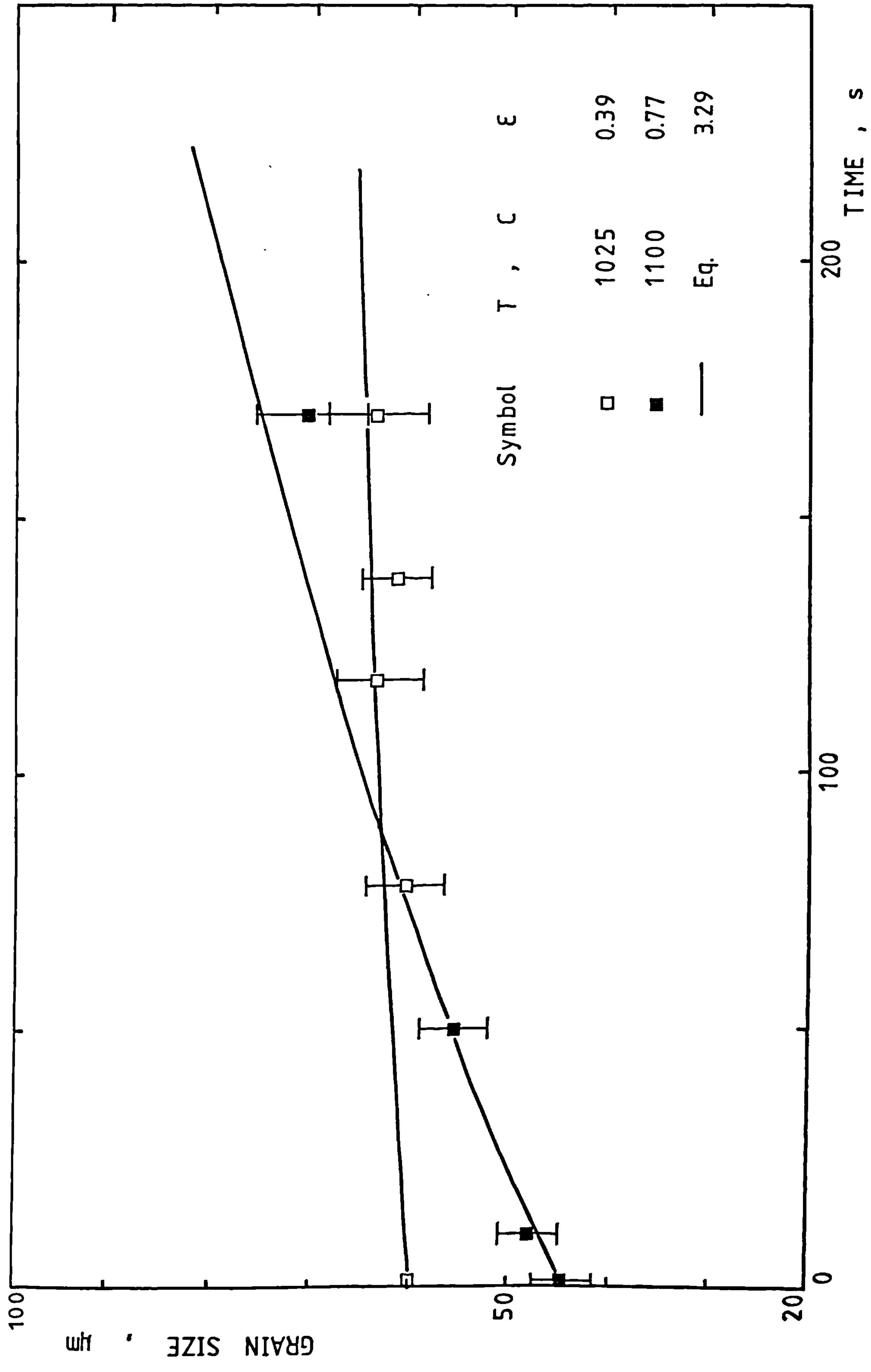

GRAIN SIZE , μm
100
50
20
TIME , s
0
100
200
Symbol T , C ε
□ 1025 0.39
■ 1100 0.77
— Eq. 3.29

FIGURE 7.1 : Strain distribution on a longitudinal cross section of a sample deformed under plane strain compression to a strain of 0.345. (After Beynon, 1979).

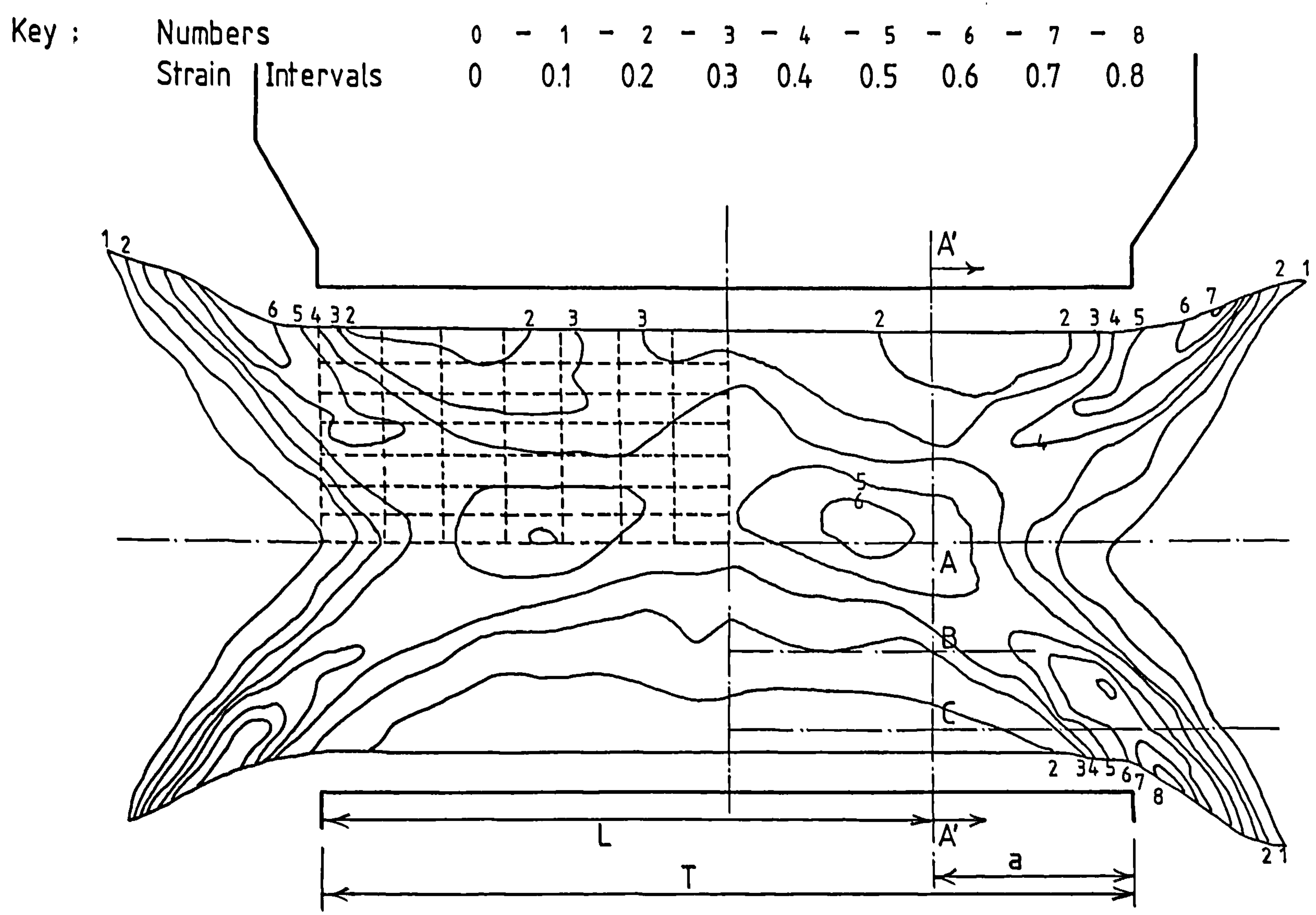
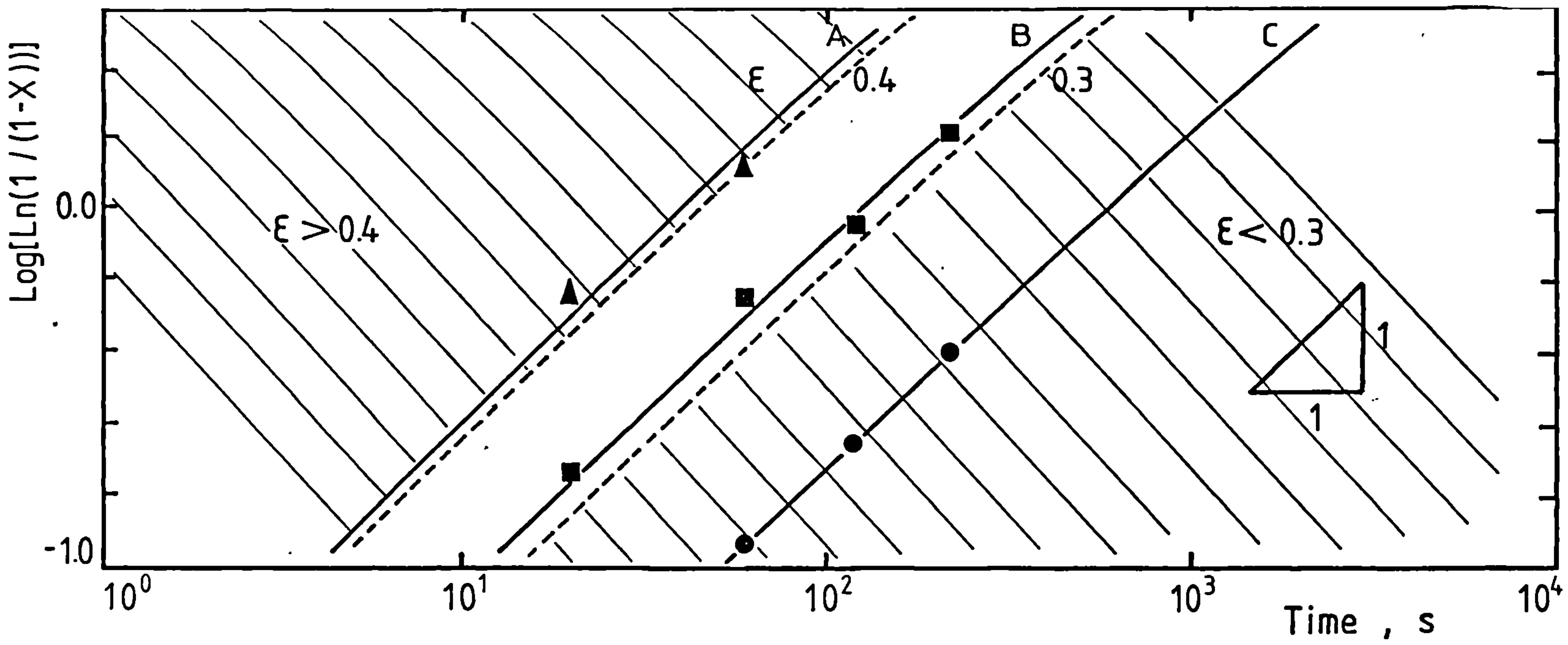

Key :
Numbers 0 – 1 – 2 – 3 – 4 – 5 – 6 – 7 – 8
Strain Intervals 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
1 2
6 5 4 3 2
2 3 3 2
2 3 4 5 6 7
2 1
4
5
6
A
B
C
A′
A′
2 3 4 5 6 7 8
2 1
L
T
a

FIGURE 7.2 : Recrystallization kinetics at lines of constant strain for samples deformed to a strain of 0.31 under plane strain compression.

FIGURE 7.3 : Total fraction of material recrystallized (full line) as a function of time. The dotted line is obtained from figure(6.14).


Log[Ln(1 / (1-X))]
0.0
-1.0
10^0
10^1
10^2
10^3
10^4
Time , s
A
B
C
ε
0.4
0.3
ε > 0.4
ε < 0.3
1
1

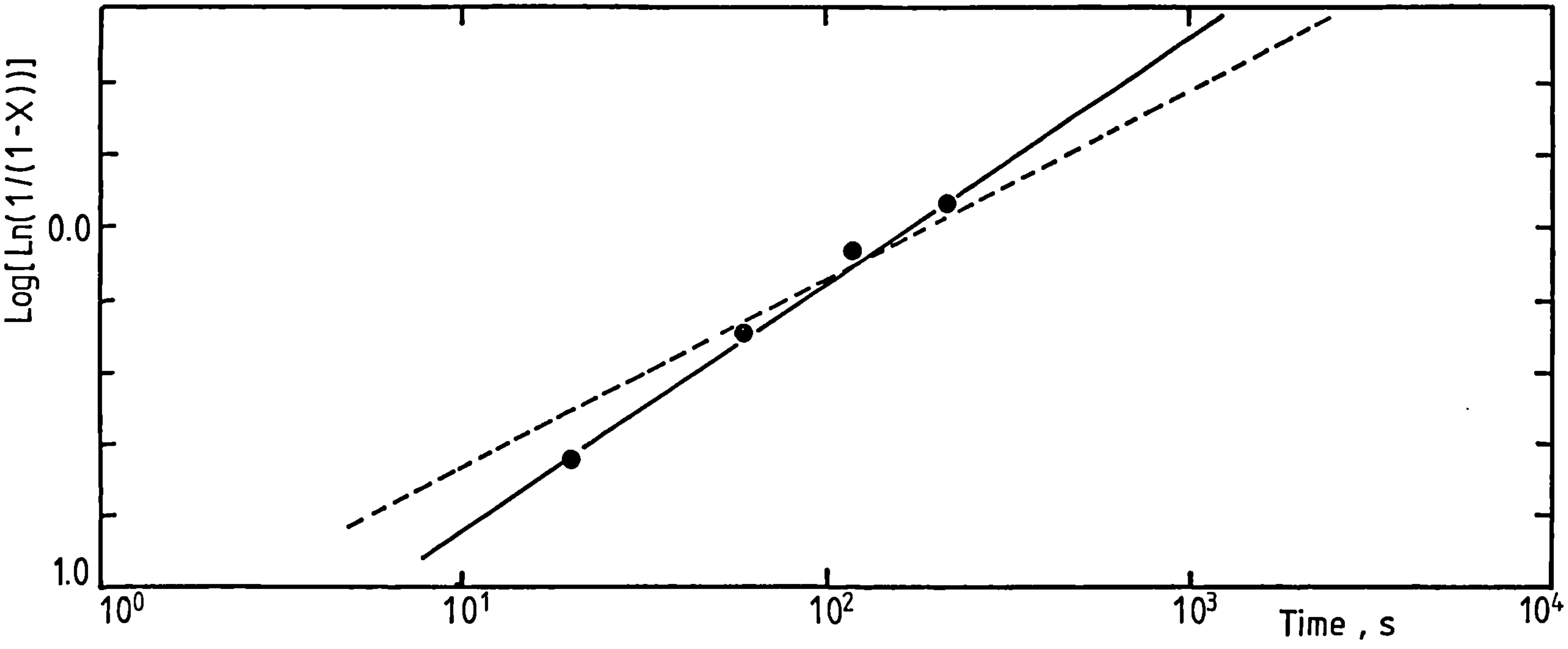

Log[Ln(1/(1-X))]
0.0
1.0
10^0
10^1
10^2
10^3
10^4
Time , s

FIGURE 7.4 : Fraction recrystallized dependence on the annealing time for curve B of figure(7.2). Points in brackets are extrapolated values from the Avrami plot in figure(7.2).

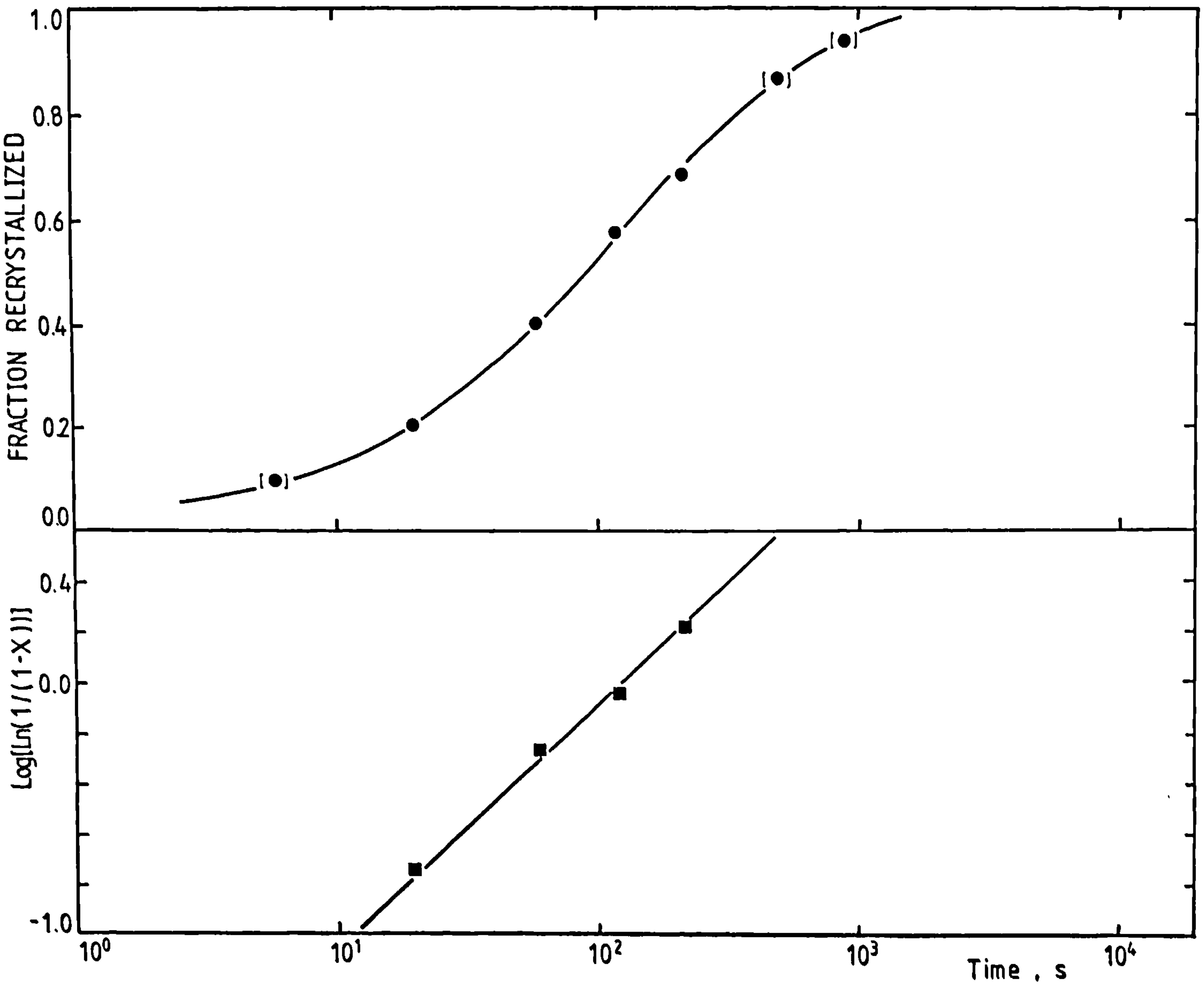
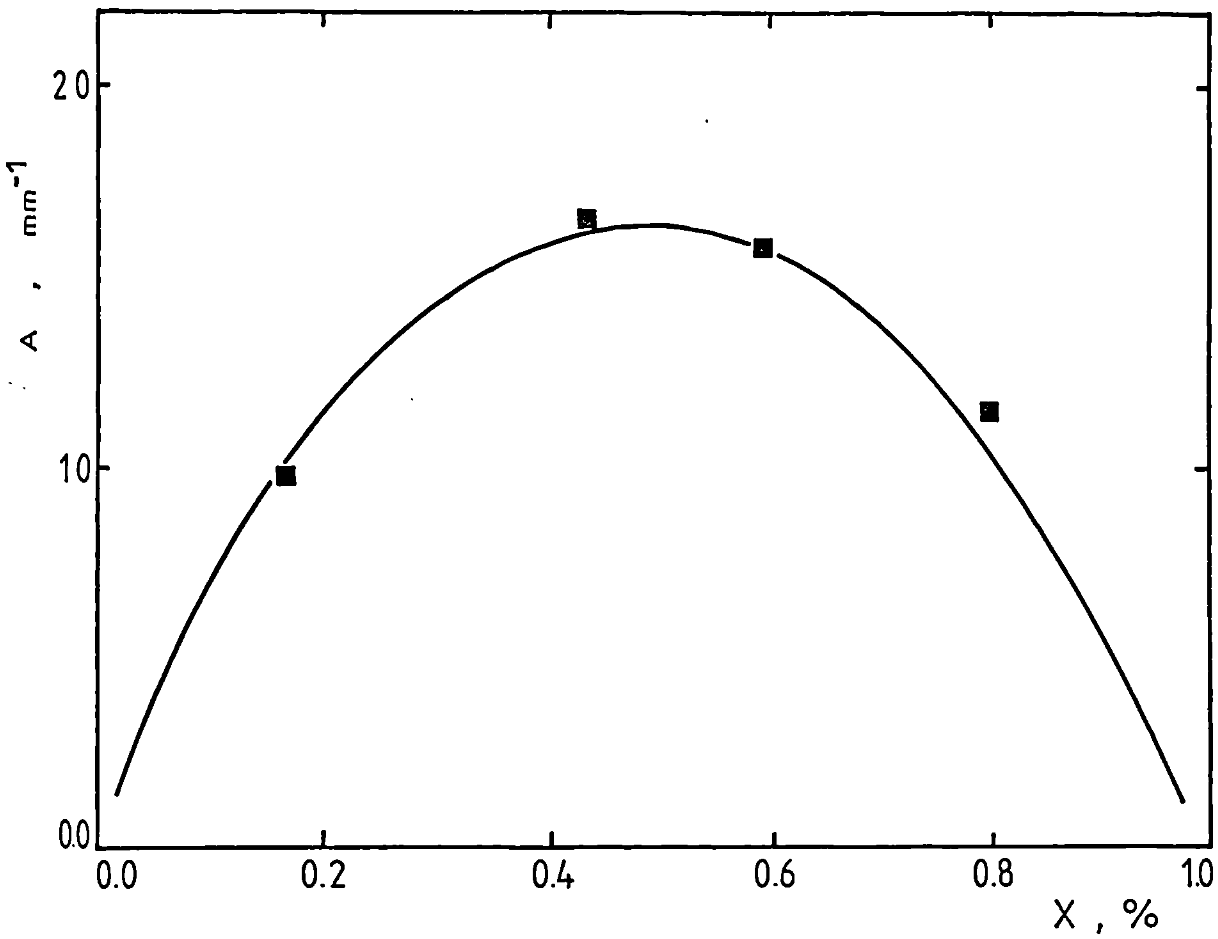

1.0
0.8
0.6
0.4
0.2
0.0
FRACTION RECRYSTALLIZED
0.4
0.0
-1.0
Log[Ln(1/(1-X))]
10^0
10^1
10^2
10^3
10^4
Time , s

FIGURE 7.5 : Migrating grain boundary area dependence on the fraction recrystallized on lines of constant strain. Samples were tested under plane strain compression at 1025C to an equivalent strain of 0.345 with original grain size of 100μm.

FIGURE 7.6 : The variation of the average grain growth rate of the recrystallizing grains with the annealing time.


A , mm^{-1}
2.0
1.0
0.0
0.0
0.2
0.4
0.6
0.8
1.0
X , %

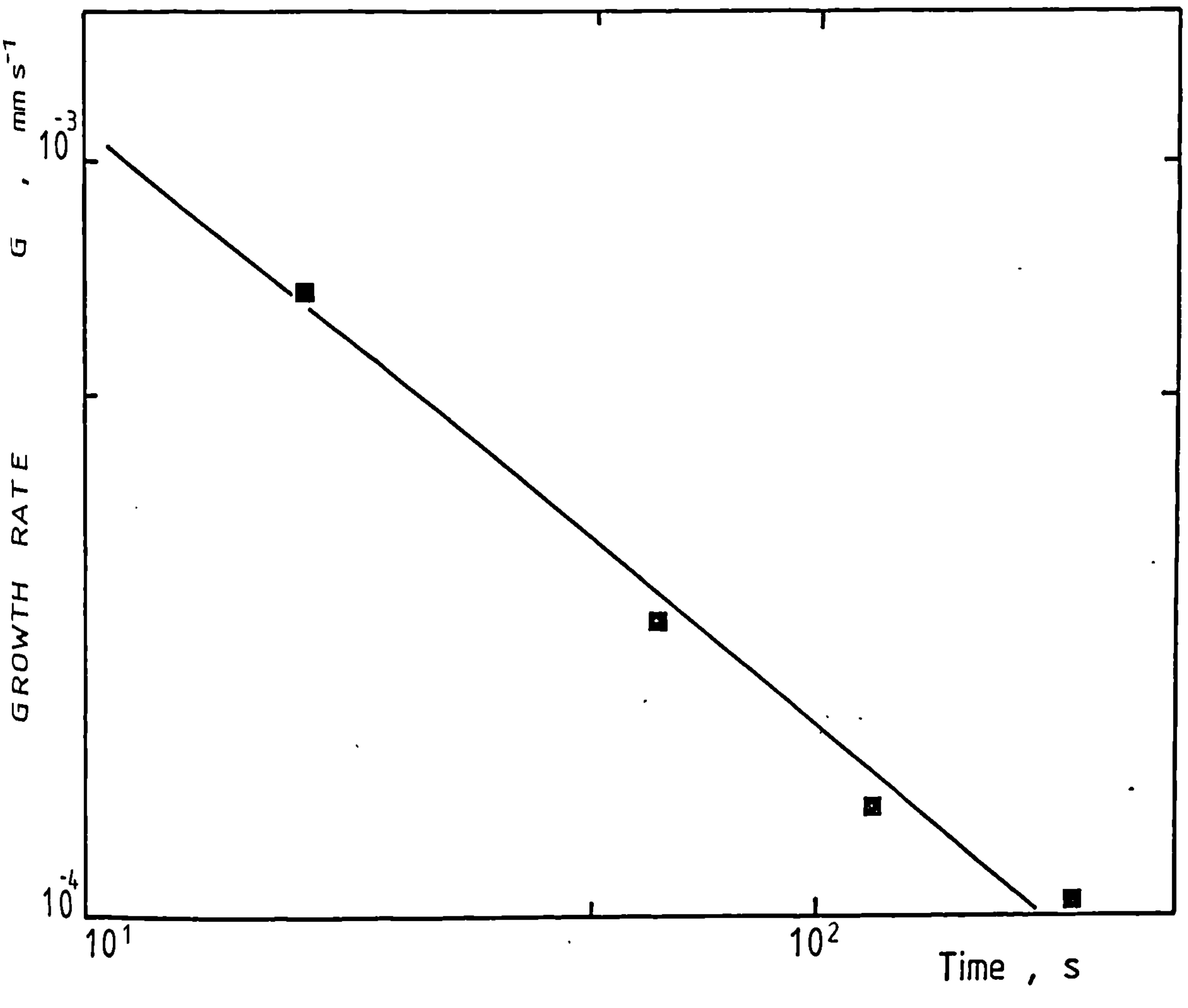
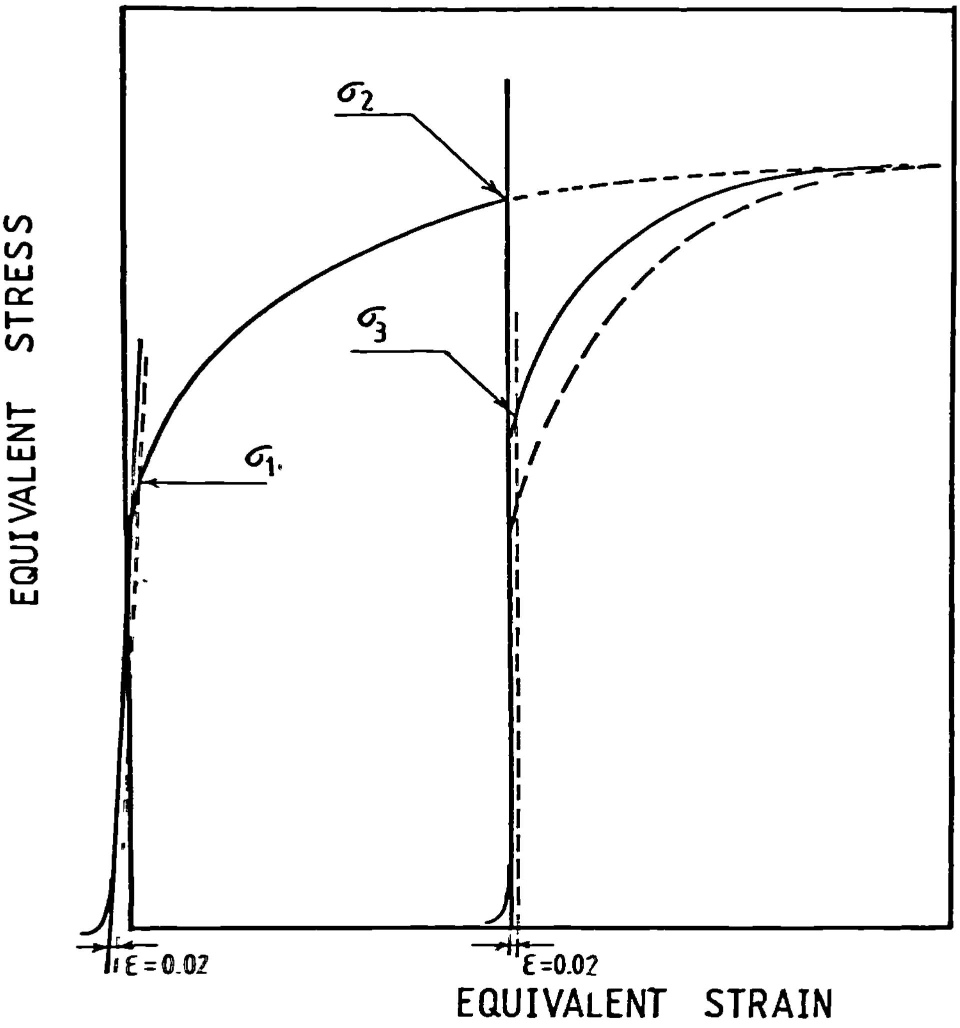
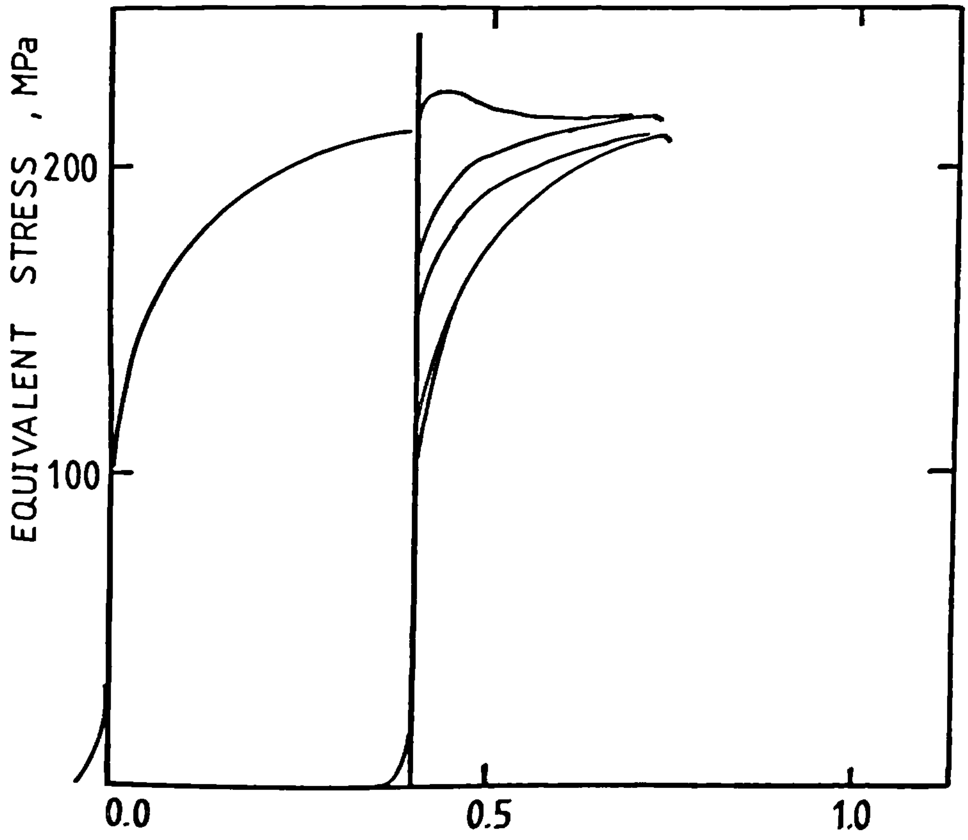

GROWTH RATE G , mm s^{-1}
10^{-3}
10^{-4}
10^{1}
10^{2}
Time , s

FIGURE 7.7 : Schematic representation of the stress-strain curve resulting from a double deformation plane strain compression test.

FIGURE 7.8 : Restoration curves for samples tested under plane strain compression with original grain size of 100μm and temperature of 1033C. The initial strain applied was 0.33.



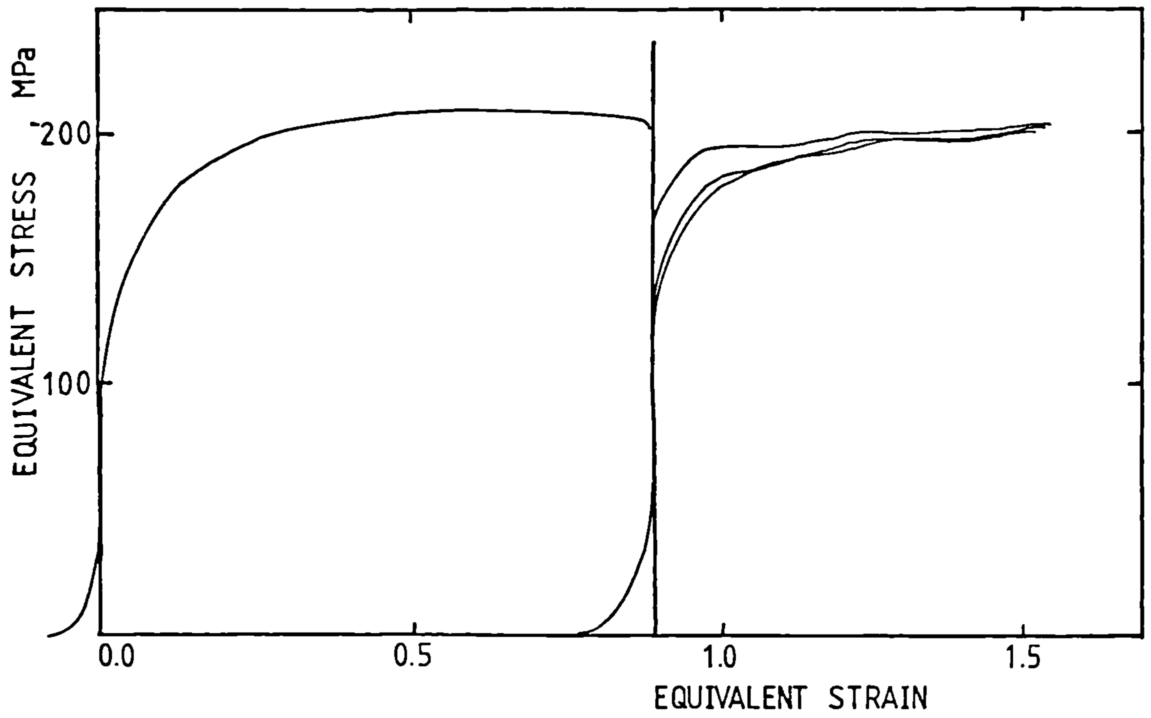
σ_2
σ_3
σ_1
EQUIVALENT STRESS
$\varepsilon = 0.02$
$\varepsilon = 0.02$
EQUIVALENT STRAIN



EQUIVALENT STRESS , MPa
200
100
0.0
0.5
1.0
EQUIVALENT STRAIN

FIGURE 7.9 : Restoration curves for samples tested under plane strain compression with original grain size of 100μm and temperature of 1033C. The strain initially applied was 0.9.

FIGURE 7.10 : Restoration curves for samples tested under plane strain compression with original grain size 100μm and at a temperature of 960C. The initial strain applied was 0.29.


EQUIVALENT STRESS , MPa
200
100
0.0
0.5
1.0
1.5
EQUIVALENT STRAIN

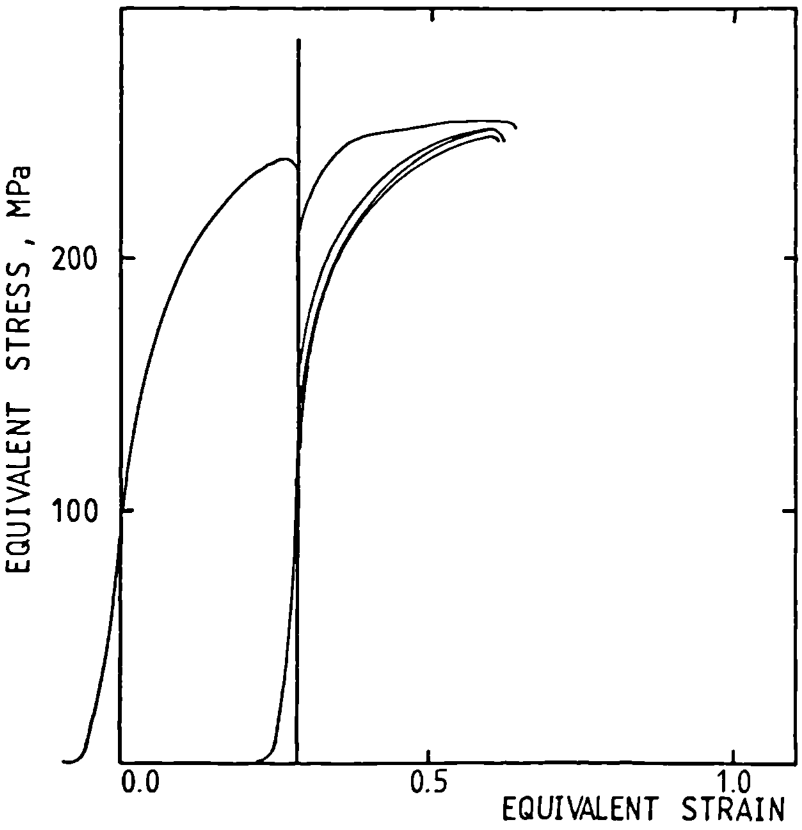
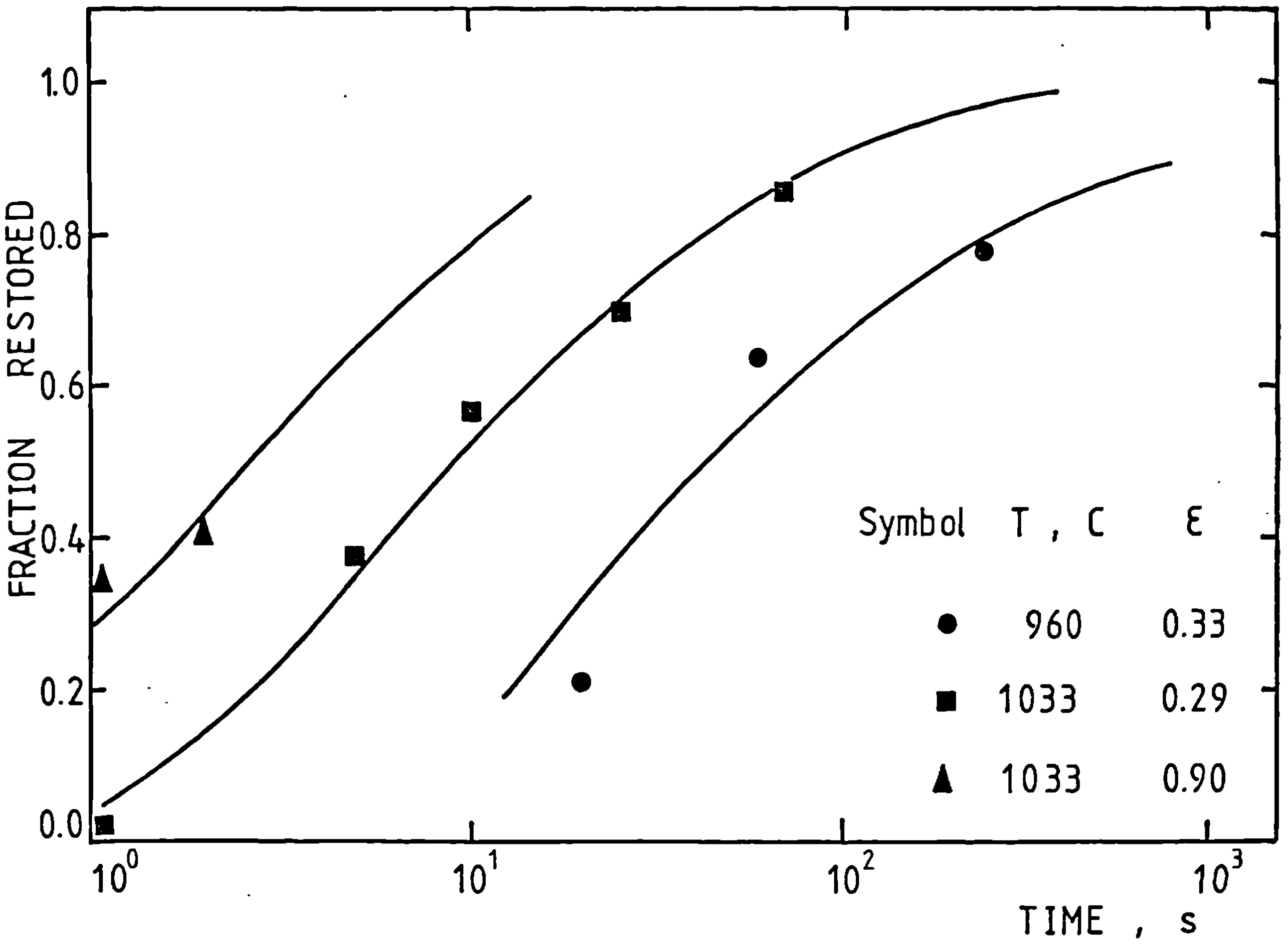

EQUIVALENT STRESS , MPa
200
100
0.0
0.5
1.0
EQUIVALENT STRAIN

FIGURE 7.11 : The fraction restored dependence on the inter-deformation period of time for samples with 100μm original grain size.

FIGURE 7.12 : The dependence of the maximum migrating grain boundary area on the equivalent strain. (After Towle and Gladman,1979).


FRACTION RESTORED
0.0
0.2
0.4
0.6
0.8
1.0
TIME , s
10^0
10^1
10^2
10^3
Symbol T , C ε
● 960 0.33
■ 1033 0.29
▲ 1033 0.90

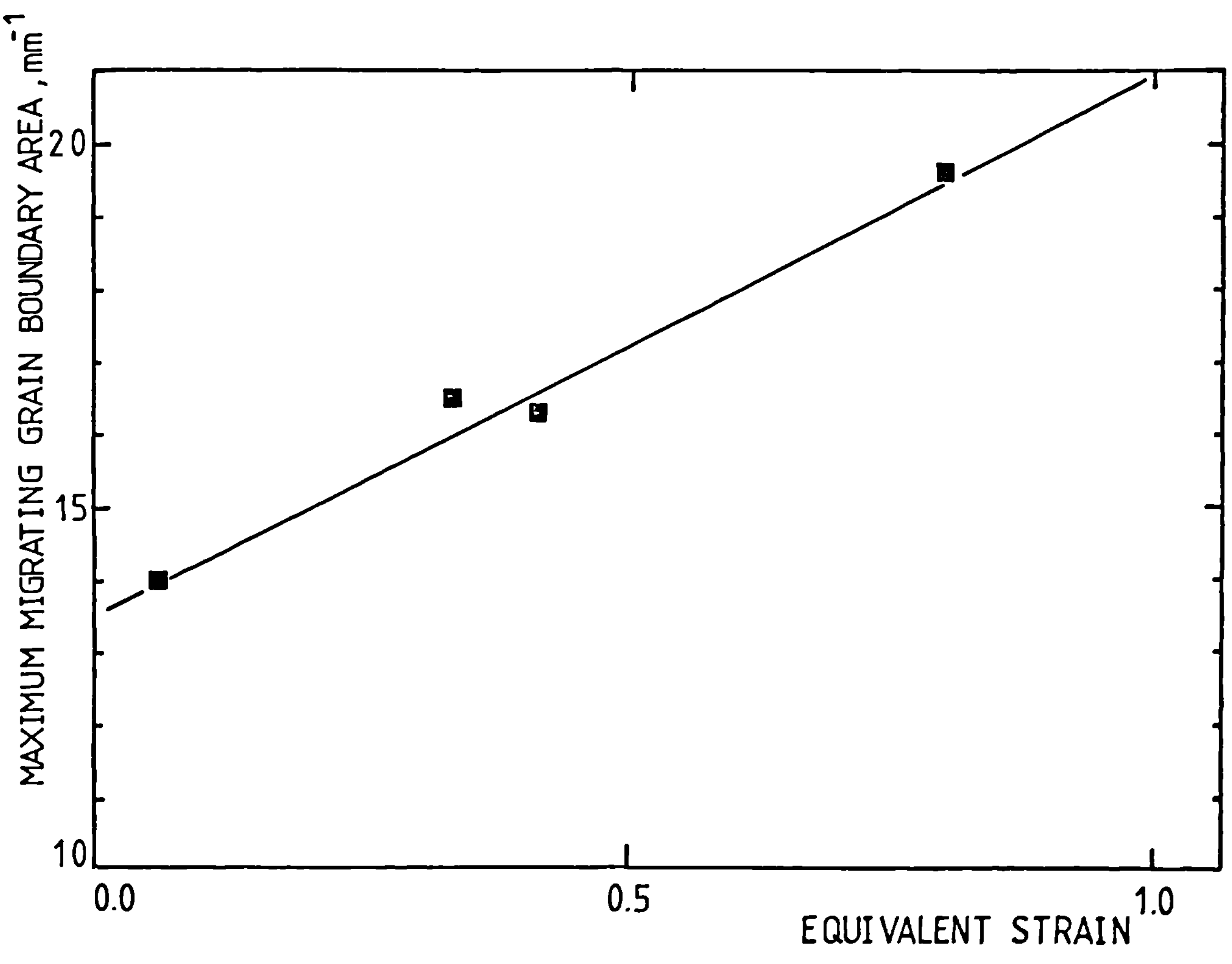
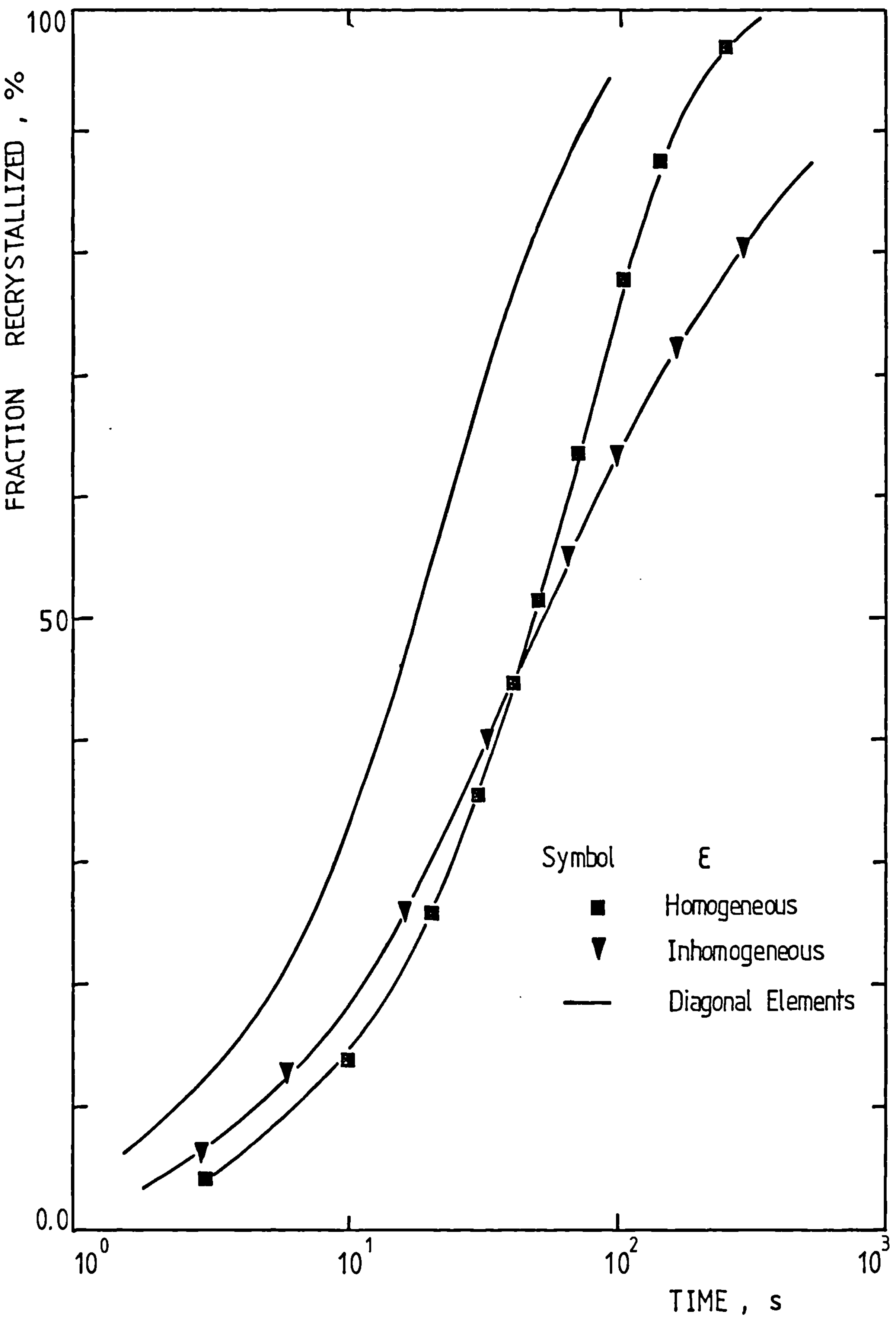

MAXIMUM MIGRATING GRAIN BOUNDARY AREA , mm^{-1}
10
15
20
EQUIVALENT STRAIN
0.0
0.5
1.0

FIGURE 7.13 : The dependence of the fraction restored on the time for a sample deformed at 1033C to a strain of 0.345 at $5s^{-1}$.



FRACTION RECRYSTALLIZED , %
100
50
0.0
10^0
10^1
10^2
10^3
TIME , s
Symbol
ε
■ Homogeneous
▼ Inhomogeneous
— Diagonal Elements

FIGURE 7.14 : Avrami plots for a sample deformed non-homogeneously and its diagonal elements. The conditions of testing are identical to the ones in figure(7.13).

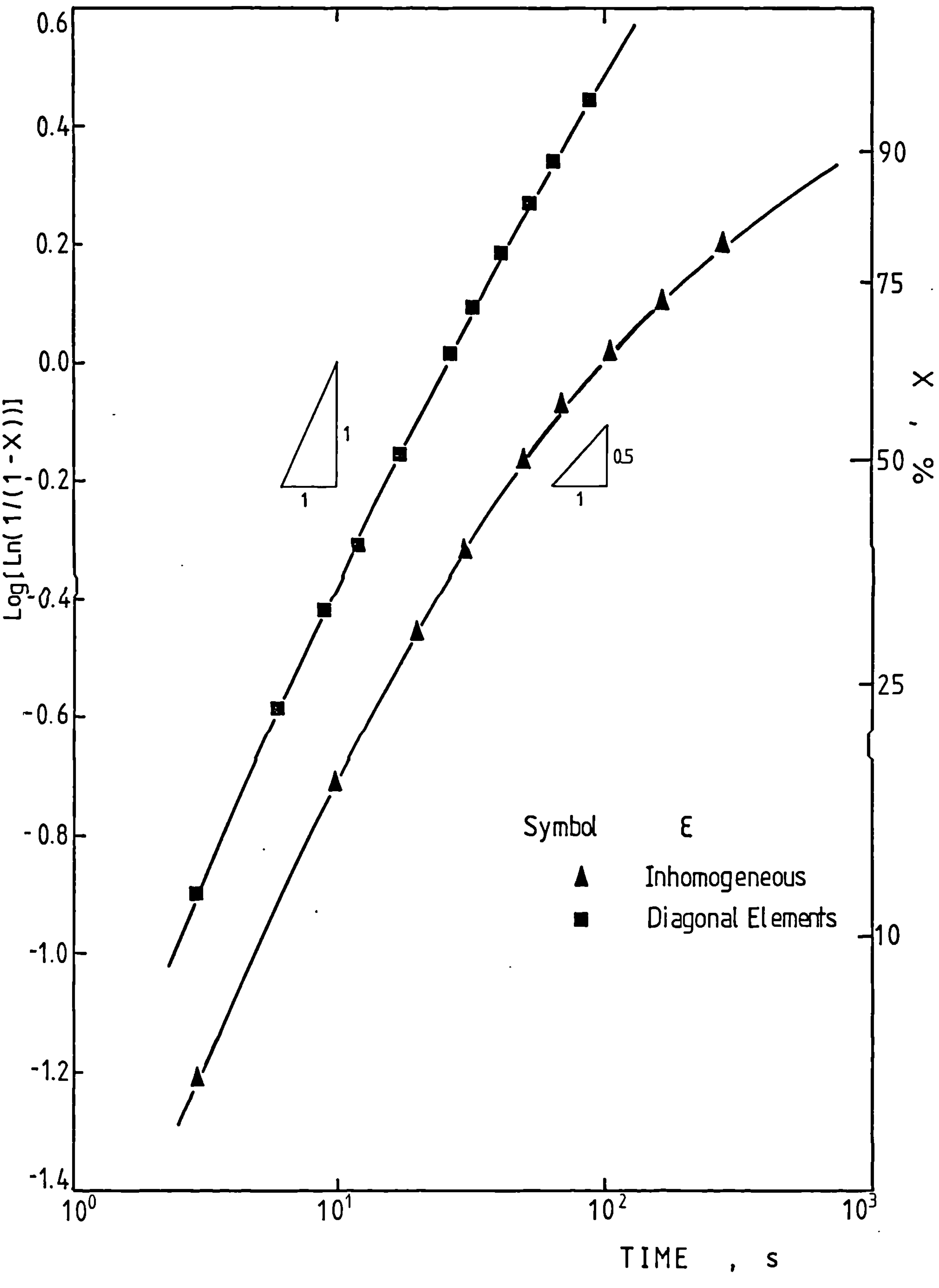

Log[Ln(1/(1-X))]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
10^0
10^1
10^2
10^3
TIME , s
X , %
90
75
50
25
10
1
1
0.5
1
Symbol
ε
▲ Inhomogeneous
■ Diagonal Elements

FIGURE 7.15 : The dependence of the migrating grain boundary area on the fraction recrystallized. Sample was deformed as described in figure(7.13).

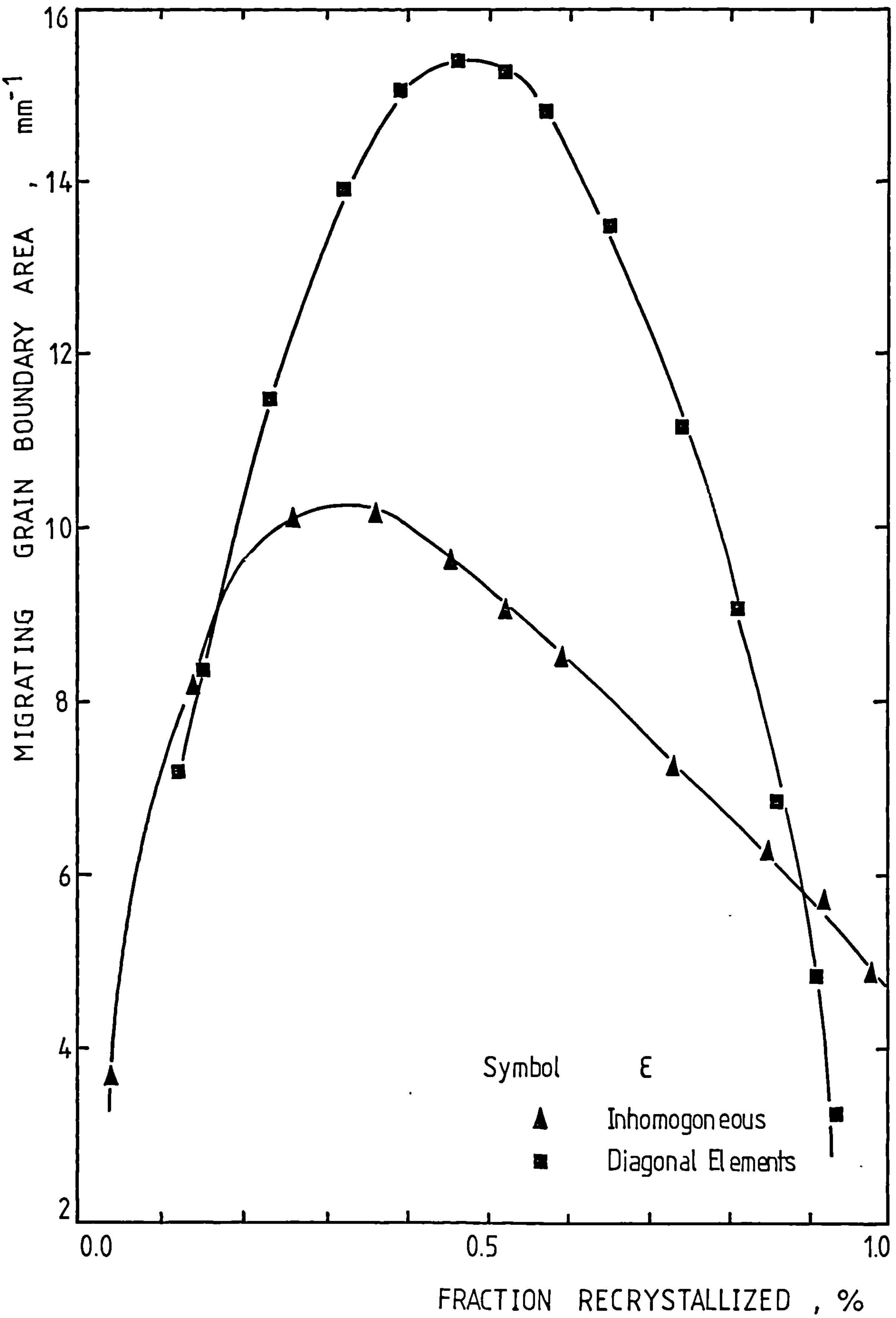

MIGRATING GRAIN BOUNDARY AREA mm^{-1}
16
14
12
10
8
6
4
2
0.0
0.5
1.0
FRACTION RECRYSTALLIZED , %
Symbol ε
▲ Inhomogoneous
■ Diagonal Elements

FIGURE 7.16 : The dependence of the grain growth rate on the delay time for the diagonal elements, non-homogeneously deformed sample and homogeneously deformed one.

Conditions of deformation:

Temperature = 1033C

Strain = 0.345

Original Grain Size = 100 μm

Strain rate = $5 s^{-1}$

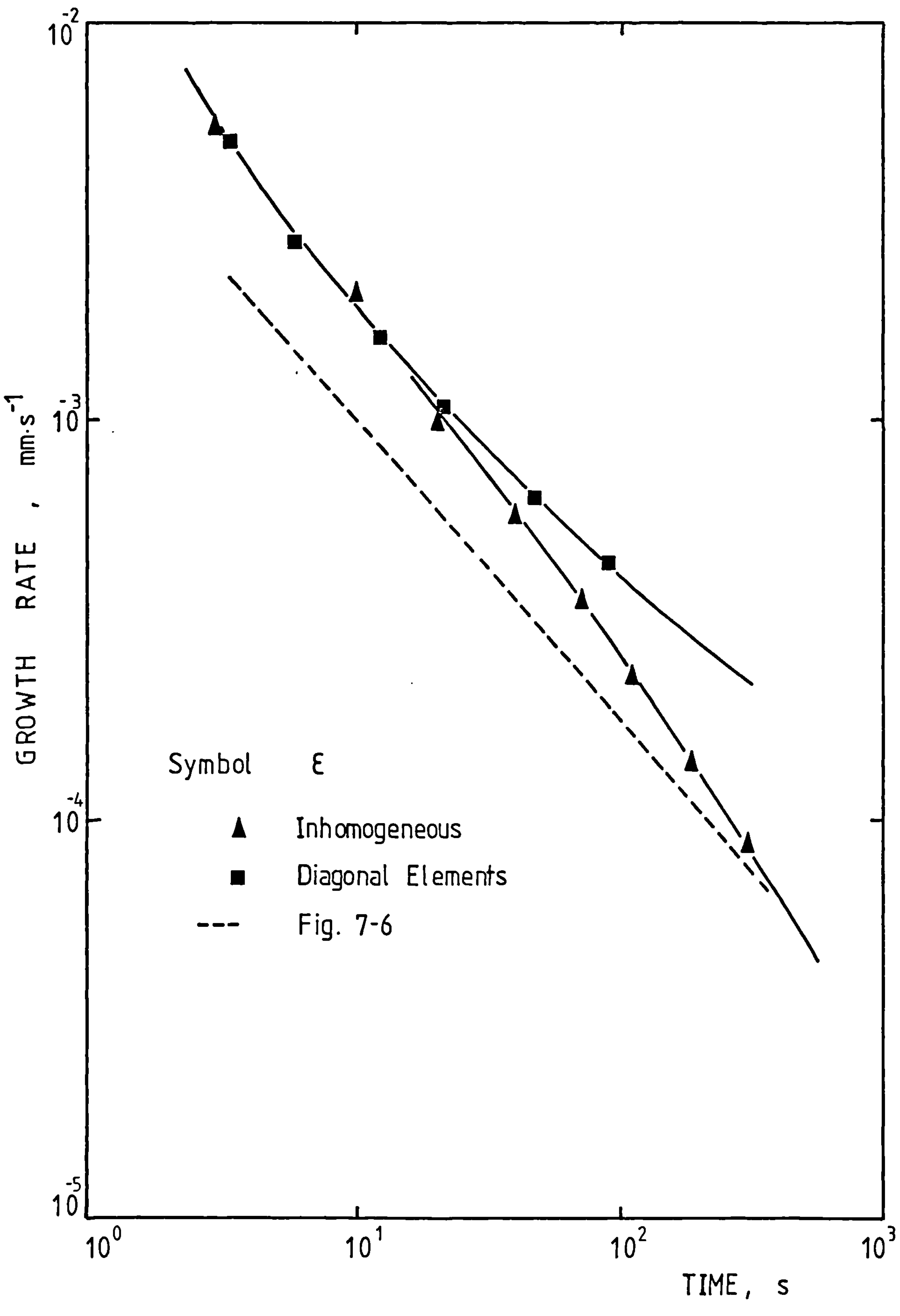

GROWTH RATE , mm·s^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{0}
10^{1}
10^{2}
10^{3}
TIME, s
Symbol ε
▲ Inhomogeneous
■ Diagonal Elements
--- Fig. 7-6

FIGURE 7.17 : The fraction restored dependence on the annealing time for the diagonal elements deformed at 950C, to 0.345 of strain at a strain rate of $5s^{-1}$.

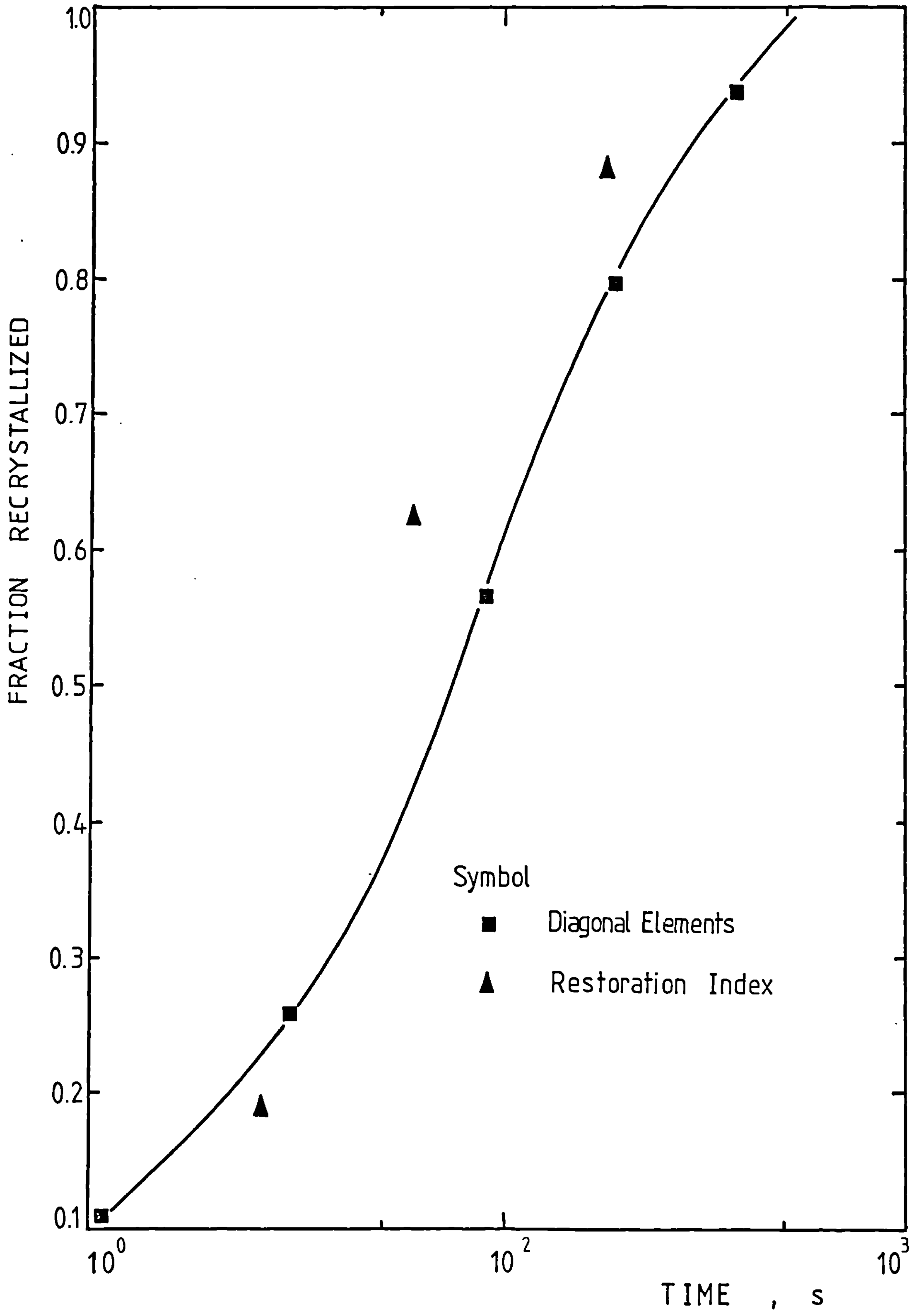

FRACTION RECRYSTALLIZED
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10^0
10^2
10^3
TIME , s
Symbol
■ Diagonal Elements
▲ Restoration Index

FIGURE 7.18 : The fraction restored dependence on the annealing time for diagonal elements deformed at 1033C to an equivalent strain of 0.345 at a strain rate of $5s^{-1}$.

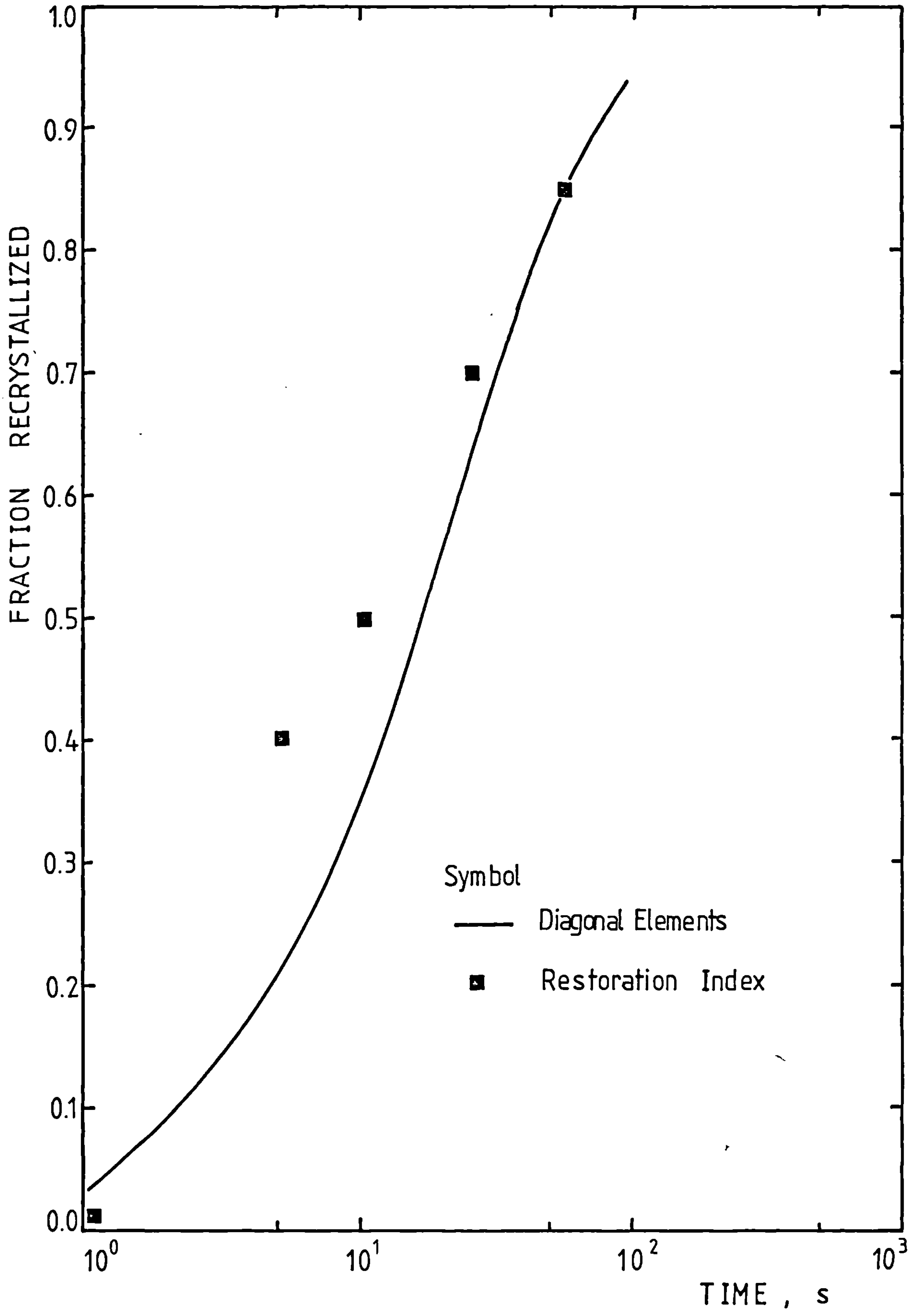

FRACTION RECRYSTALLIZED
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10^0
10^1
10^2
10^3
TIME , s
Symbol
Diagonal Elements
■ Restoration Index

FIGURE 7.19 : The fraction restored dependence on the annealing time for the diagonal elements of a sample deformed at 1033C to a strain of 0.9 at a strain rate equal $5s^{-1}$.

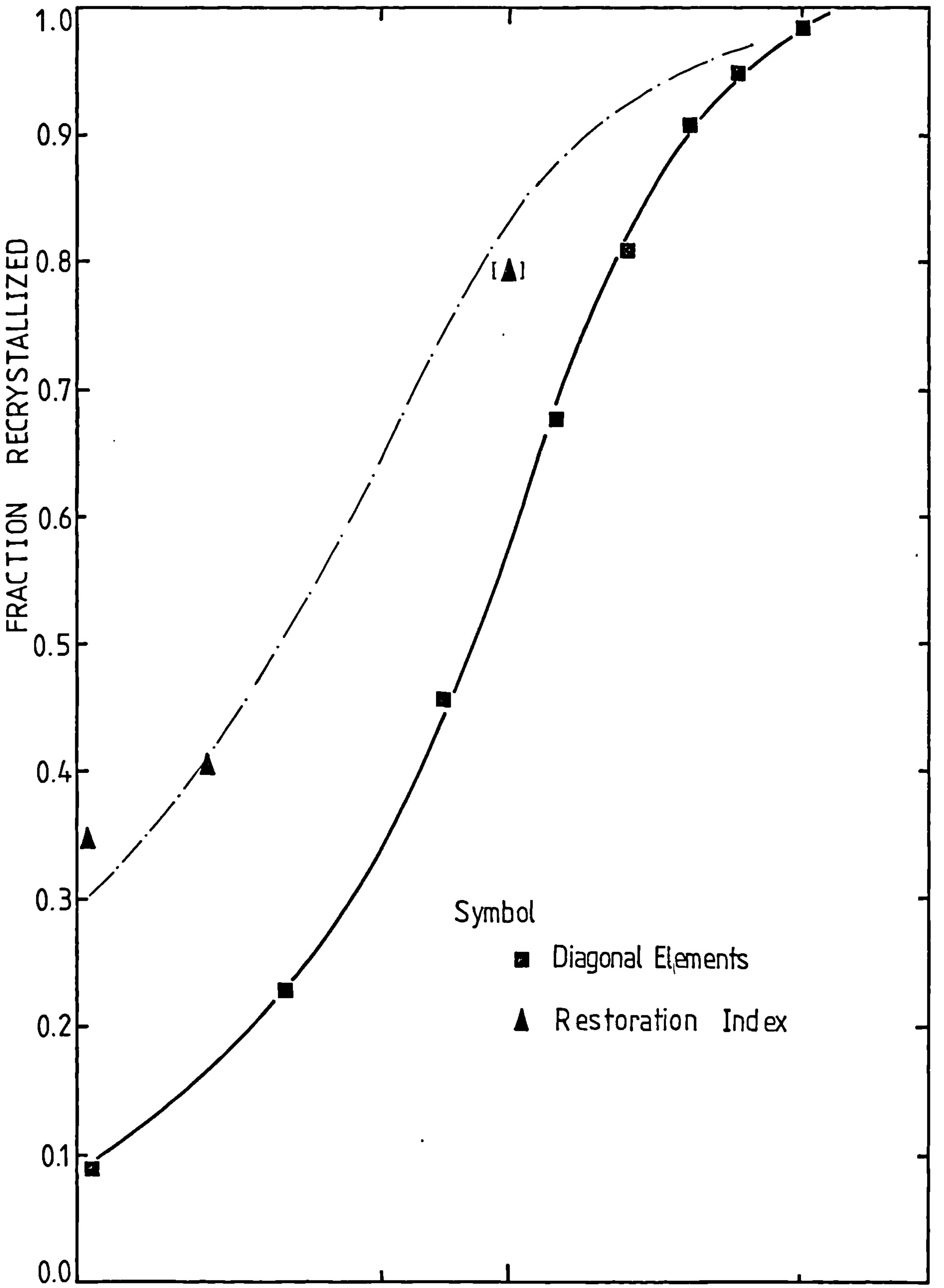

FRACTION RECRYSTALLIZED
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10^0
10^1
10^2
TIME , s
Symbol
■ Diagonal Elements
▲ Restoration Index
[▲]

FIGURE 8.1 : Dependence of the original grain size on the annealing temperature. Samples were heat treated for periods of 1/2 hour.

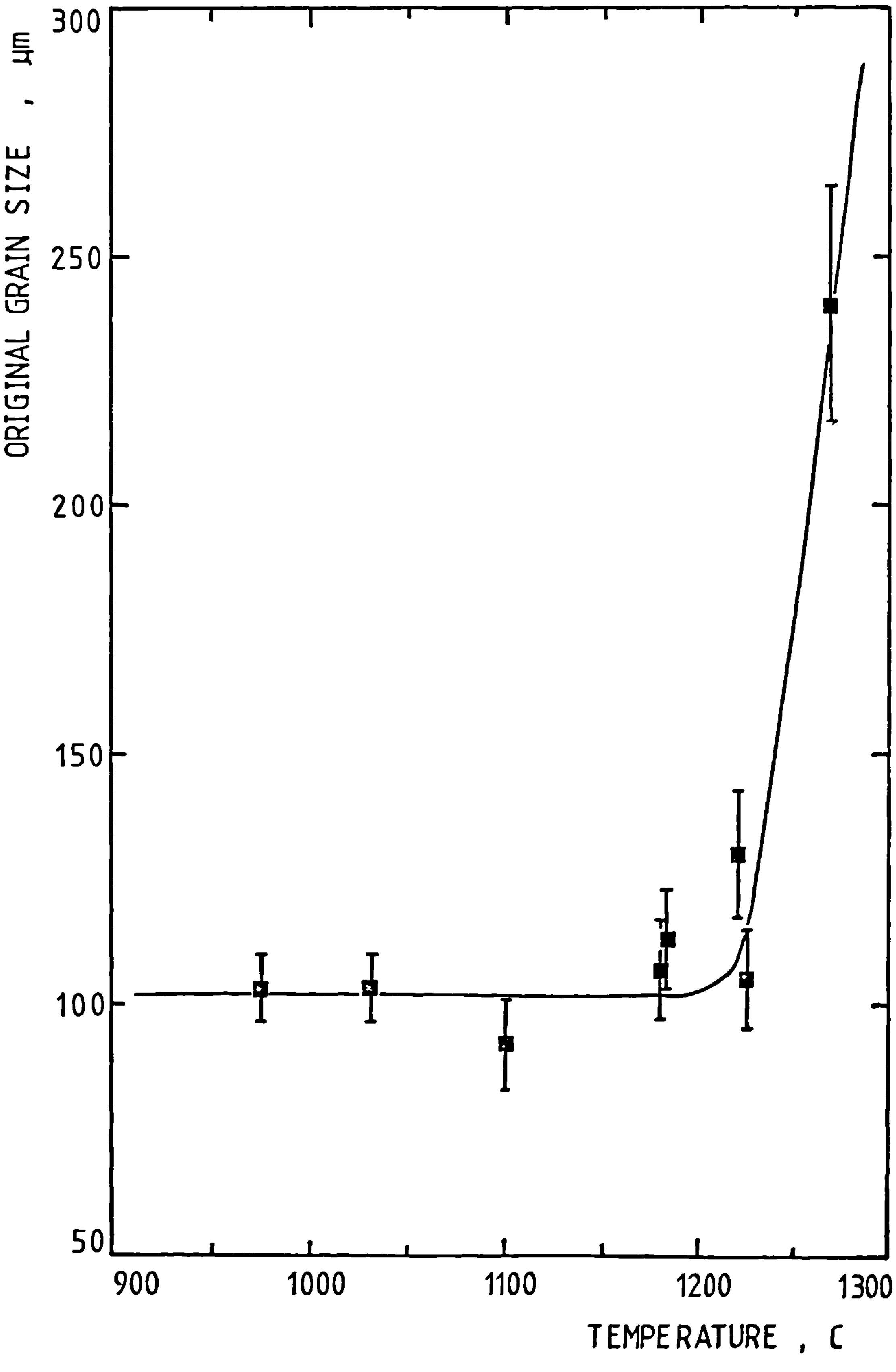

ORIGINAL GRAIN SIZE , µm
300
250
200
150
100
50
900
1000
1100
1200
1300
TEMPERATURE , C

FIGURE 8.2 : Comparison of cooling curves of identical slabs of 304 and 316 cooled in air.

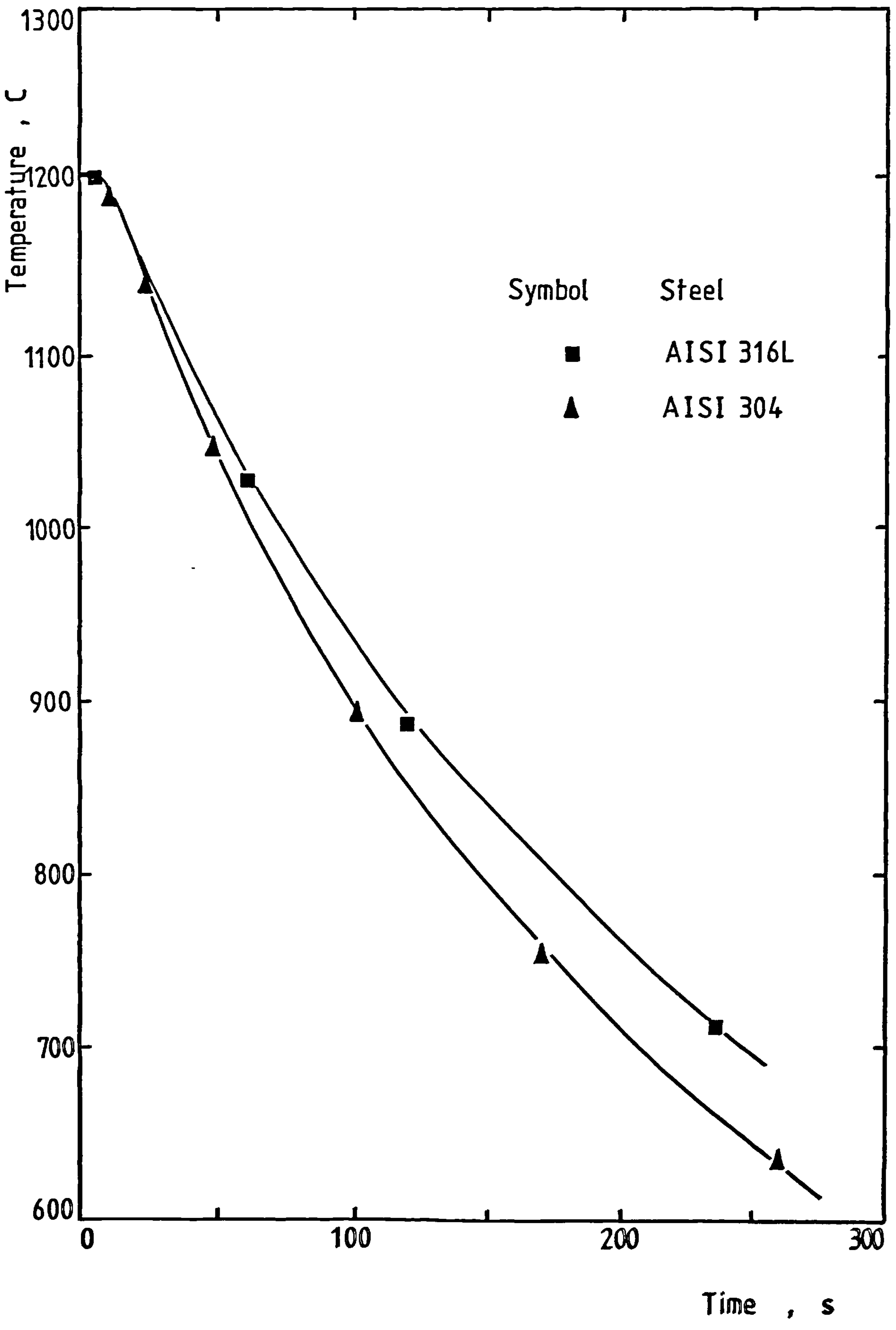

1300
1200
1100
1000
900
800
700
600
Temperature , C
0
100
200
300
Time , s
Symbol
Steel
■ AISI 316L
▲ AISI 304

FIGURE 8.3 : Air cooling characteristics of AISI316L.

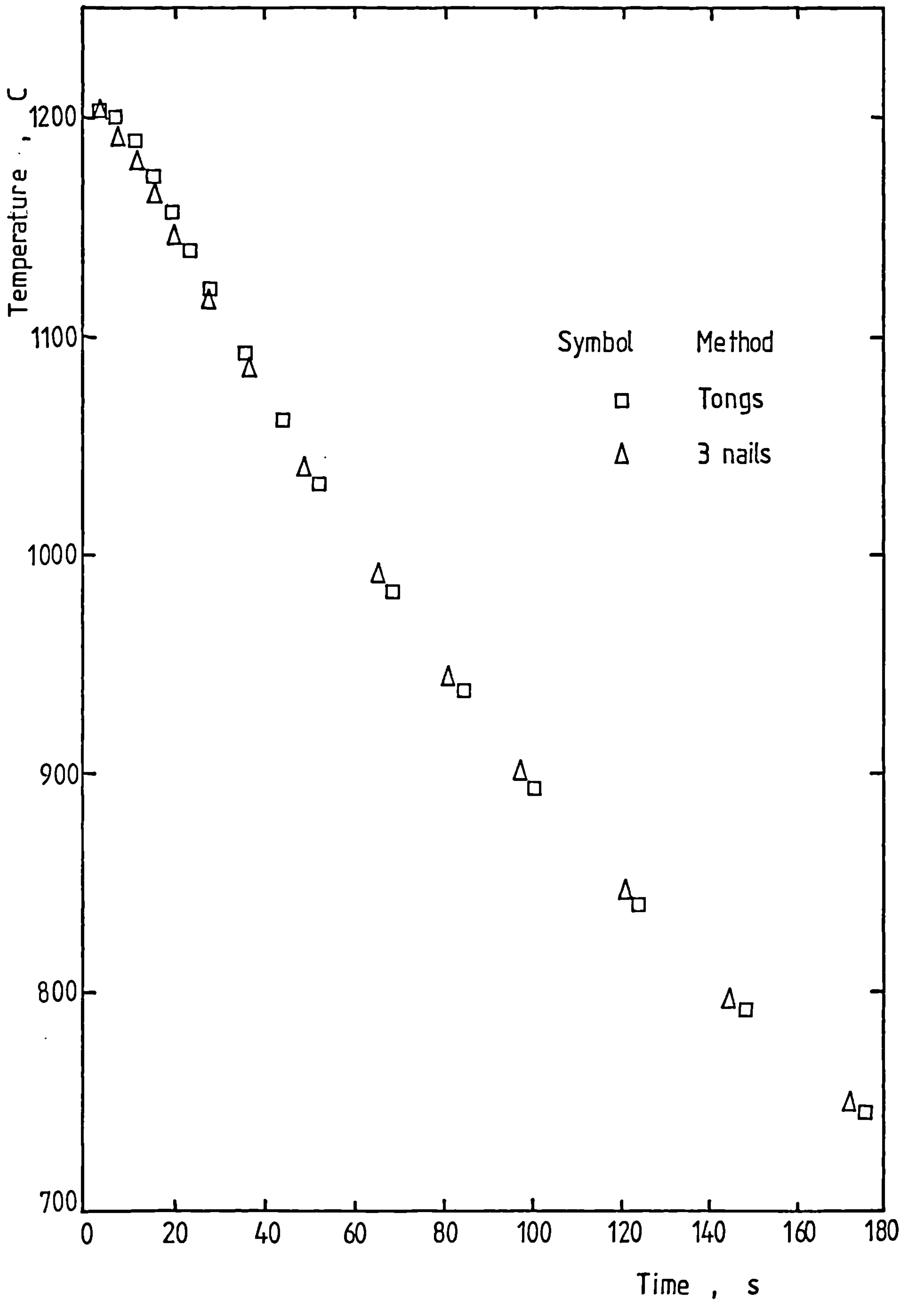

Temperature , C
1200
1100
1000
900
800
700
0
20
40
60
80
100
120
140
160
180
Time , s
Symbol
Method
□
Tongs
Δ
3 nails

FIGURE 8.4 : Dependence of the heat transfer coefficient on the slab surface temperature. Full line represents the theoretical curve given by equation(8.1).

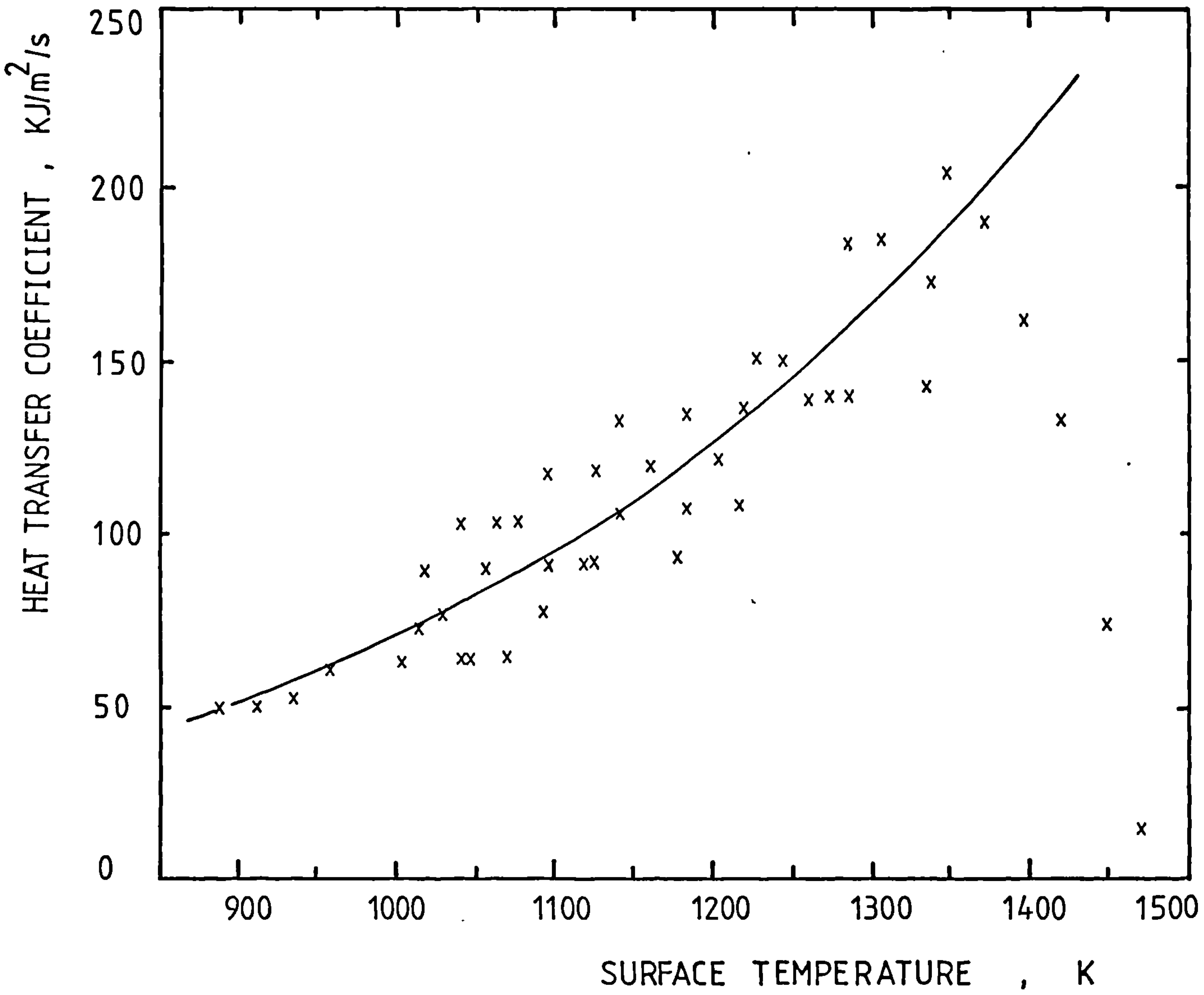

HEAT TRANSFER COEFFICIENT , KJ/m²/s
250
200
150
100
50
0
900
1000
1100
1200
1300
1400
1500
SURFACE TEMPERATURE , K

FIGURE 8.5 : Comparison between experimental and predicted (full line) air cooling behaviour of AISI316L.

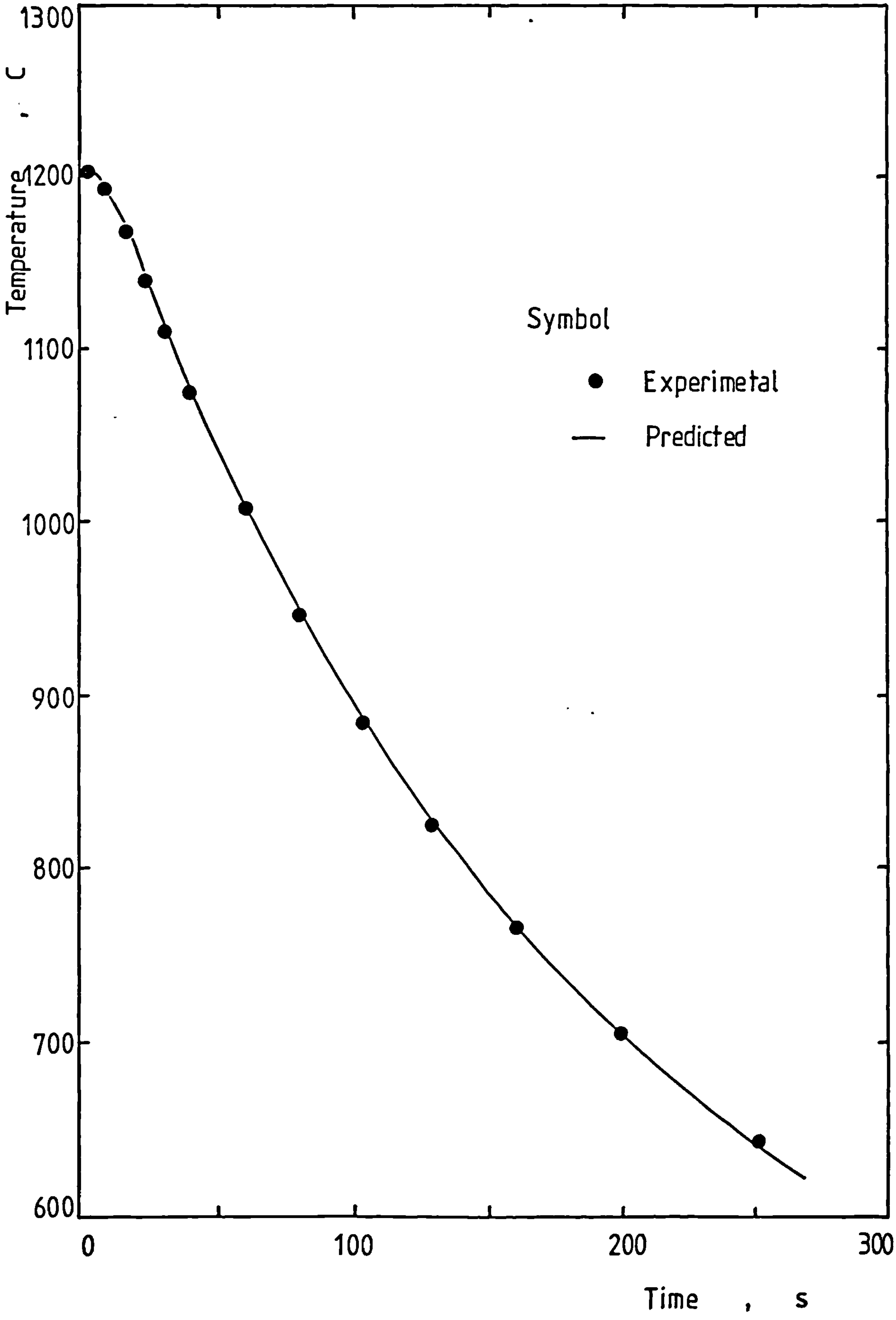

1300
1200
1100
1000
900
800
700
600
Temperature , C
0
100
200
300
Time , s
Symbol
● Experimetal
— Predicted

FIGURE 8.6 : Dependence of the average spread during rolling on the roll radius and rolling reduction. The samples' original width was 51mm.

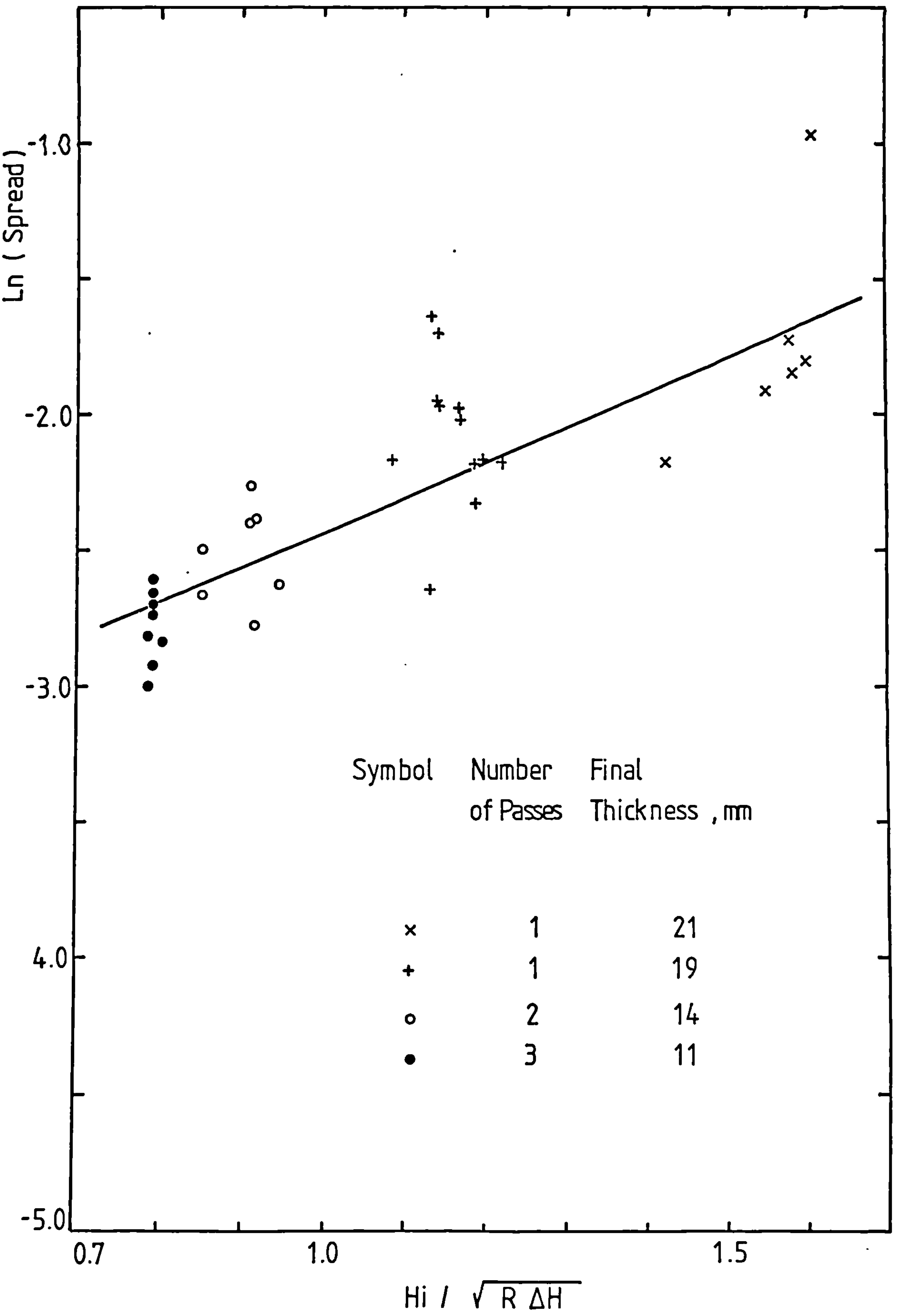

Ln (Spread)
-1.0
-2.0
-3.0
4.0
-5.0
0.7
1.0
1.5
Hi / √ R ΔH
Symbol
Number of Passes
Final Thickness , mm
× 1 21
+ 1 19
○ 2 14
● 3 11

FIGURE 8.7 : Dependence of the average spread during hot rolling on the roll radius and rolling reduction for samples with original width 25mm.

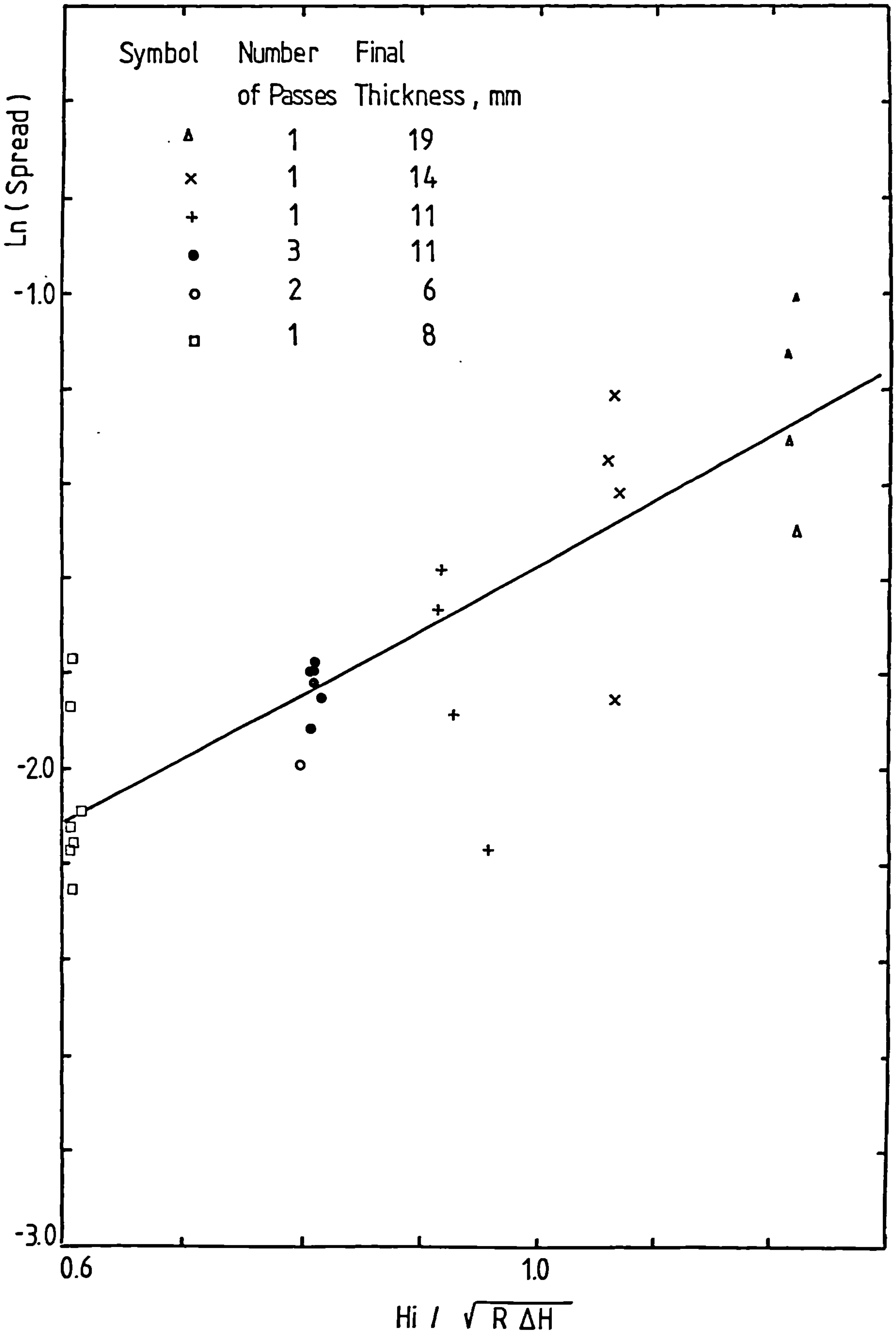

Symbol
Number of Passes
Final Thickness, mm
▲ 1 19
× 1 14
+ 1 11
● 3 11
○ 2 6
□ 1 8
Ln (Spread)
-1.0
-2.0
-3.0
0.6
1.0
Hi / $\sqrt{R \Delta H}$

FIGURE 8.8 : Correlation between predicted mean final width and measured mean final width for samples 51mm original width.

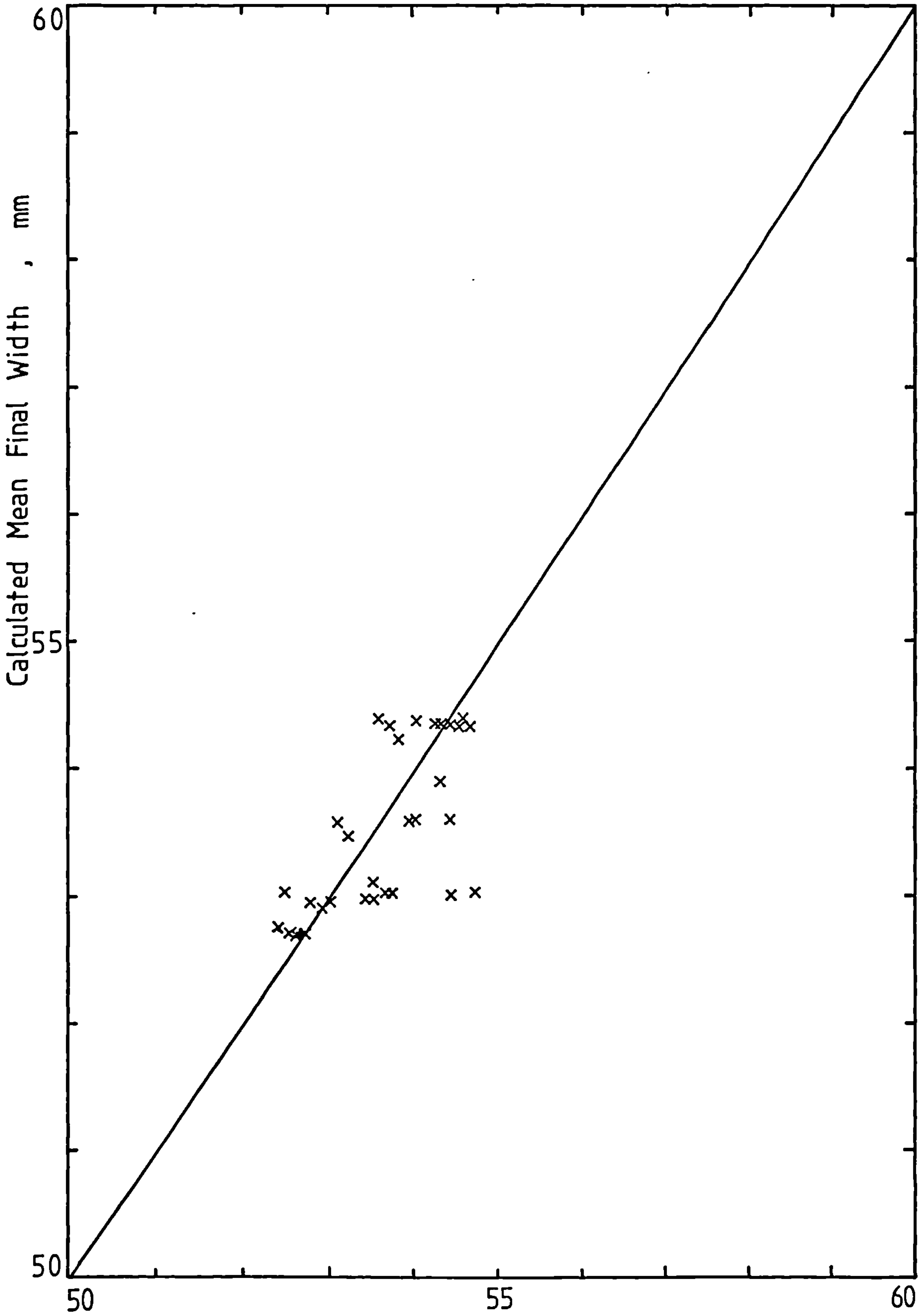

60
55
50
Calculated Mean Final Width , mm
50
55
60
Measured Mean Final Width, mm

FIGURE 8.9 : Correlation between predicted mean final width and measured one for samples 25mm initial width.

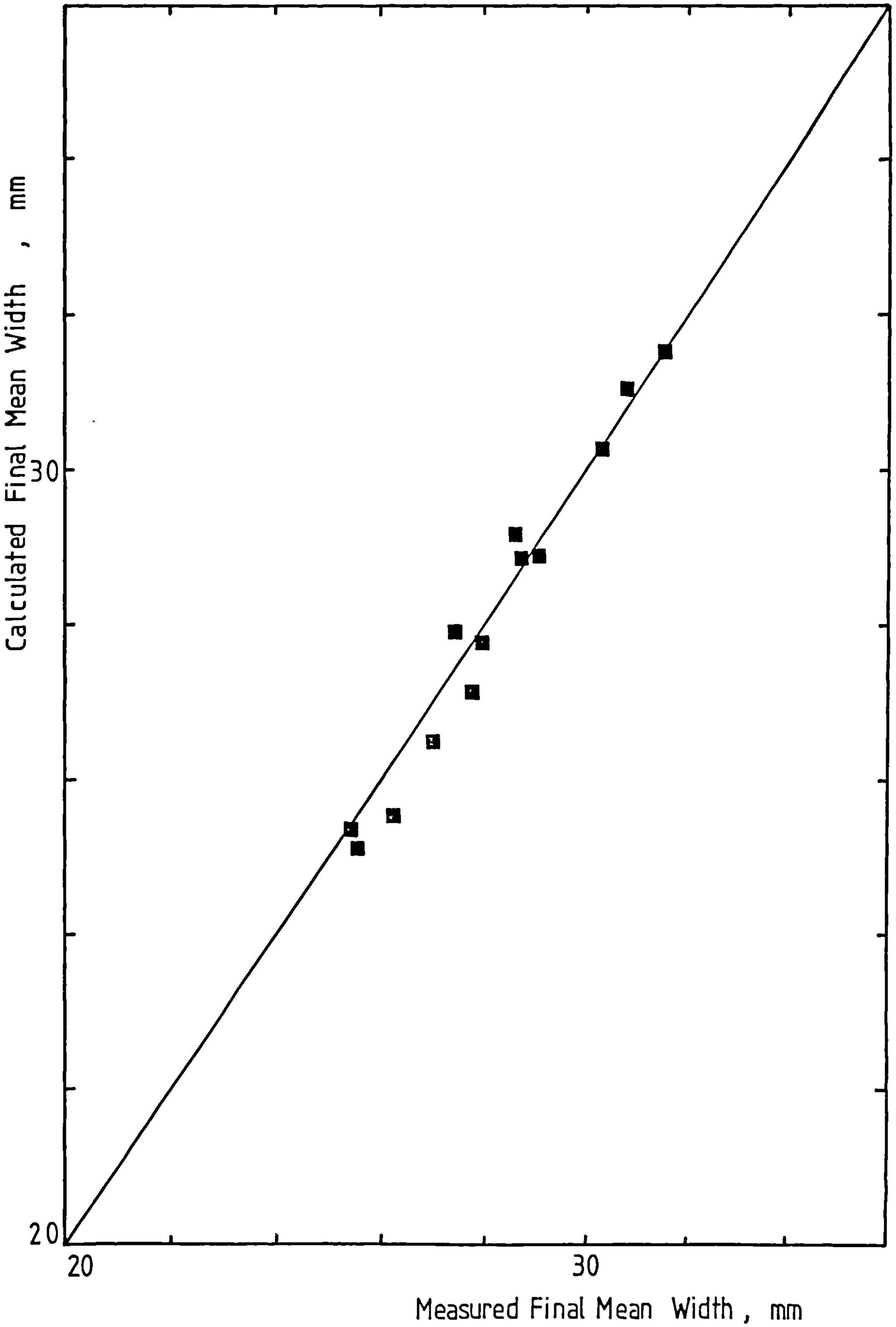

Calculated Final Mean Width , mm
30
20
20
30
Measured Final Mean Width , mm

FIGURE 8.10 : The effect of the original grain size on the mean plane strain strength during rolling. Samples were deformed in a 25% reduction pass at 900C (measured centre temperature at the rolling gap entry).

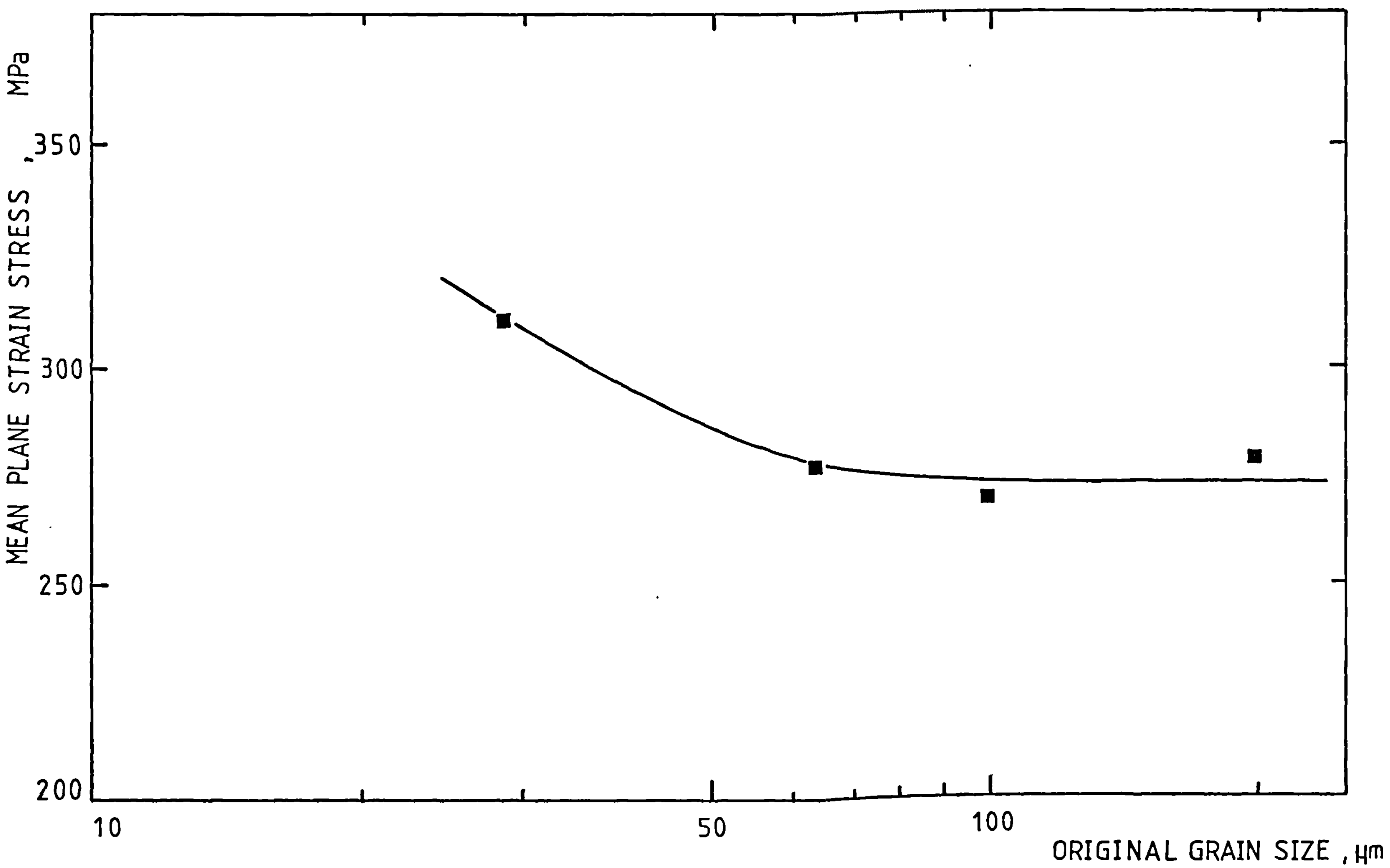

MEAN PLANE STRAIN STRESS , MPa
350
300
250
200
10
50
100
ORIGINAL GRAIN SIZE , μm

FIGURE 8.11 : The rolling load dependence on the equivalent strain for samples rolled at 950C (measured centre temperature at the rolling gap entry).

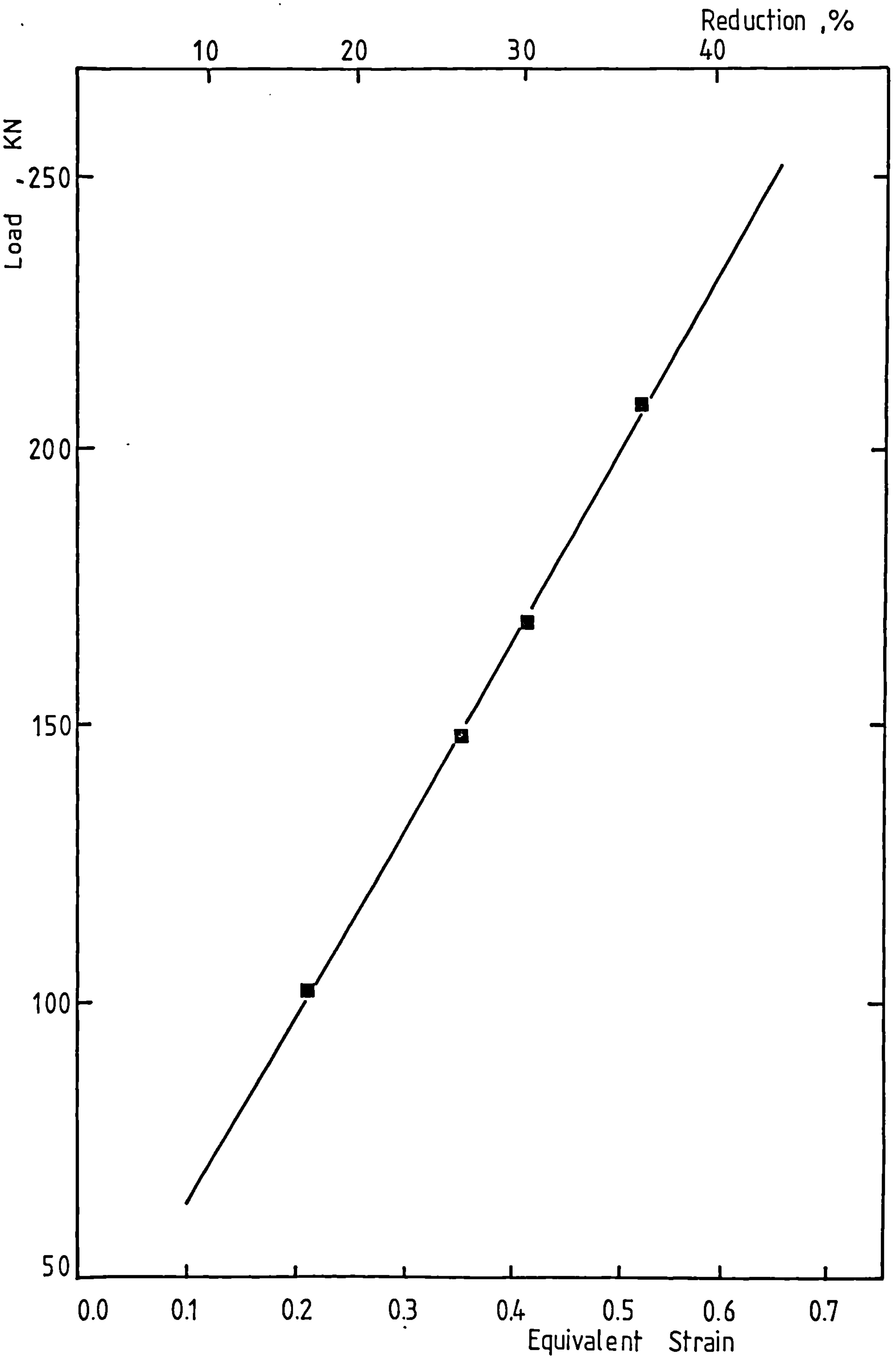

Reduction ,%
10
20
30
40
Load KN
-250
200
150
100
50
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Equivalent Strain

FIGURE 8.12 : The dependence of the mean equivalent stress during hot rolling. Samples were hot rolled at 950C (measured centre temperature at the rolling gap entry).

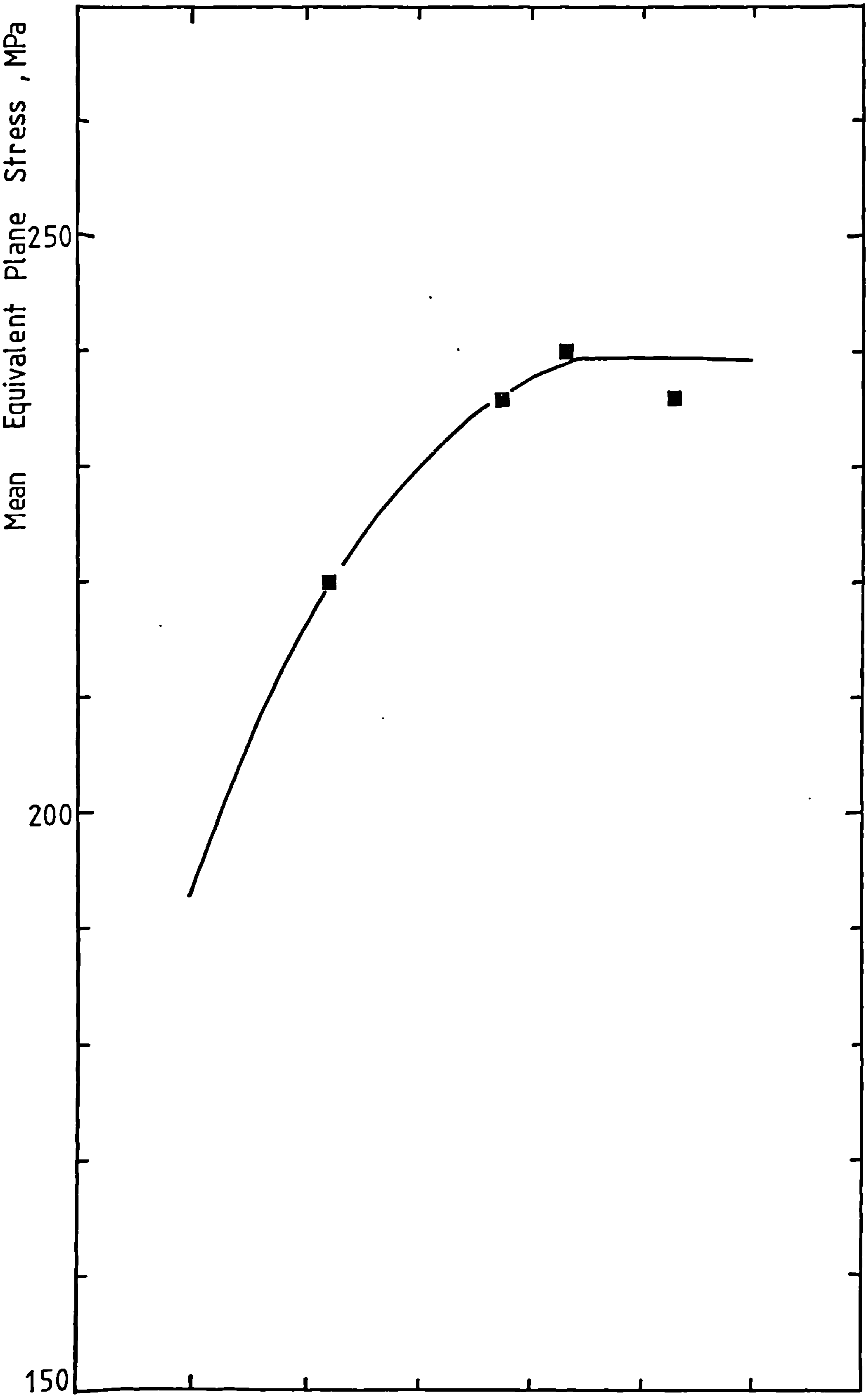

Mean Equivalent Plane Stress , MPa
250
200
150
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Equivalent Strain

FIGURE 8.13 : The dependence of the plane strain strength on the Zener-Hollomon parameter for samples hot rolled by 25% reduction in thickness in a single pass.

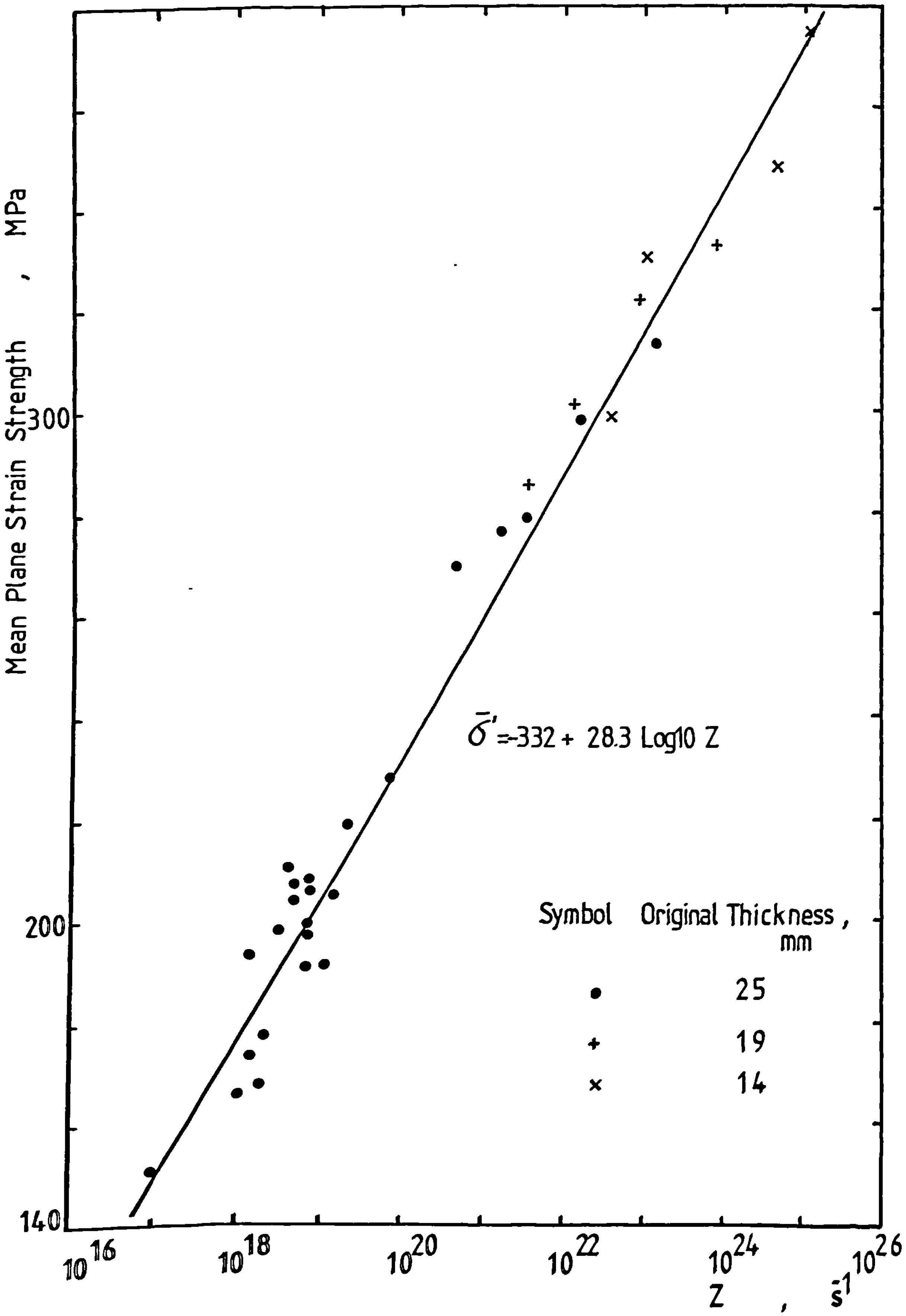

Mean Plane Strain Strength , MPa
140
200
300
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
10^{26}
Z , s^{-1}
$\bar{\sigma}' = -332 + 28.3 \text{ Log10 } Z$
Symbol
Original Thickness , mm
● 25
+ 19
× 14

FIGURE 8.14 : The dependence of the mean plane strain strength in second passes on the Zener-Hollomon parameter. Samples were hot rolled in a 2x25% schedule.

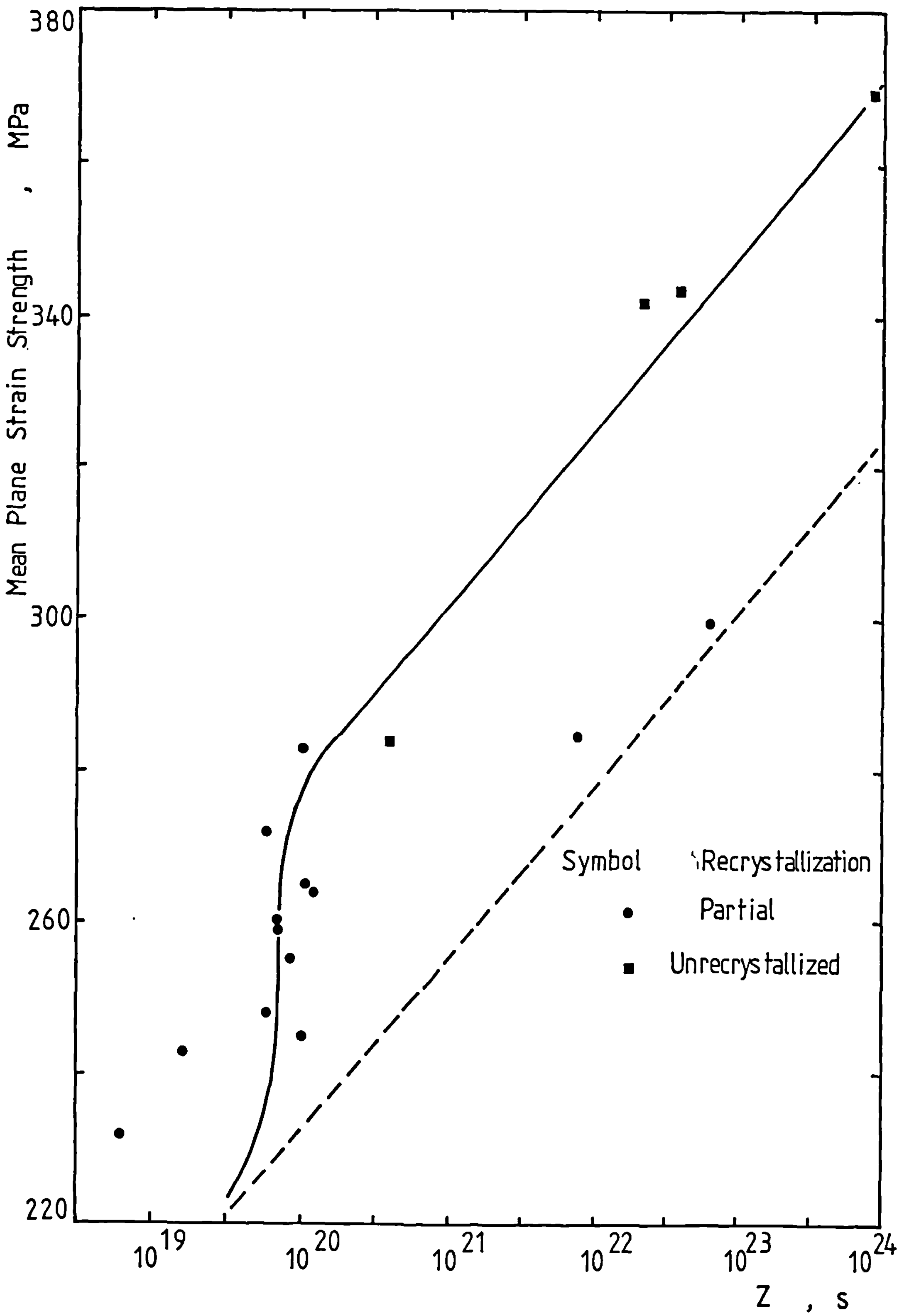
 Mean Plane Strain Strength , MPa
380
340
300
260
220
10^19
10^20
10^21
10^22
10^23
10^24
Z , s
Symbol
Recrystallization
● Partial
■ Unrecrystallized

FIGURE 8.15 : The dependence of the mean plane strain strength in the third pass on the Zener-Hollomon parameter. Samples were hot rolled in a 3x25% pass schedule. Dotted line represents the strength in the second pass of an unrecrystallized material hot rolled in a two pass schedule.

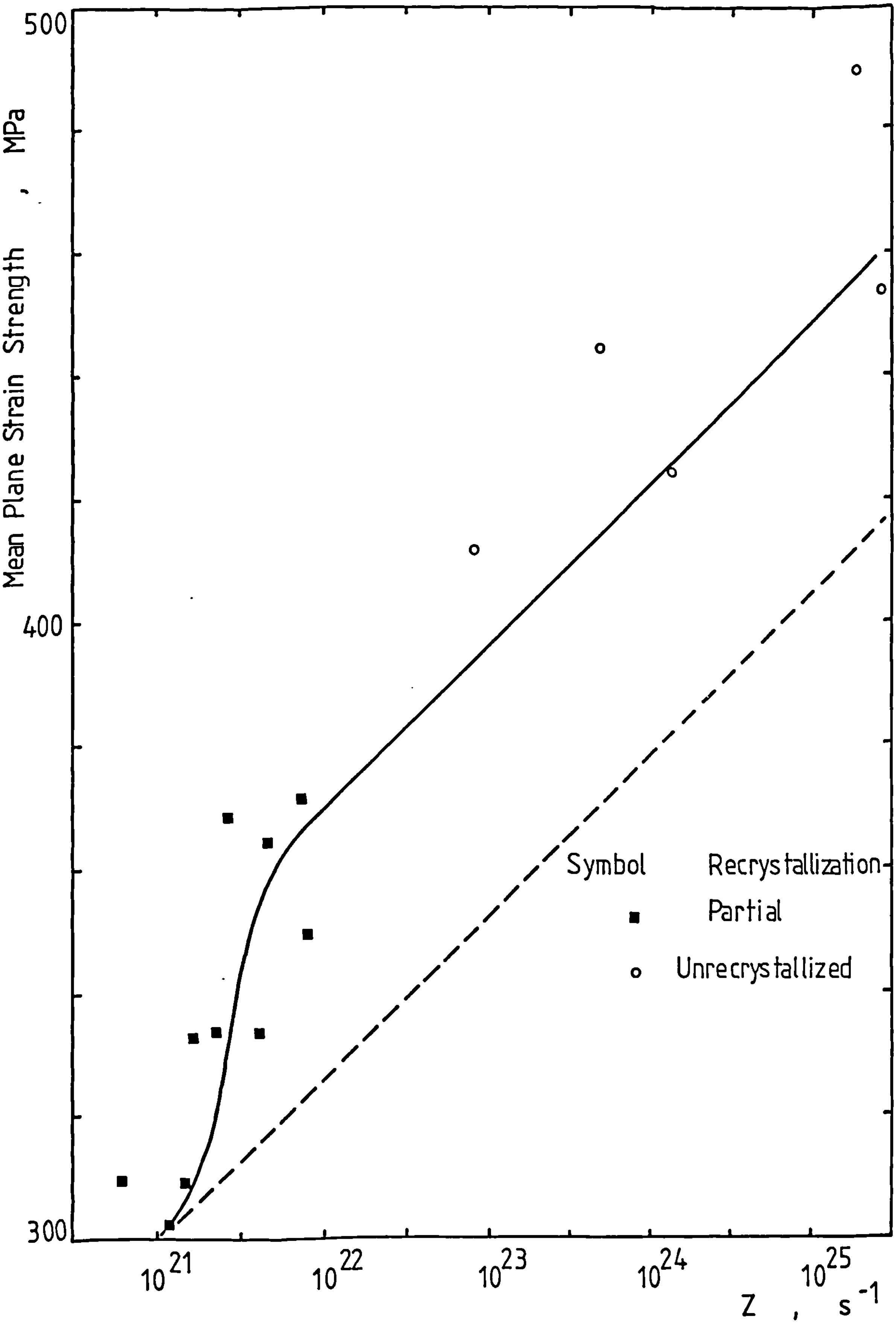
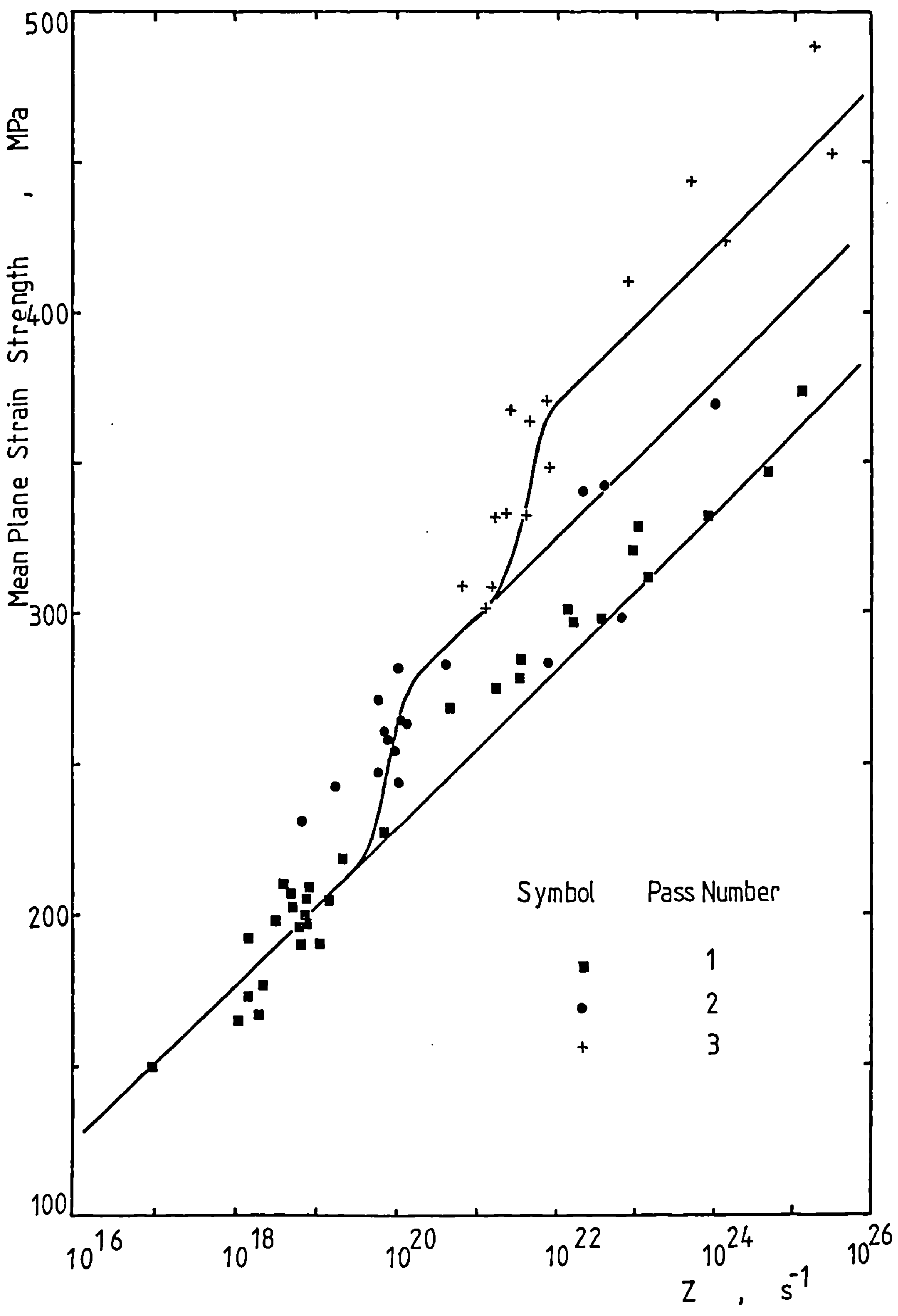

500
400
300
Mean Plane Strain Strength , MPa
10^{21}
10^{22}
10^{23}
10^{24}
10^{25}
Z , s^{-1}
Symbol
Recrystallization
■ Partial
○ Unrecrystallized

FIGURE 8.16 : An overall view of the mean plane strain strength on the Zener-Hollomon parameter during hot rolling of AISI316L.



Mean Plane Strain Strength , MPa
500
400
300
200
100
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
10^{26}
Z , s^{-1}
Symbol
Pass Number
■ 1
● 2
+ 3

FIGURE 8.17 : The mean plane strain strength dependence on the average rolling temperature for samples hot rolled in a single, double and treble pass schedule.

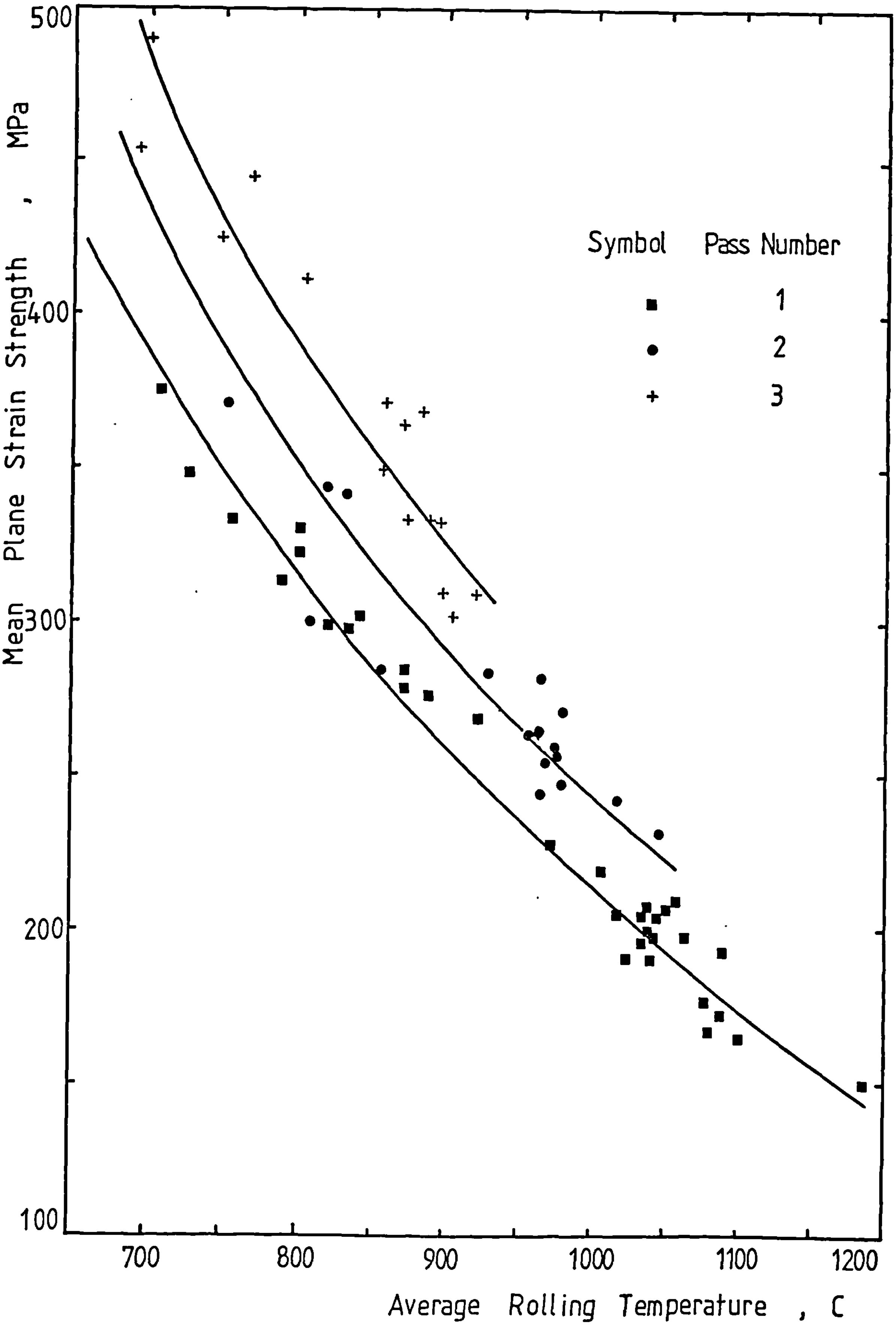

Mean Plane Strain Strength , MPa
500
400
300
200
100
700
800
900
1000
1100
1200
Average Rolling Temperature , C
Symbol Pass Number
■ 1
● 2
+ 3

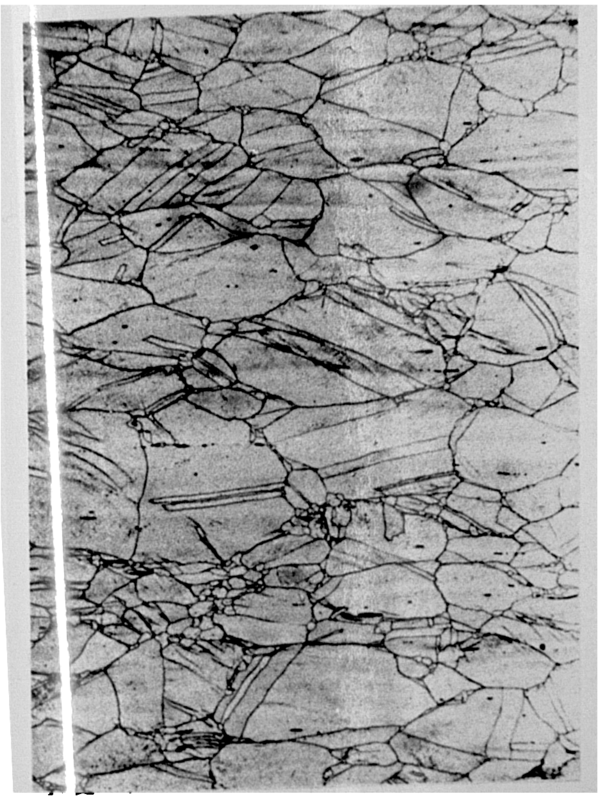
FIGURE 8.18 : Microstructure after hot rolling of AISI316L. Samples were given a single 25% reduction pass and air cooled to room temperature.

Mag. x84

a- 7% recrystallized

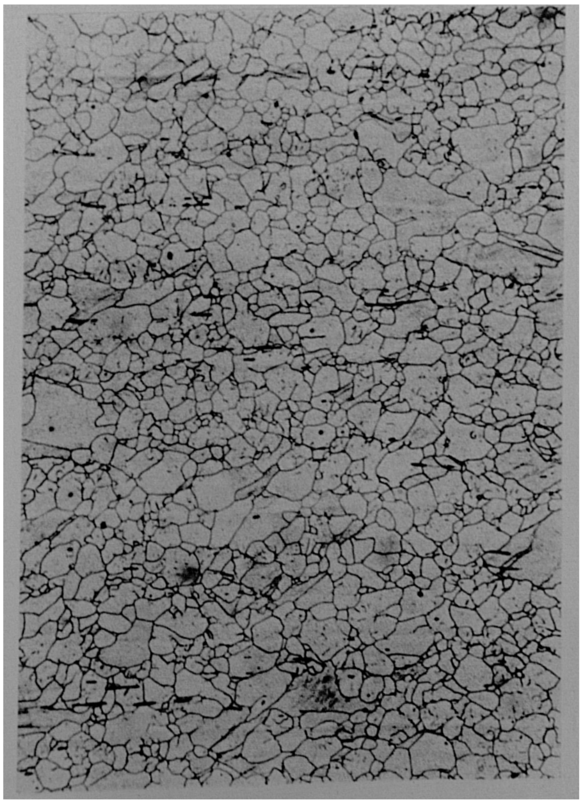
b- 43% recrystallized

c- 83% recrystallized



a

b



c

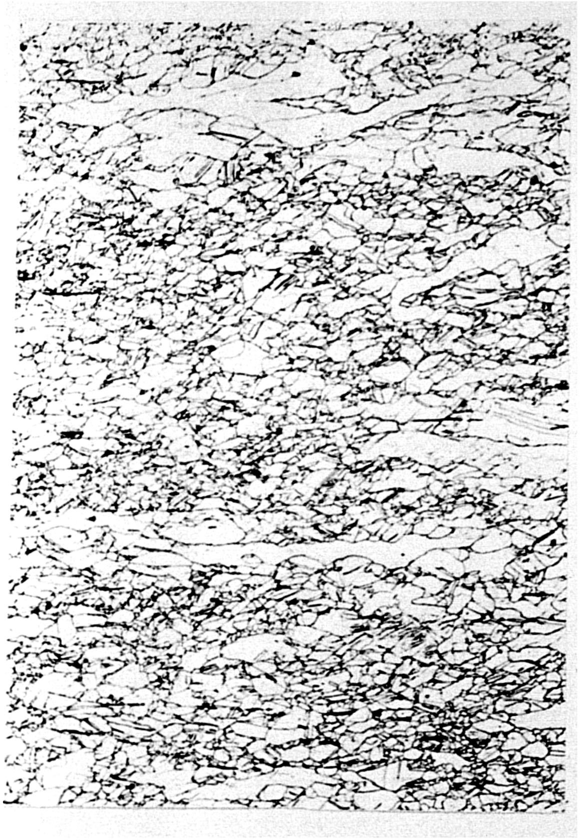
FIGURE 8.19 : Microstructural characteristics of a sample hot rolled in a 3x25% reduction schedule.

a- overall view

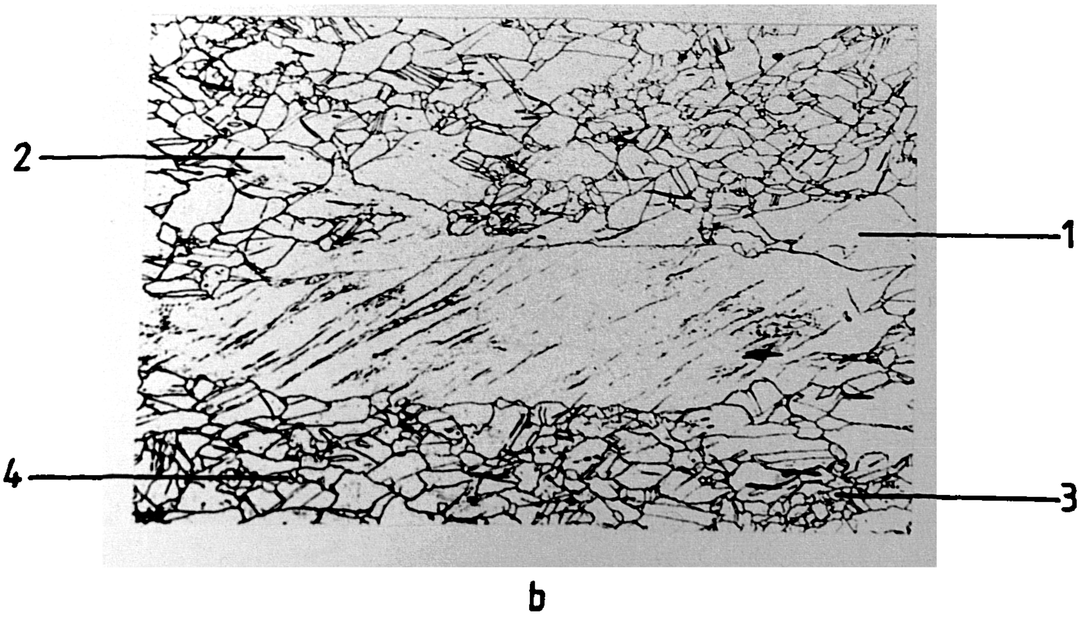
Mag. x84

b- grains with different accumulated strains

- 1- $\varepsilon \sim 0.99$
- 2- $\varepsilon \sim 0.66$
- 3- $\varepsilon \sim 0.33$
- 4- $\varepsilon = 0.00$



a



b

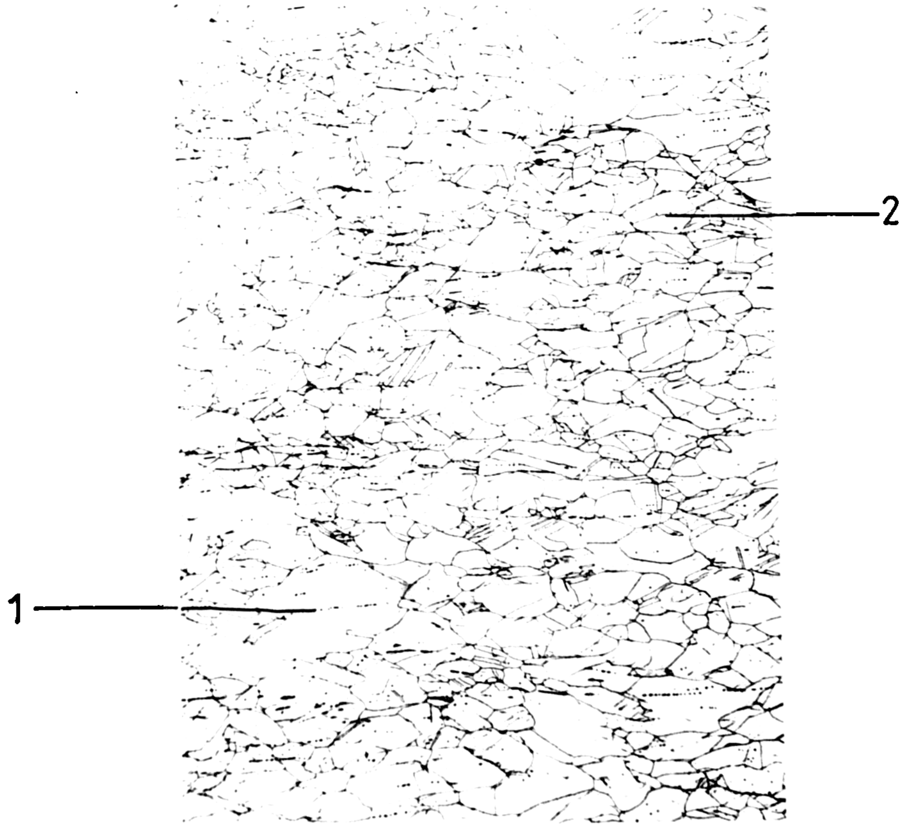
FIGURE 8.20 : Microstructural characteristics of a sample hot rolled in a 2x25% schedule and quenched immediately after the second pass.

Mag. x84

a- 44% recrystallized

b- 77% recrystallized

a



b

FIGURE 8.21 : The effect of the average rolling temperature on the fraction of material statically recrystallized for samples air cooled during 15s and samples air cooled to room temperature.

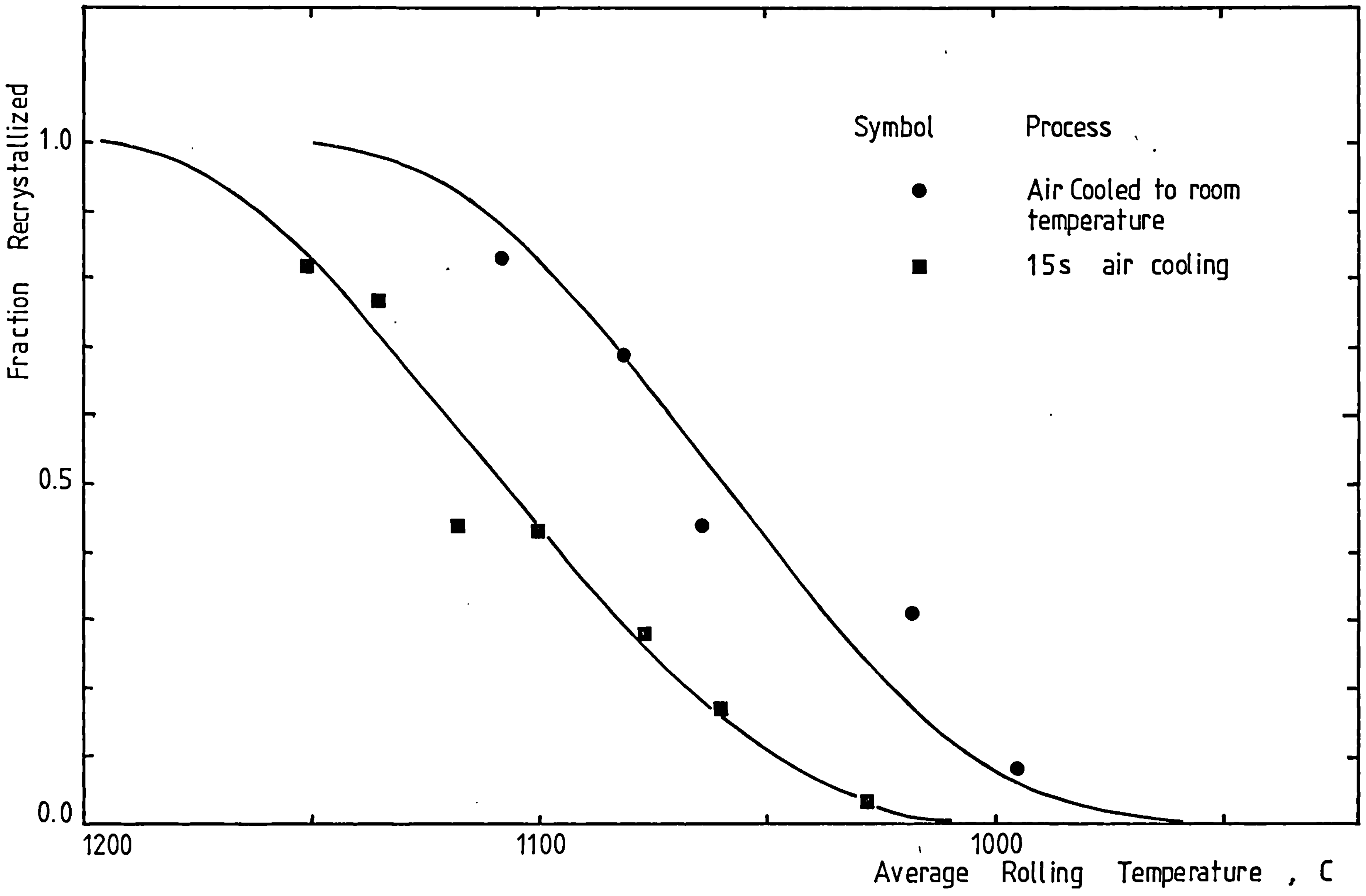

Symbol
Process
●
Air Cooled to room temperature
■
15s air cooling
Fraction Recrystallized
1.0
0.5
0.0
1200
1100
1000
Average Rolling Temperature , C

FIGURE 8.22 : The influence of the original grain size on the dependence of the fraction recrystallized on the average rolling temperature.

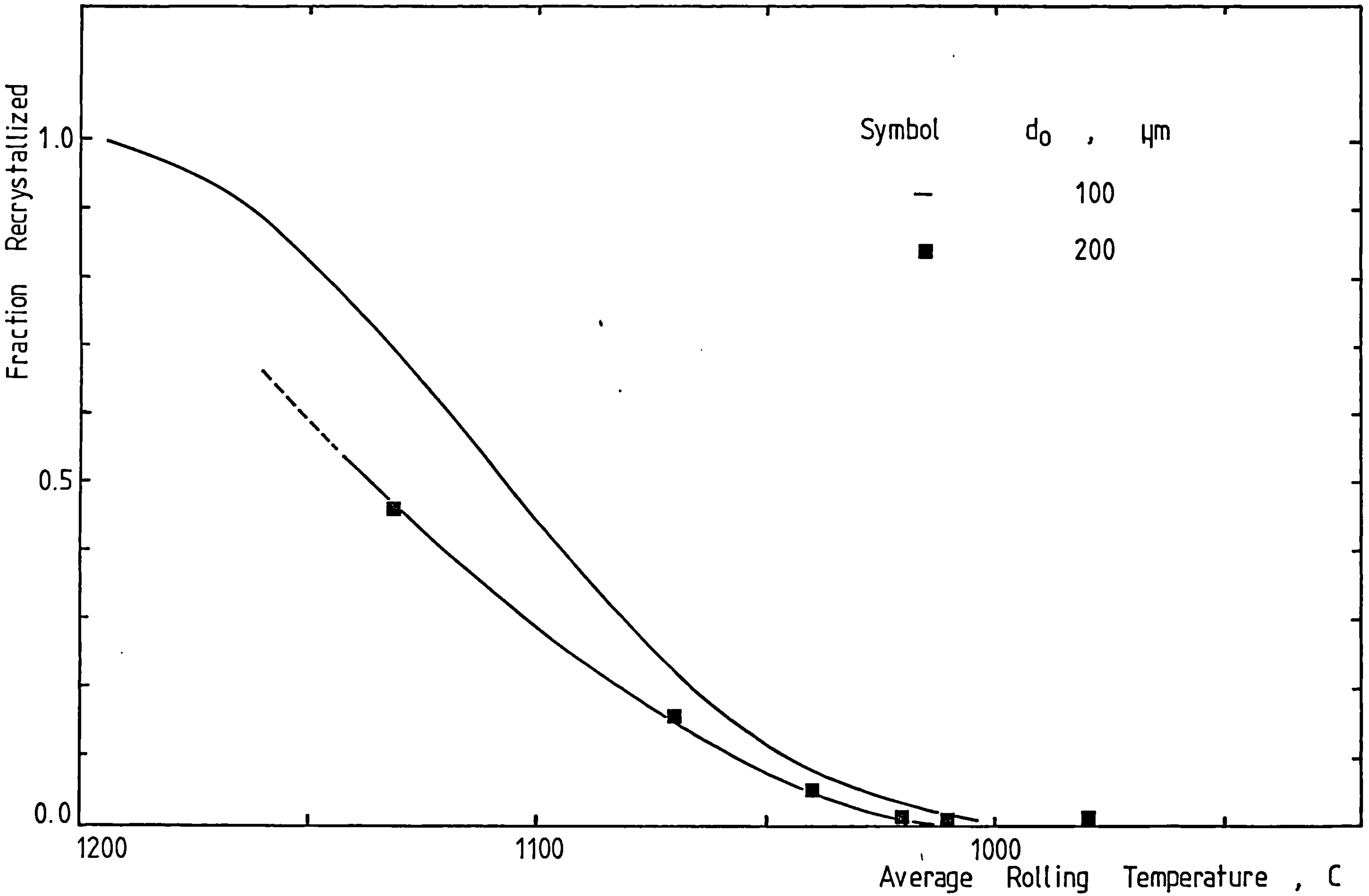

Symbol
d_o , μm
— 100
■ 200
Fraction Recrystallized
1.0
0.5
0.0
1200
1100
1000
Average Rolling Temperature , C

FIGURE 8.23 : The dependence of the average grain size during recrystallization on the average rolling temperature.

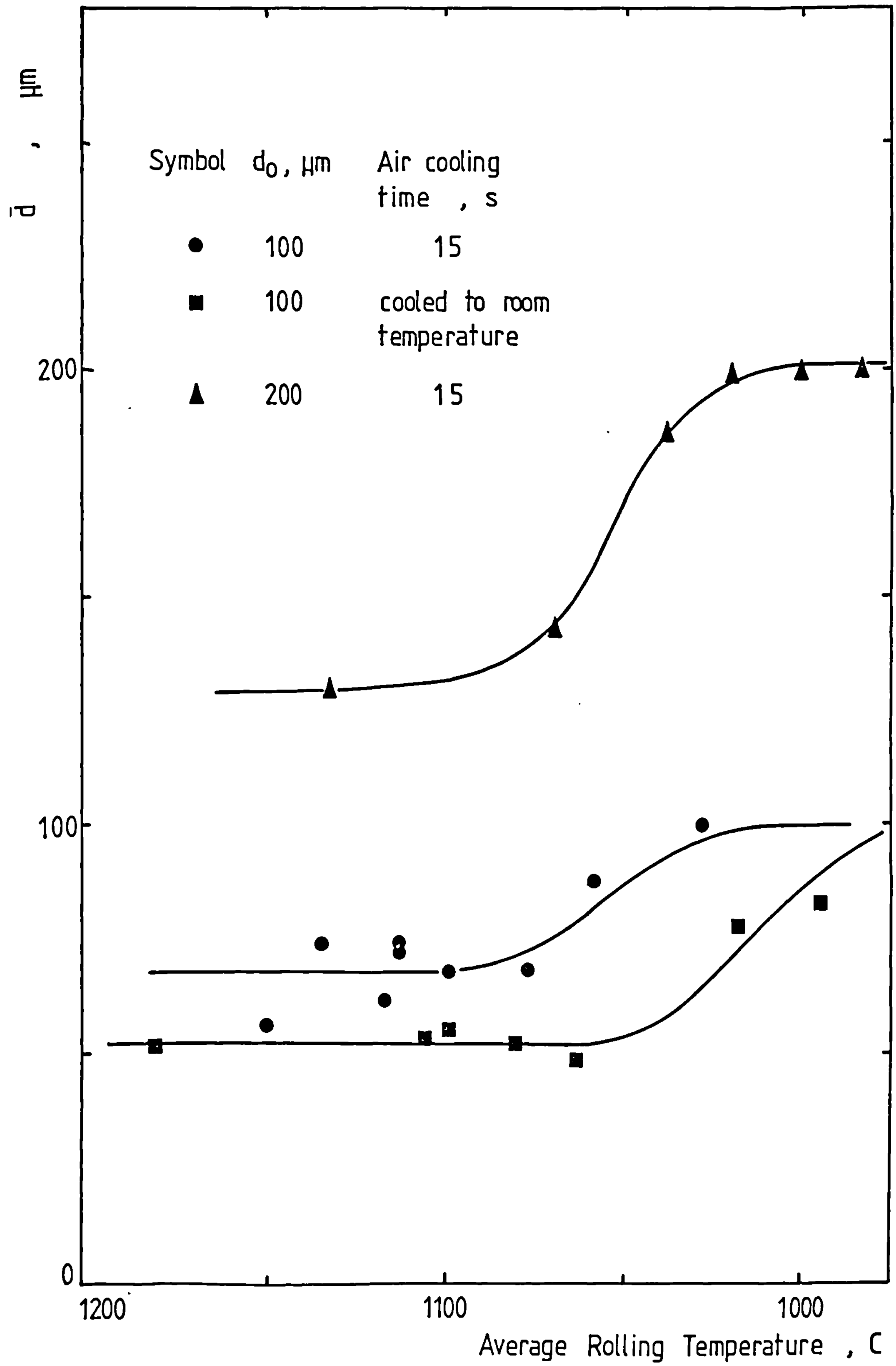

$\bar{d}$, μm
Symbol
d_0, μm
Air cooling time , s
● 100 15
■ 100 cooled to room temperature
▲ 200 15
200
100
0
1200
1100
1000
Average Rolling Temperature , C

FIGURE 8.24 : The dependence of the average grain size during recrystallization on the fraction of material statically recrystallized after a single 25% reduction.

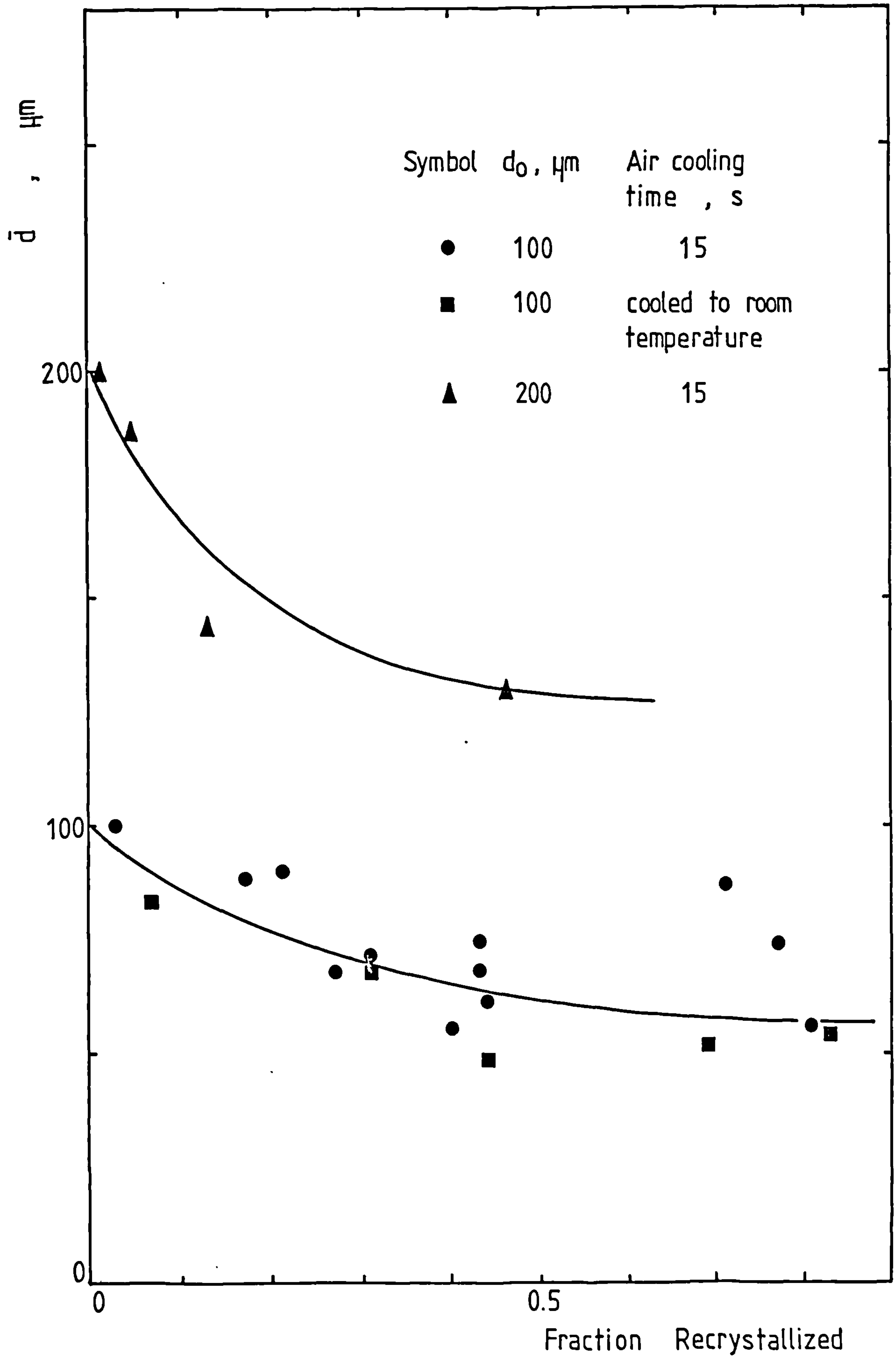
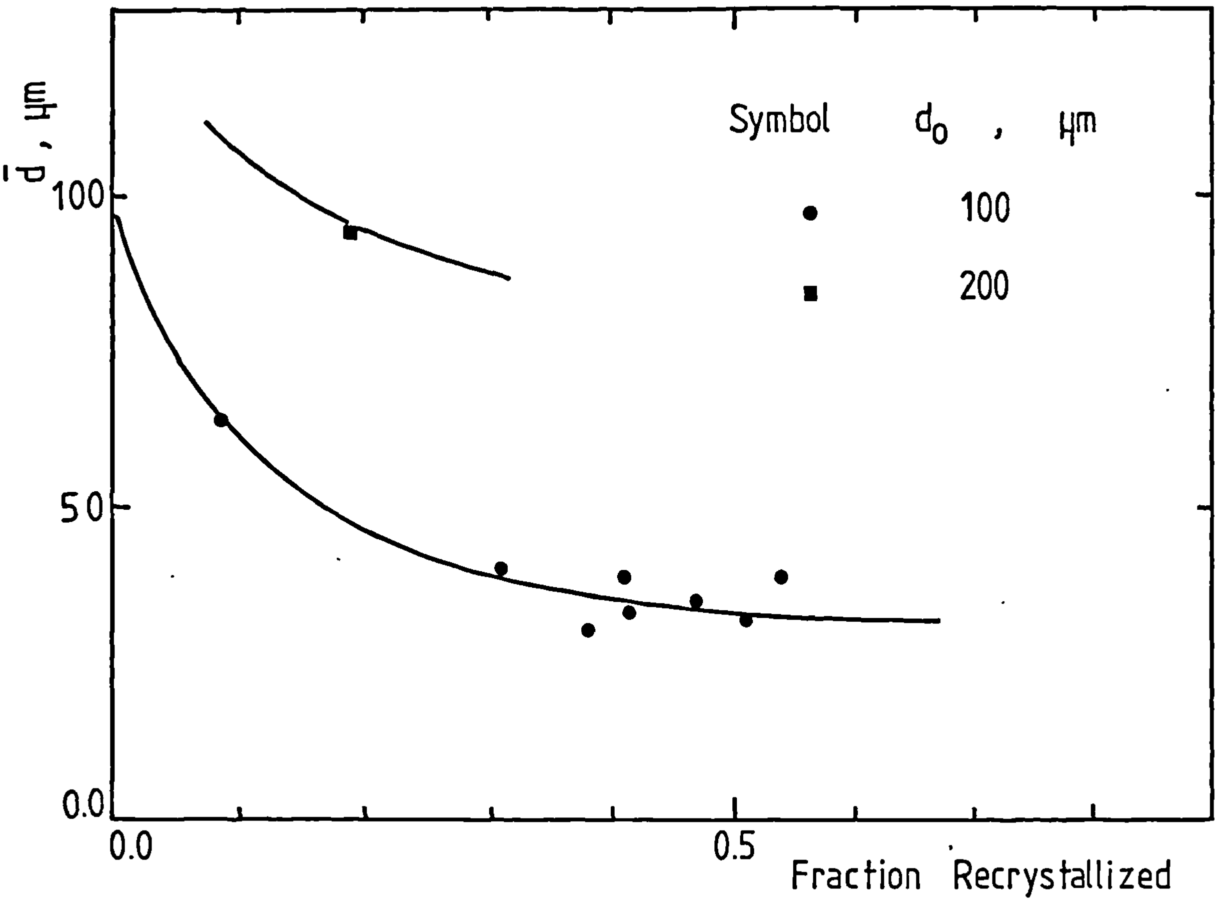
d̄ , μm
200
100
0
0
0.5
Fraction Recrystallized
Symbol
d_0, μm
Air cooling time , s
● 100 15
■ 100 cooled to room temperature
▲ 200 15

FIGURE 8.25 : The effect of the fraction recrystallized material on the average grain size during recrystallization after two hot rolling passes of 25% reduction each.

FIGURE 8.26 : The dependence of the average grain size during recrystallization on the average hot rolling temperature for samples hot rolled in a 2x25% schedule.


d̄ , μm
100
50
0.0
0.0
0.5
Fraction Recrystallized
Symbol
d₀ , μm
● 100
■ 200

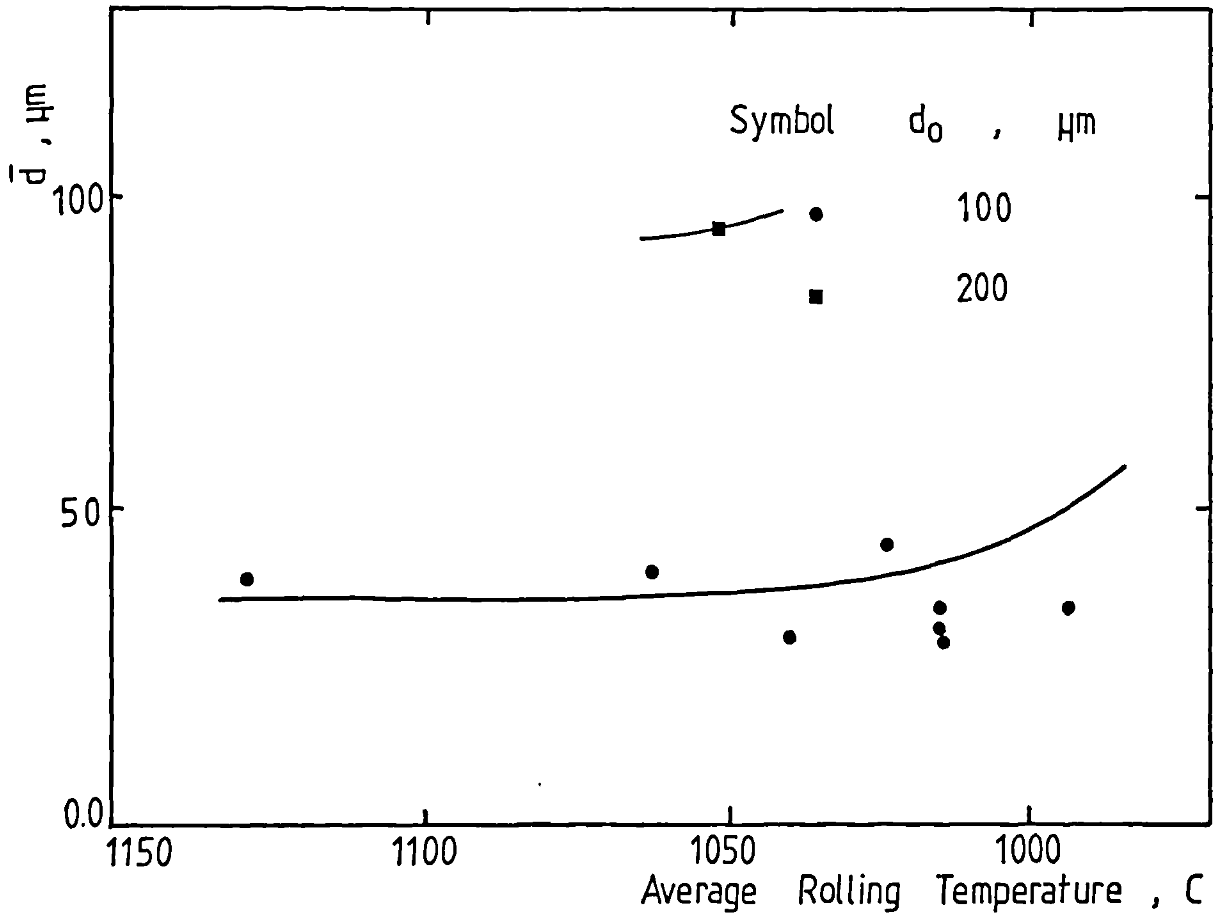
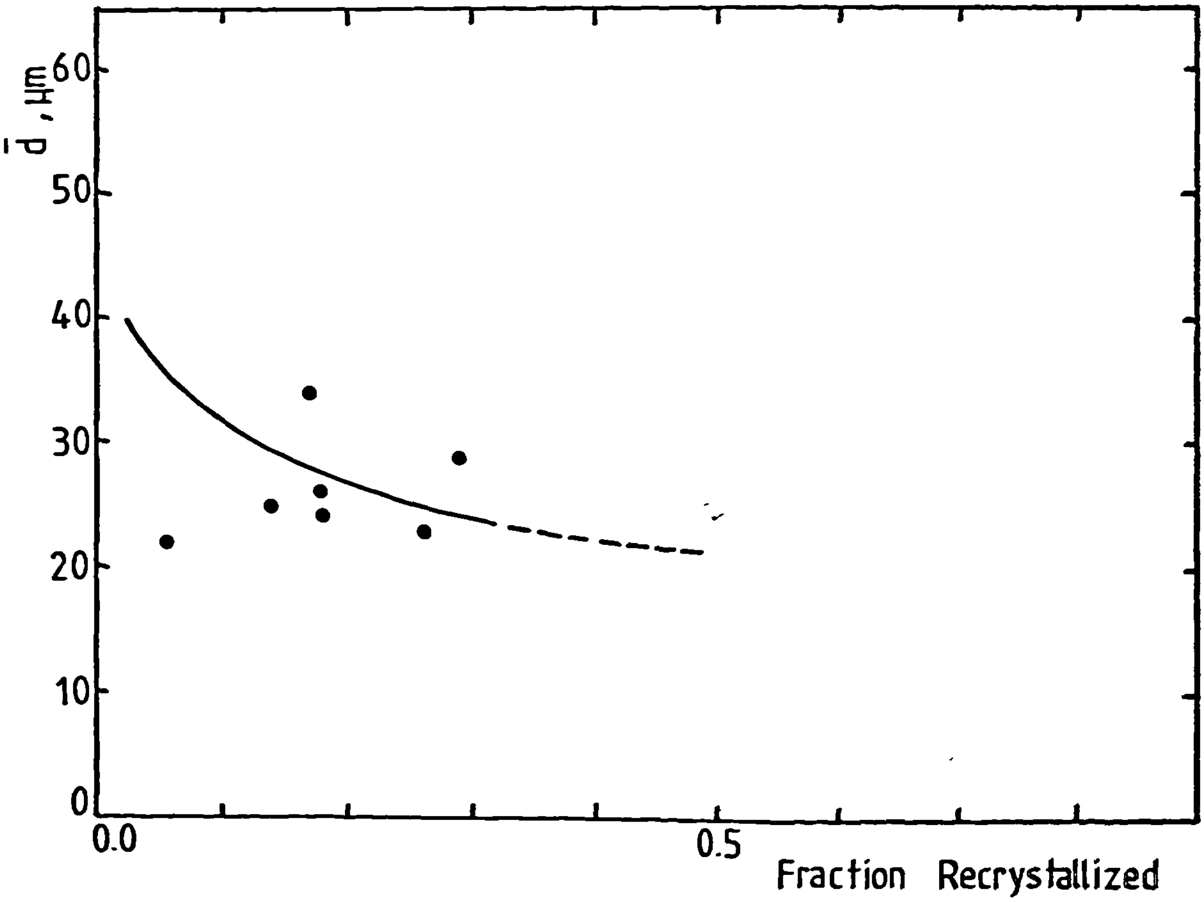

d̄ , μm
100
50
0.0
1150
1100
1050
1000
Average Rolling Temperature , C
Symbol
d₀ , μm
● 100
■ 200

FIGURE 8.27 : The effect of the fraction recrystallized material on the average grain size during recrystallization after a 3x25% pass hot rolling schedule was given to the slab. The samples had an original grain size of 100μm.

FIGURE 8.28 : The dependence of the average grain size during recrystallization on the hot rolling temperature for samples from a 3x25% pass schedule. The original grain size was 100μm.


$\bar{d}$, μm
60
50
40
30
20
10
0
0.0
0.5
Fraction Recrystallized

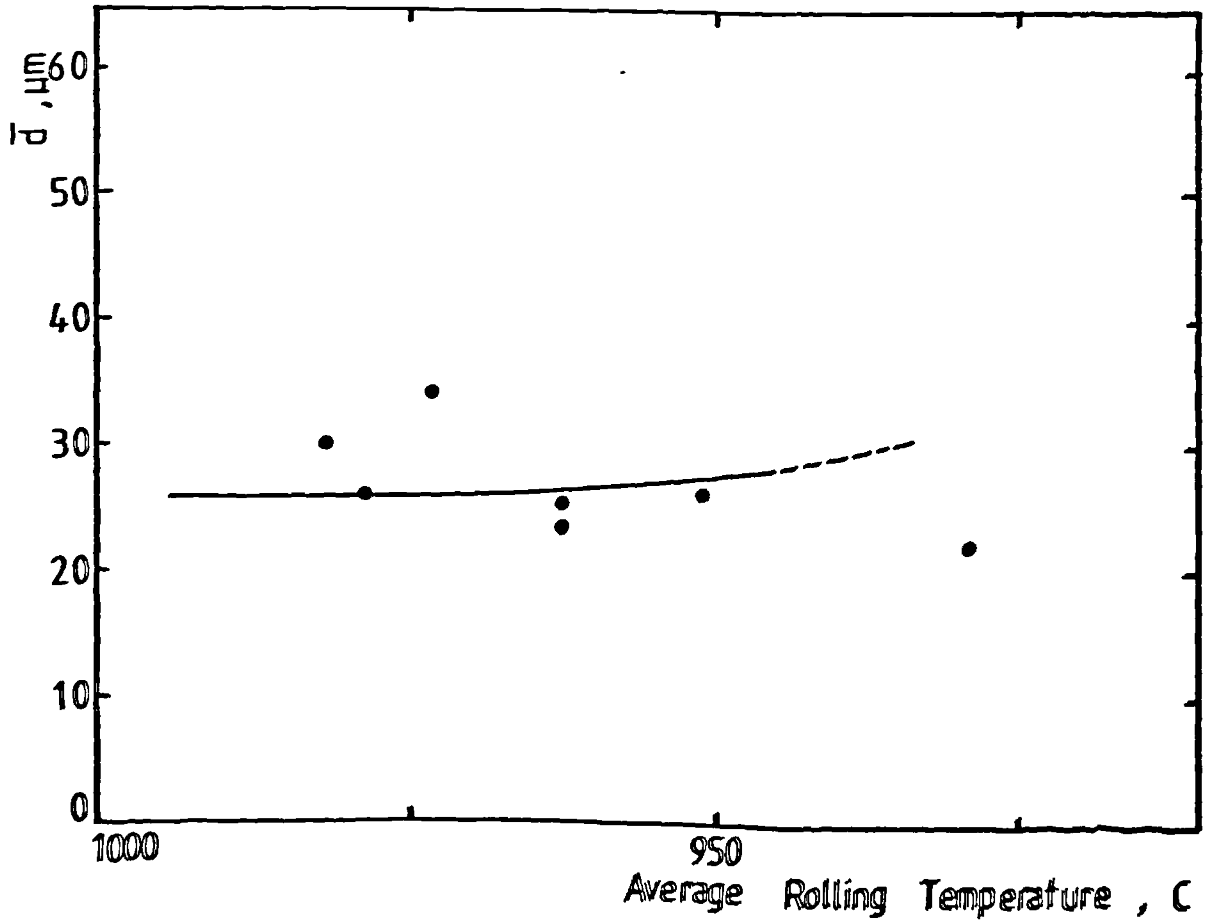
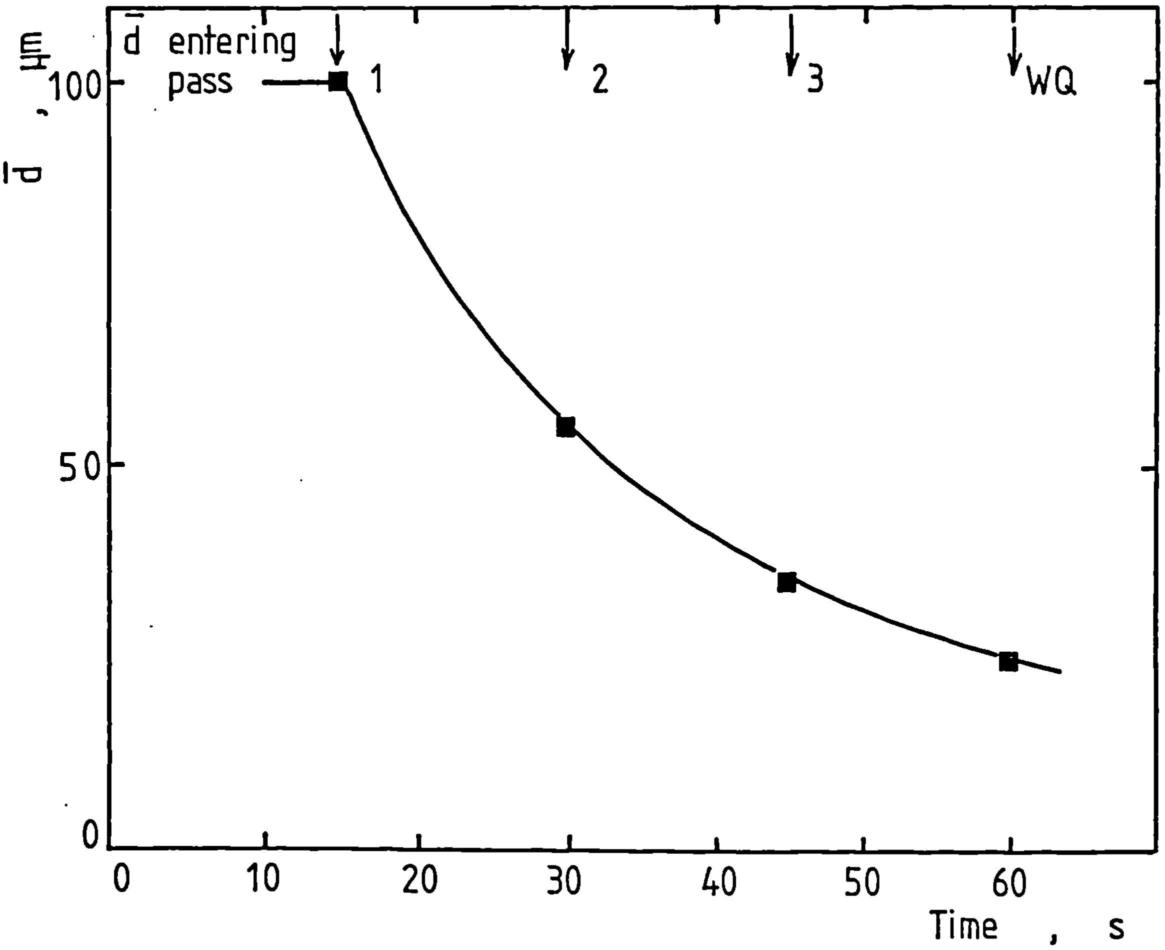
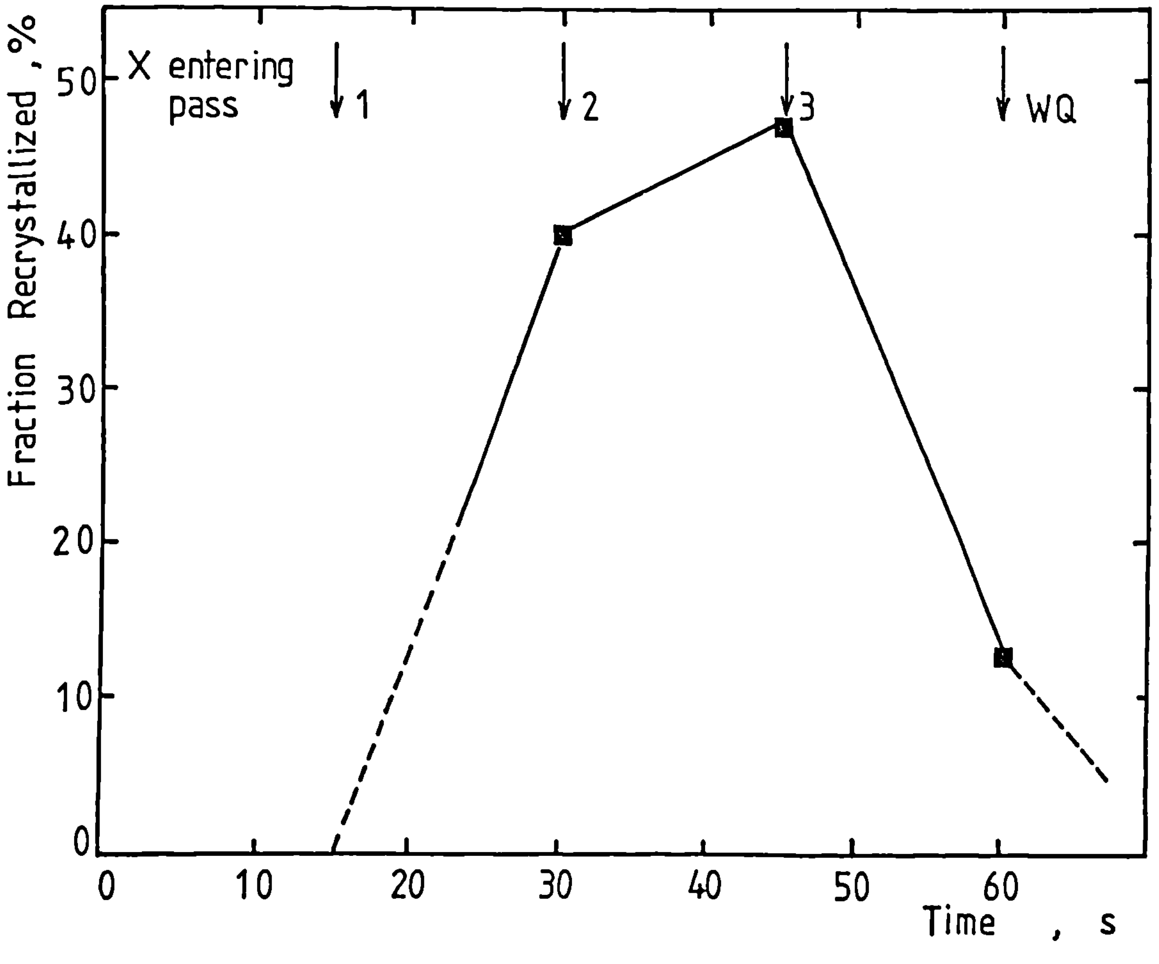

$\bar{d}$, μm
60
50
40
30
20
10
0
1000
950
Average Rolling Temperature , C

FIGURE 8.29 : Typical evolution of the average grain size during recrystallization during hot rolling of AISI316L in a 3 pass schedule of 25% reduction in thickness each. Points represent the average grain size during recrystallization entering a given pass.

FIGURE 8.30 : Typical fraction recrystallized evolution during hot rolling of AISI316L in a 3x25% reduction schedule. Points represent material statically recrystallized entering a given pass.



d̄ entering pass
1
2
3
WQ
d̄ , μm
100
50
0
0
10
20
30
40
50
60
Time , s



X entering pass
1
2
3
WQ
Fraction Recrystallized , %
50
40
30
20
10
0
0
10
20
30
40
50
60
Time , s

FIGURE 8.31 : The dependence of the rolling load on the fraction recrystallized. Samples were given a 2 pass schedule of 25% and 21% reduction in the first and second pass respectively. The original grain size was 100μm. The first pass was given at a measured centre temperature entering the pass, T^{mc}_{entry}, ranging from 1200 to 1050C. The second pass T^{mc}_{entry} was kept constant (950C).

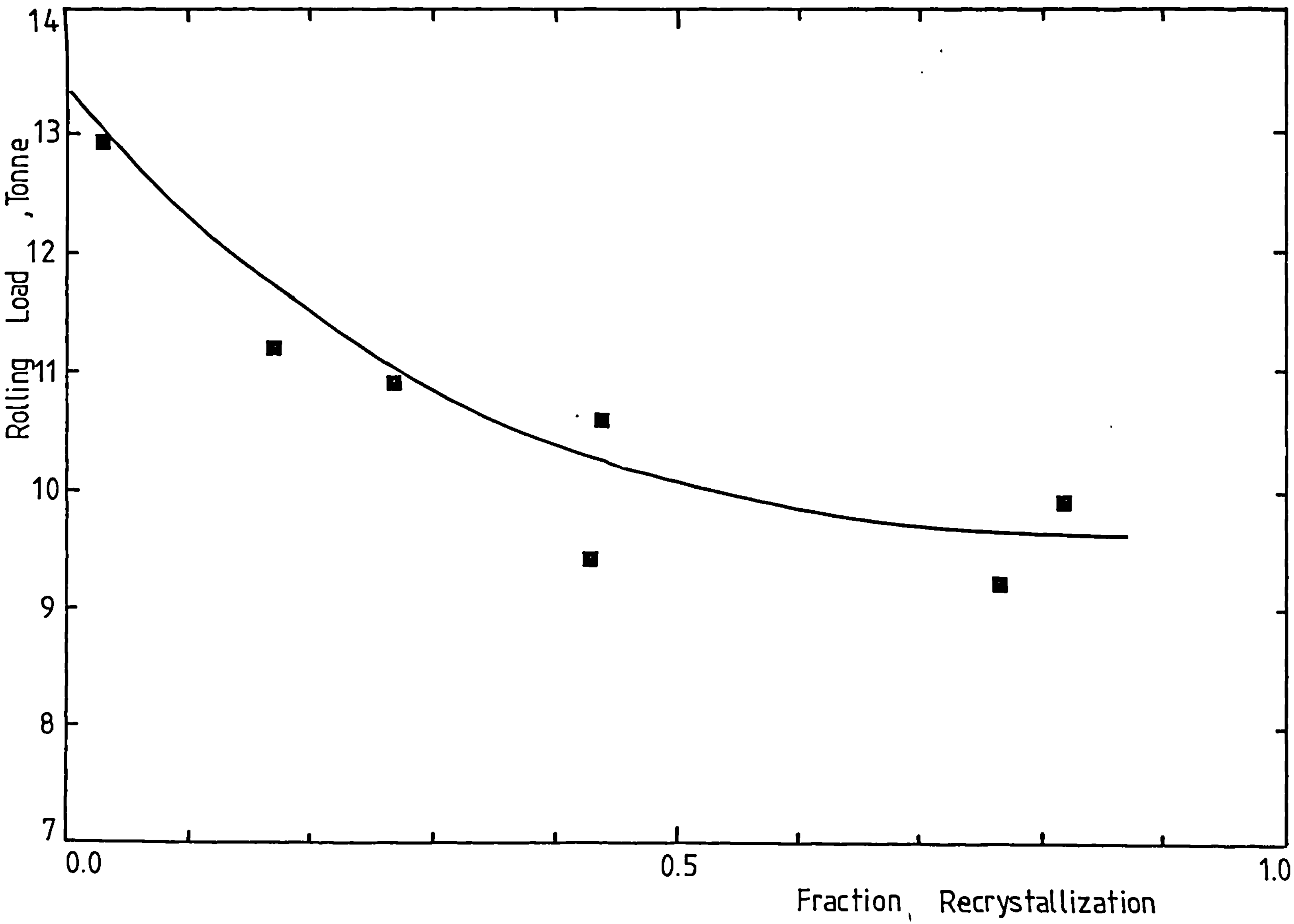

14
13
12
11
10
9
8
7
Rolling Load , Tonne
0.0
0.5
1.0
Fraction, Recrystallization

FIGURE 8.32 : Dependence of the second pass rolling load on the first pass T^{mc}_{entry}. Schedule details are as given in figure(8.31).

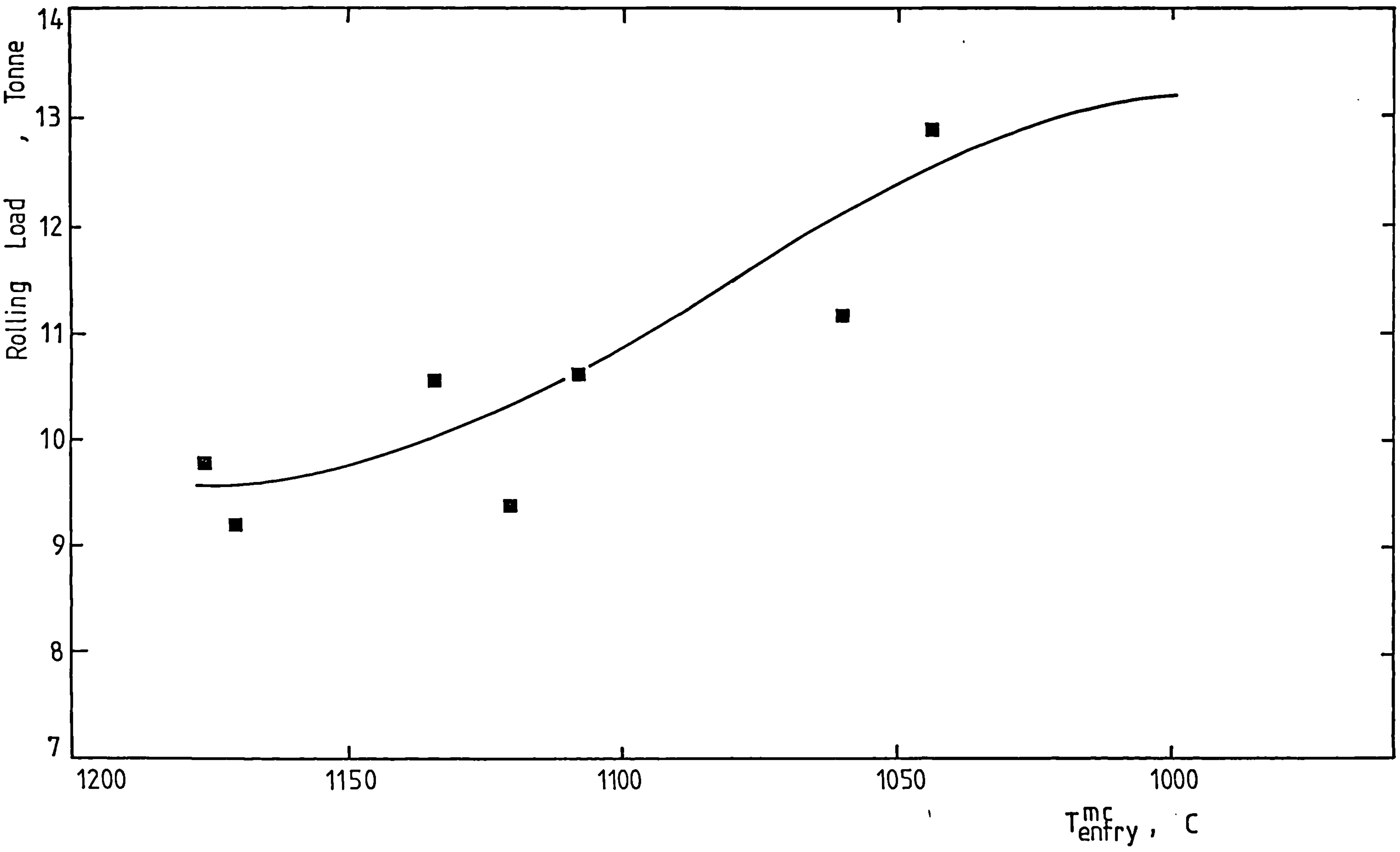
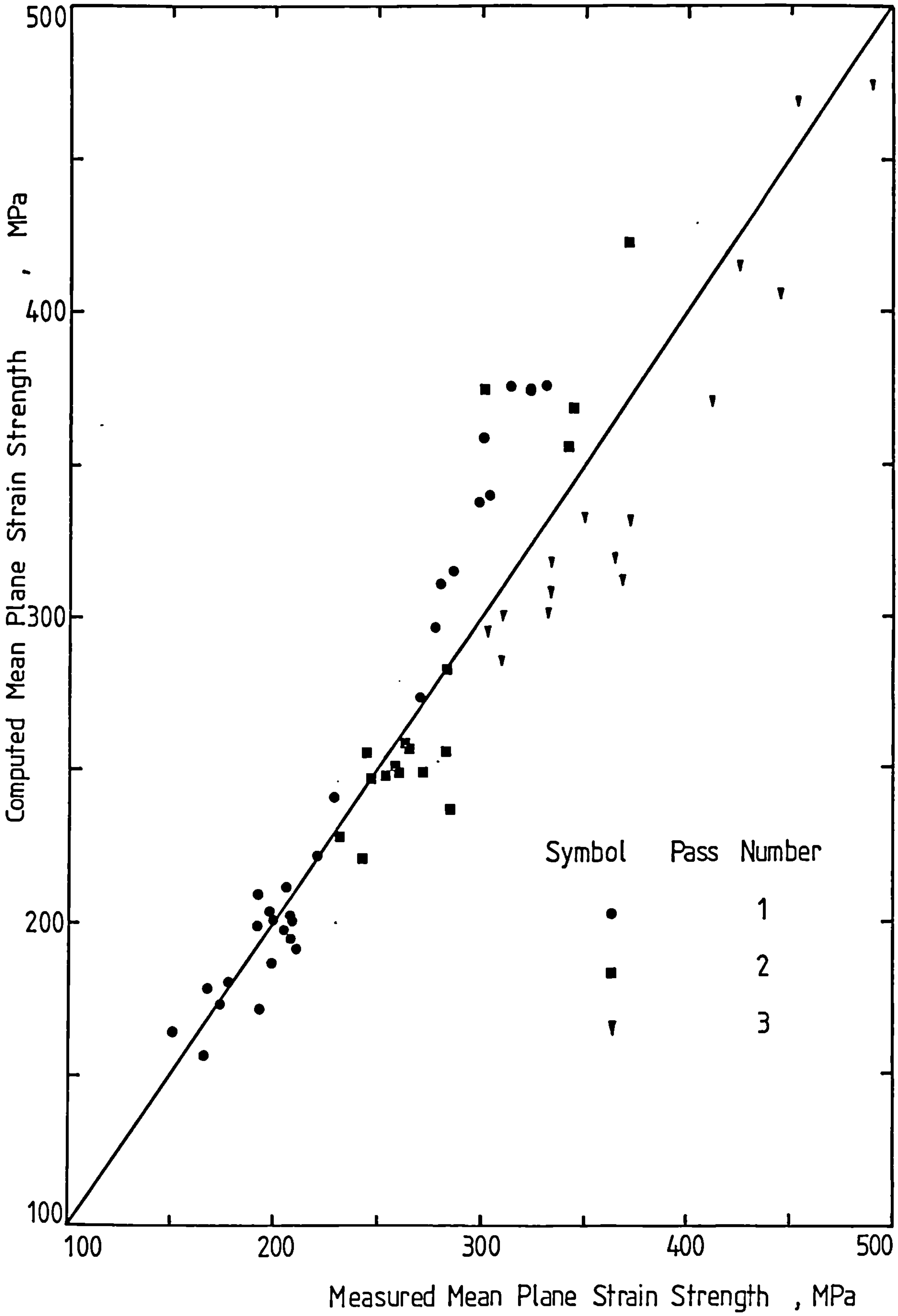

Rolling Load , Tonne
14
13
12
11
10
9
8
7
1200
1150
1100
1050
1000
T^{mf}_{entry} , C

FIGURE 8.33 : Correlation between computed mean plane strain strength and the measured mean plane strain strength during hot rolling.



Computed Mean Plane Strain Strength , MPa
Measured Mean Plane Strain Strength , MPa
100
200
300
400
500
100
200
300
400
500
Symbol
Pass Number
● 1
■ 2
▼ 3

FIGURE 8.34 : *The dependence* of the computed average pass temperature on the measured centre rolling temperature at rolling gap entry.

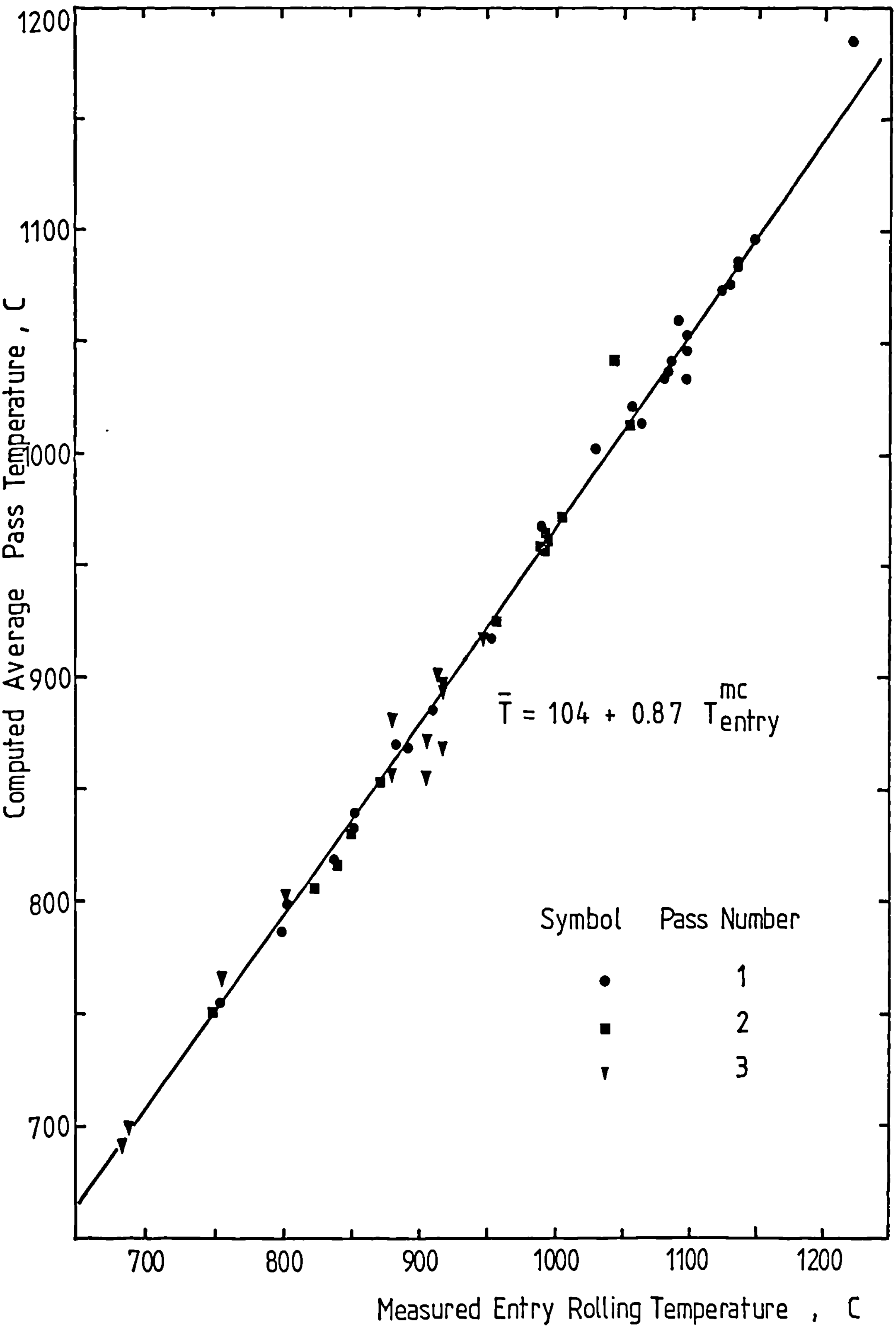

1200
1100
1000
900
800
700
Computed Average Pass Temperature , C
700
800
900
1000
1100
1200
Measured Entry Rolling Temperature , C
$\bar{T}^{mc} = 104 + 0.87\ T_{entry}$
Symbol
Pass Number
●
1
■
2
▼
3

FIGURE 8.35 : Comparison of the computed average grain size with the measured average grain size during hot rolling of AISI316L. Samples were deformed in a 25% single pass rolling schedule.

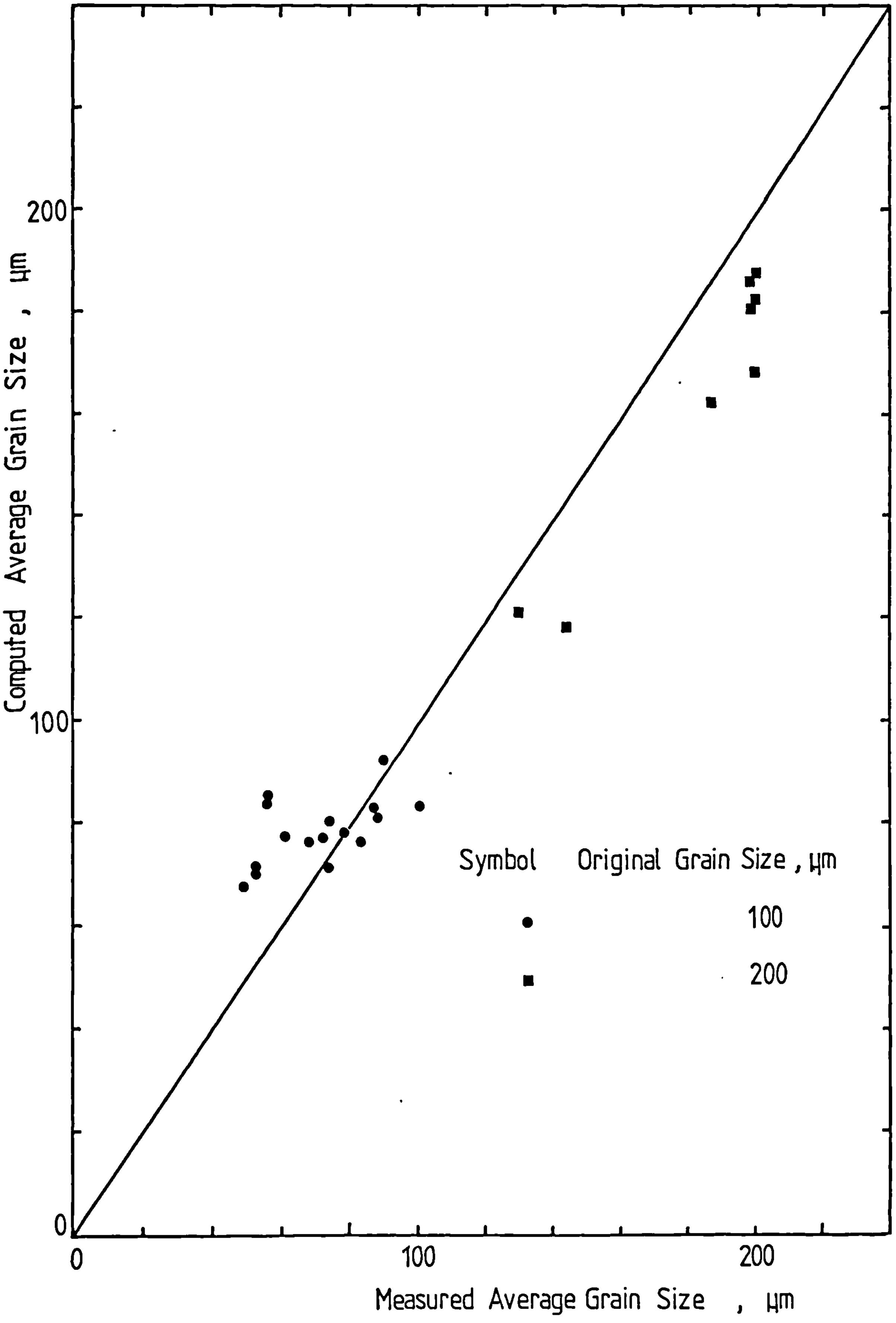

Computed Average Grain Size , μm
200
100
0
0
100
200
Measured Average Grain Size , μm
Symbol Original Grain Size , μm
● 100
■ 200

FIGURE 8.36 : Correlation between predicted and experimental average grain size during recrystallization. Samples were given a 2x25% reduction pass schedule.

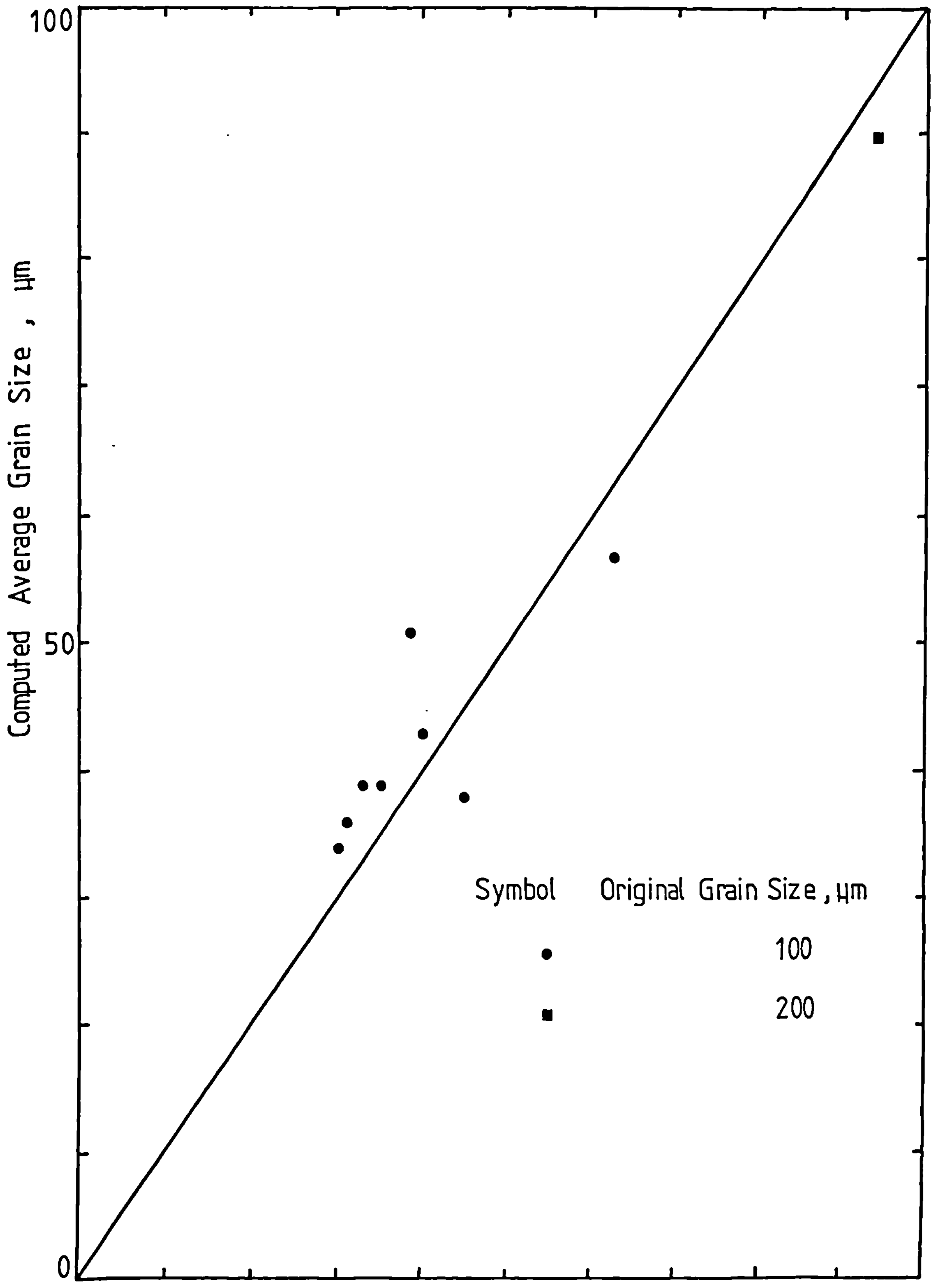

100
50
0
0
50
100
Computed Average Grain Size , μm
Measured Average Grain Size , μm
Symbol
Original Grain Size , μm
● 100
■ 200

FIGURE 8.37 : Correlation between computed and measured average grain size during recrystallization. Samples were given a 3x25% reduction pass schedule. The original grain size was 100μm.

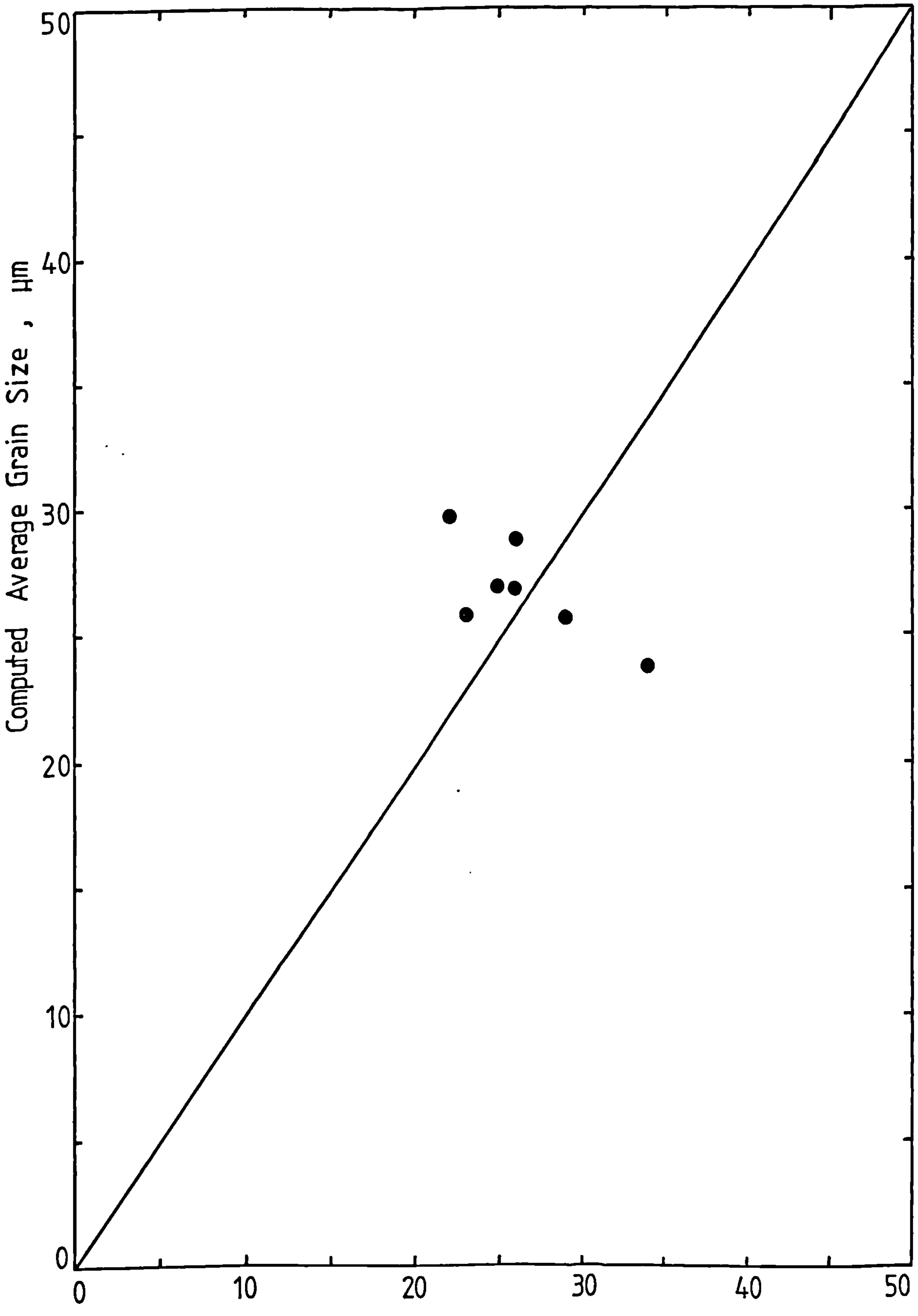
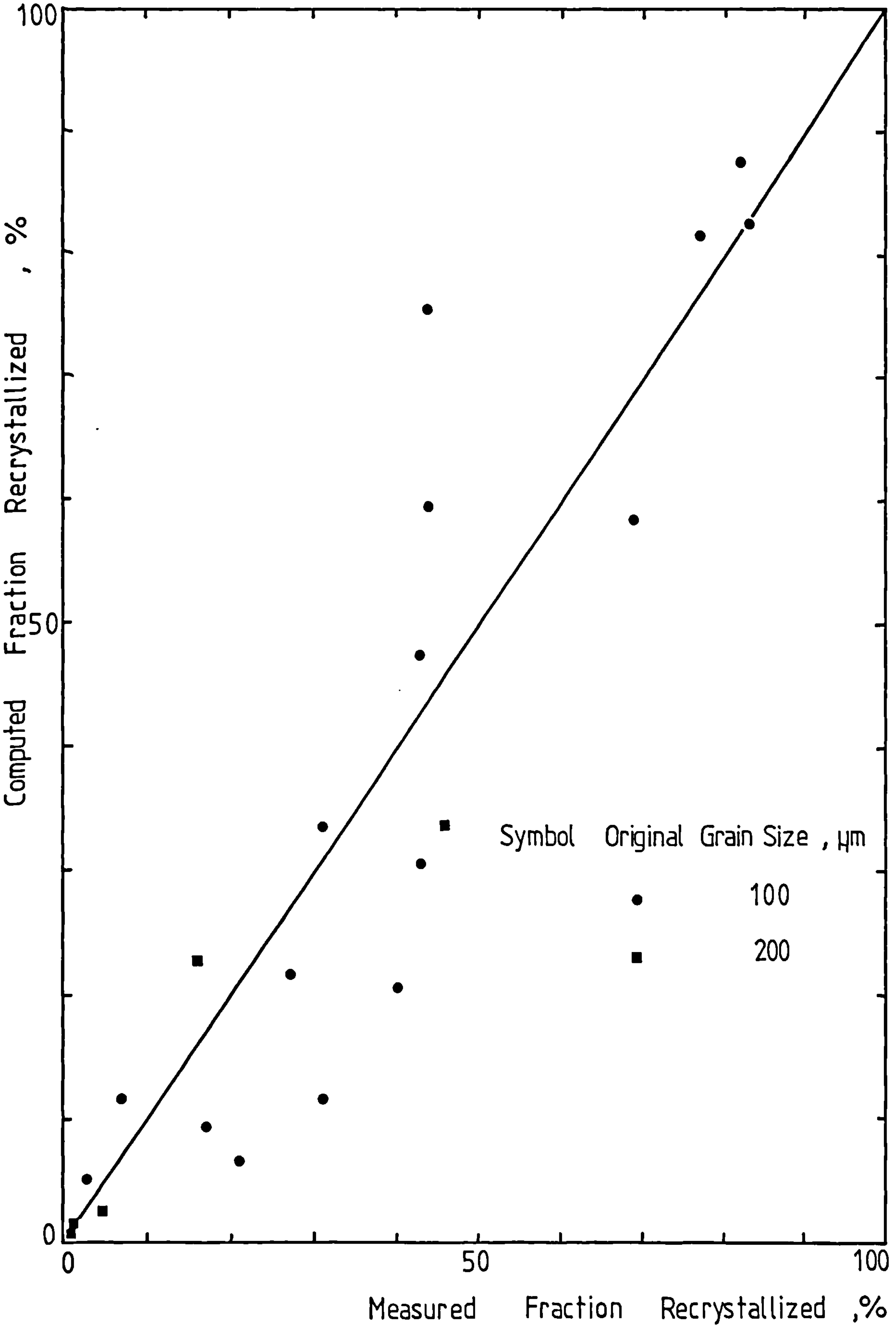

Computed Average Grain Size , μm
Measured Average Grain Size , μm
0
10
20
30
40
50
0
10
20
30
40
50

FIGURE 8.38 : Comparison between predicted and measured fraction recrystallized. Samples were deformed in a 25% single pass hot rolling schedule and quenched 15s after the pass was given.



100
50
0
0
50
100
Computed Fraction Recrystallized , %
Measured Fraction Recrystallized ,%
Symbol Original Grain Size , μm
● 100
■ 200

FIGURE 8.39 : Correlation between predicted and experimental fraction recrystallized. Samples were deformed in a 2x25% reduction pass schedule.

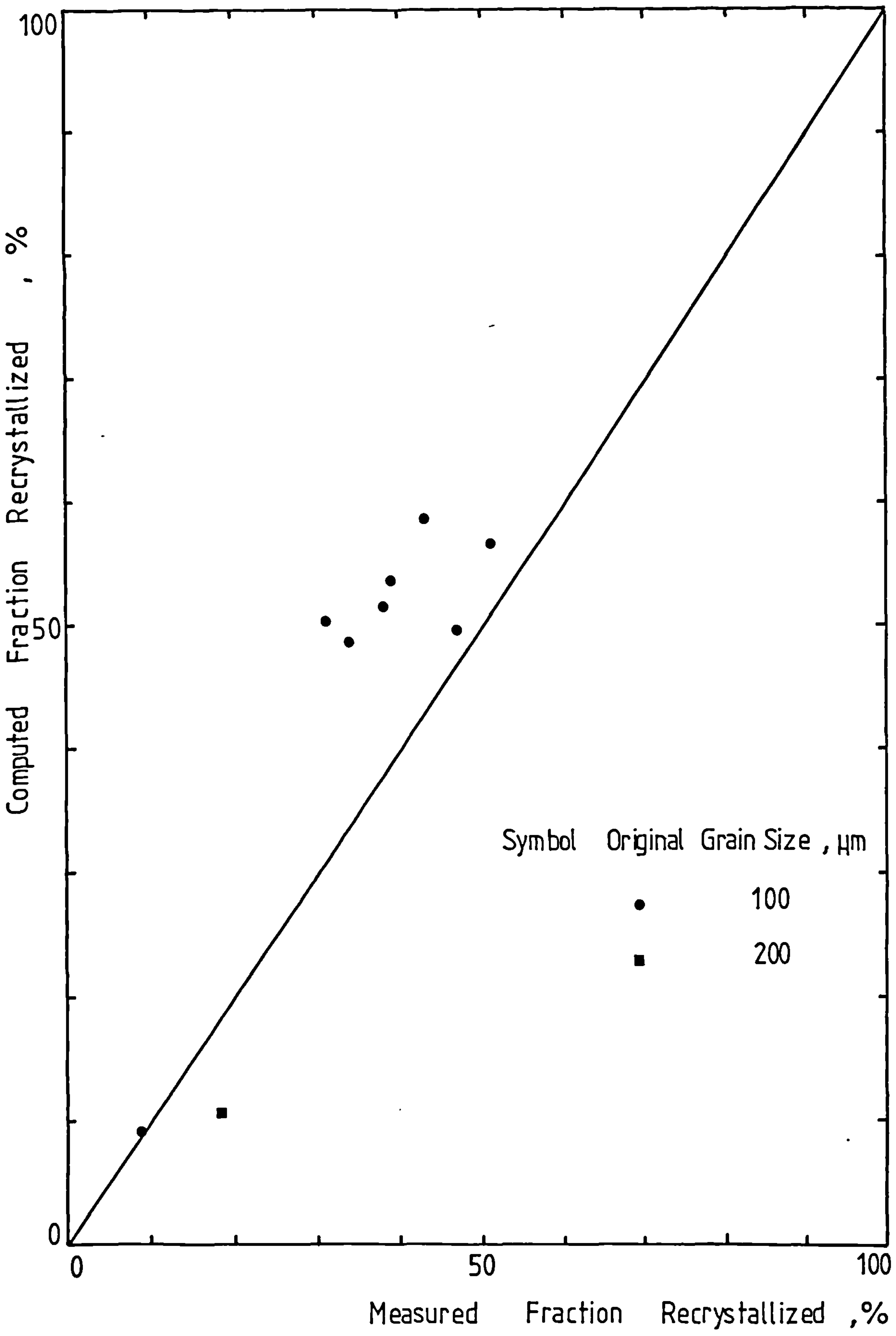

Computed Fraction Recrystallized , %
100
50
0
0
50
100
Measured Fraction Recrystallized ,%
Symbol Original Grain Size , μm
● 100
■ 200

FIGURE 8.40 : Correlation between computed and measured recrystallized fraction after a 3x25% reduction pass schedule was given. The original grain size is 100μm.

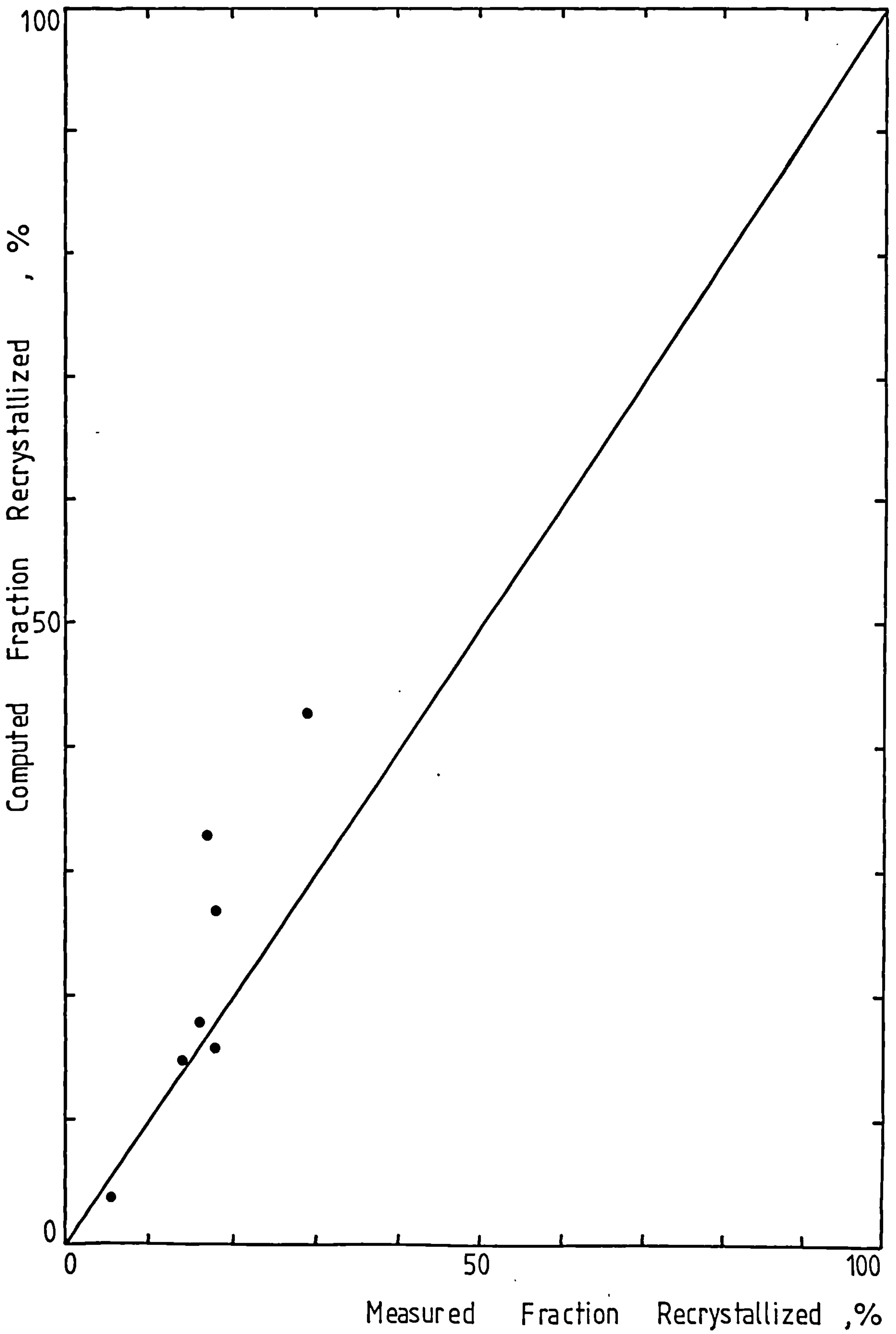
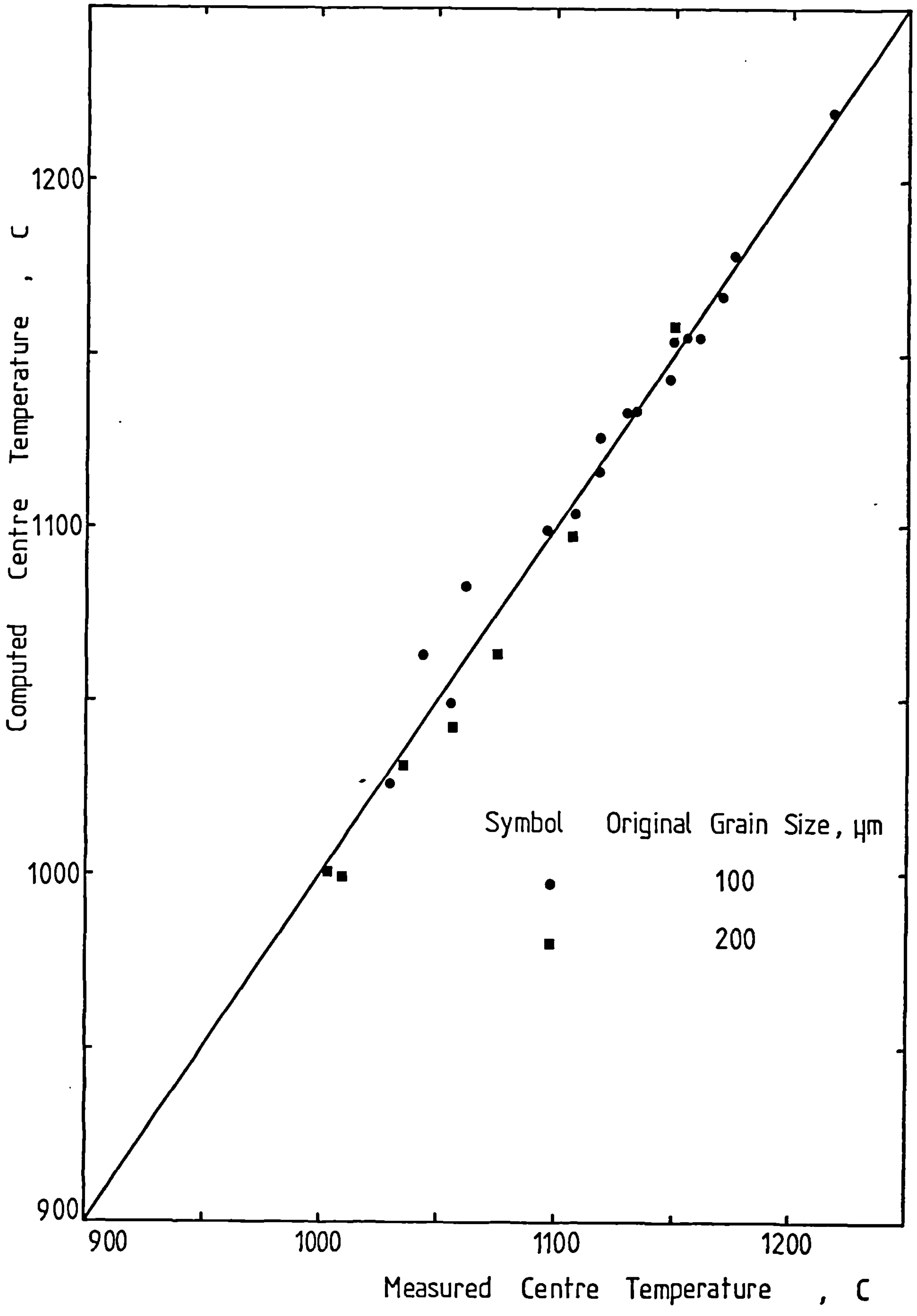

100
50
0
Computed Fraction Recrystallized , %
0
50
100
Measured Fraction Recrystallized ,%

FIGURE 8.41 : Comparison between computed temperature at the centre of the slab at the roll gap entry and the measured one for a sample deformed in a single pass rolling schedule.



1200
1100
1000
900
Computed Centre Temperature , C
900
1000
1100
1200
Measured Centre Temperature , C
Symbol Original Grain Size, µm
● 100
■ 200

FIGURE 8.42 : Correlation between predicted and measured centre temperature for samples hot rolled in 2x25% hot rolling schedule. Samples had original grain sizes of 100 and 200µm.

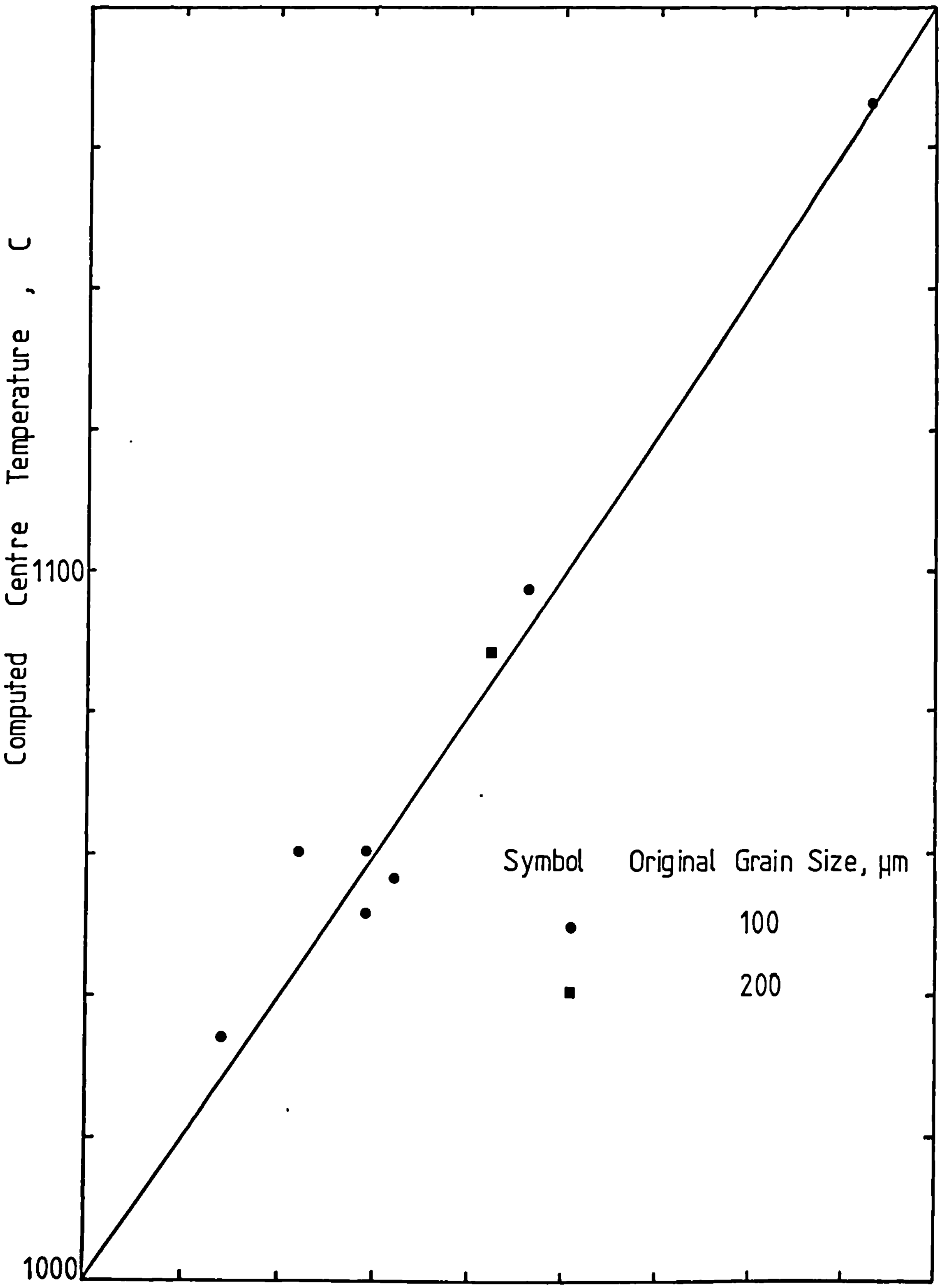

Computed Centre Temperature , C
1100
1000
1000
1100
Measured Centre Temperature , C
Symbol Original Grain Size, µm
● 100
■ 200

FIGURE 8.43 : Correlation between computed and measured centre temperature at the roll gap entry during a 3x25% reduction rolling schedule. The samples' original grain size is 100μm.

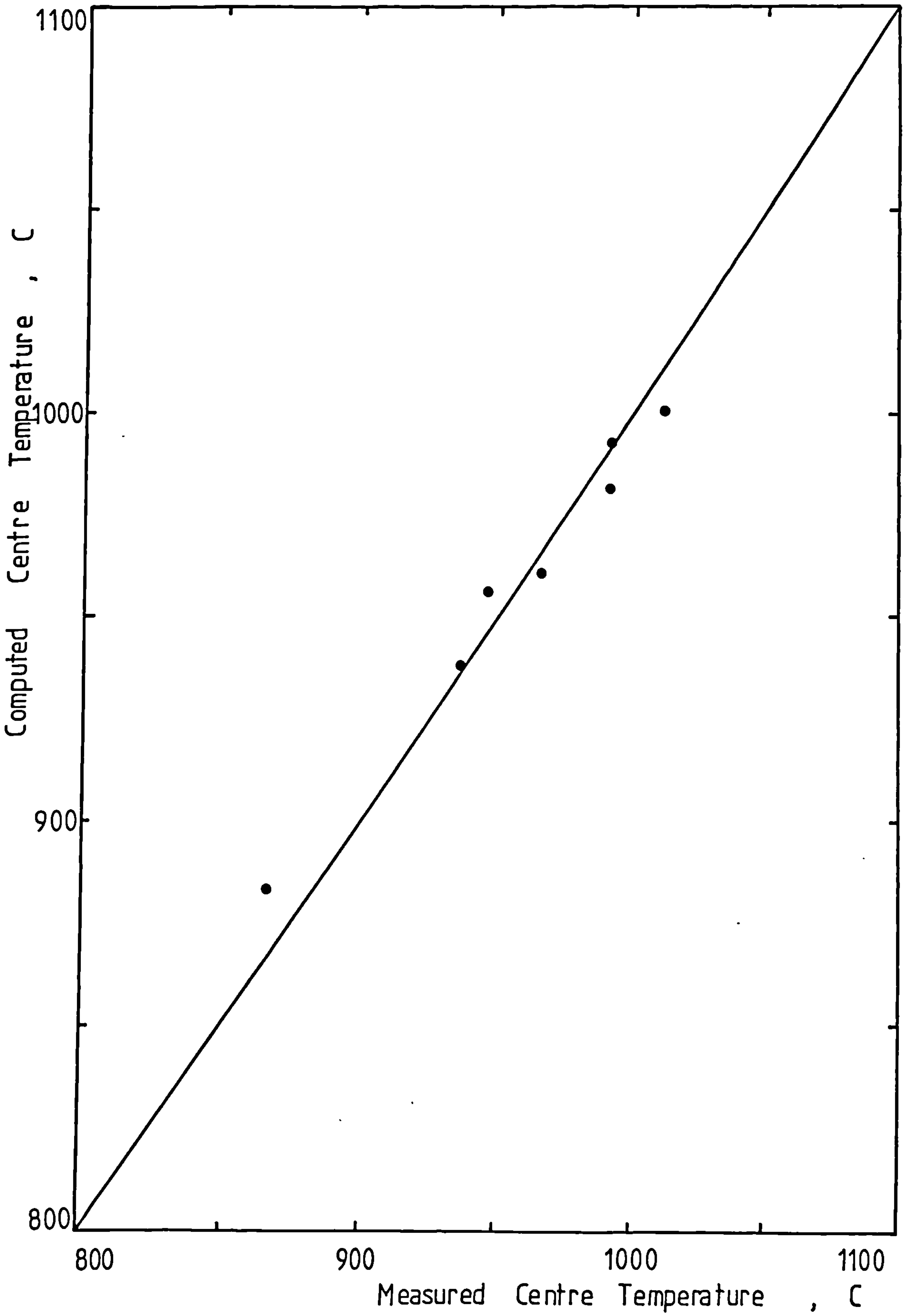
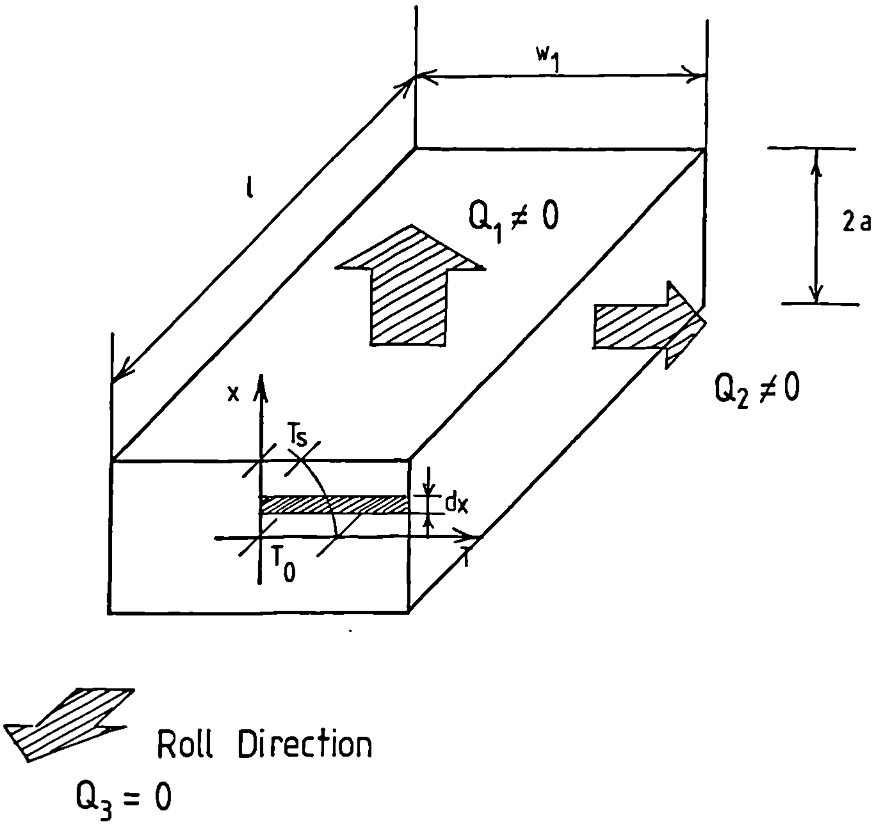

1100
1000
900
800
Computed Centre Temperature , C
800
900
1000
1100
Measured Centre Temperature , C

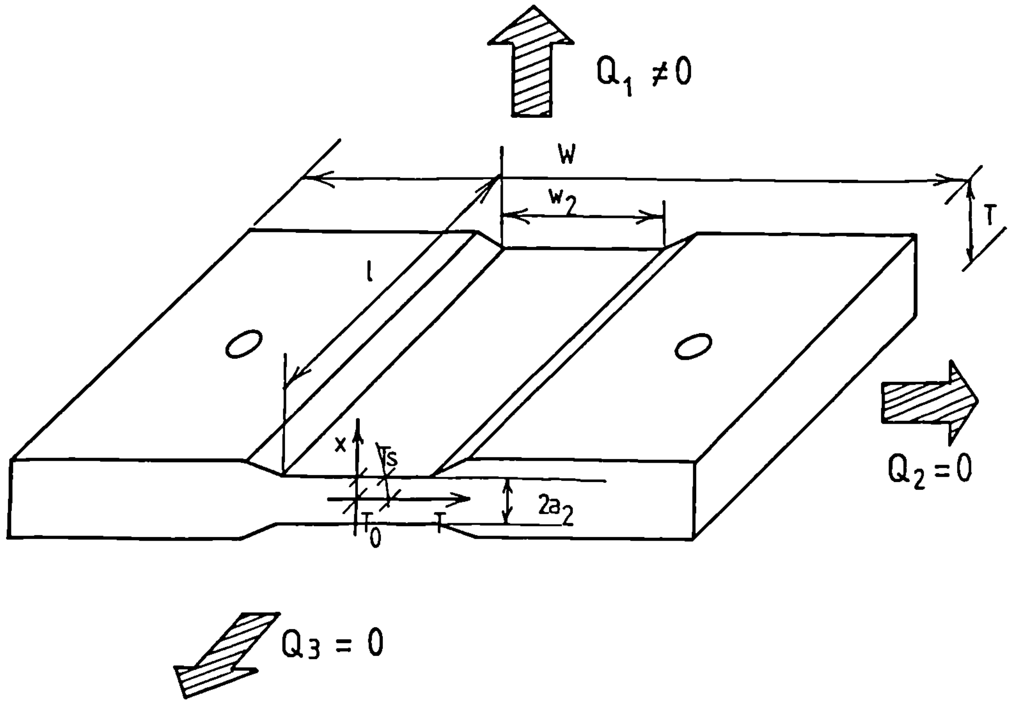
FIGURE 8.44 : Active surfaces during air cooling and geometry of

a- hot rolling samples

b- plane strain compression samples.


w1
l
$Q_1 \neq 0$
2a
$Q_2 \neq 0$
x
Ts
dx
T0
T
Roll Direction
$Q_3 = 0$

(a)


$Q_1 \neq 0$
W
w2
T
l
$Q_2 = 0$
x
Ts
2a2
T0
T
$Q_3 = 0$

(b)

FIGURE 8.45 : Strength during hot rolling as a function of the original grain size.

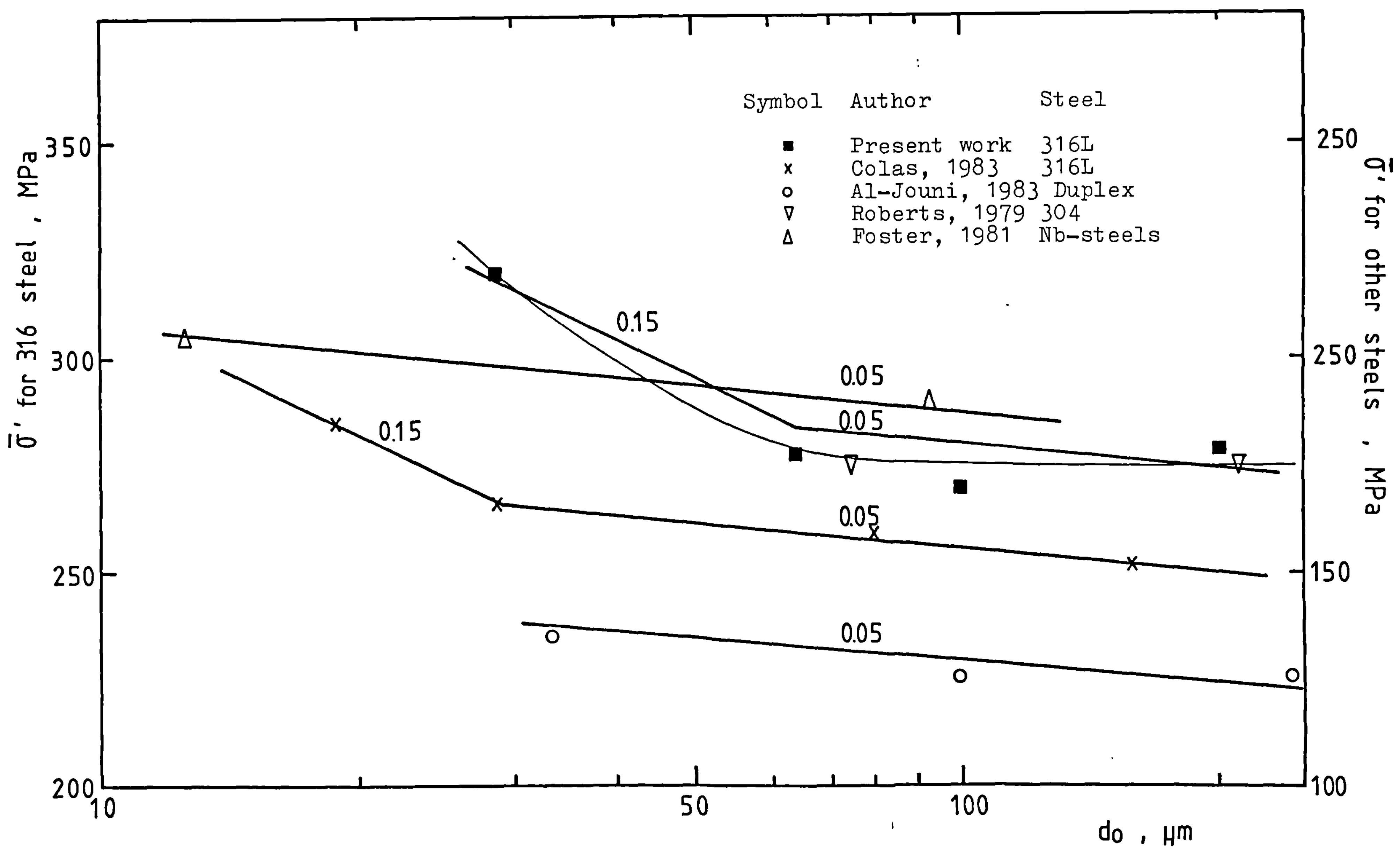

Symbol Author Steel
■ Present work 316L
x Colas, 1983 316L
o Al-Jouni, 1983 Duplex
∇ Roberts, 1979 304
Δ Foster, 1981 Nb-steels
$\bar{\sigma}'$ for 316 steel , MPa
350
300
250
200
$\bar{\sigma}'$ for other steels , MPa
250
250
150
100
10
50
100
do , μm
0.15
0.05
0.05
0.15
0.05
0.05

FIGURE 8.46 : Evolution of microstructure during hot rolling.

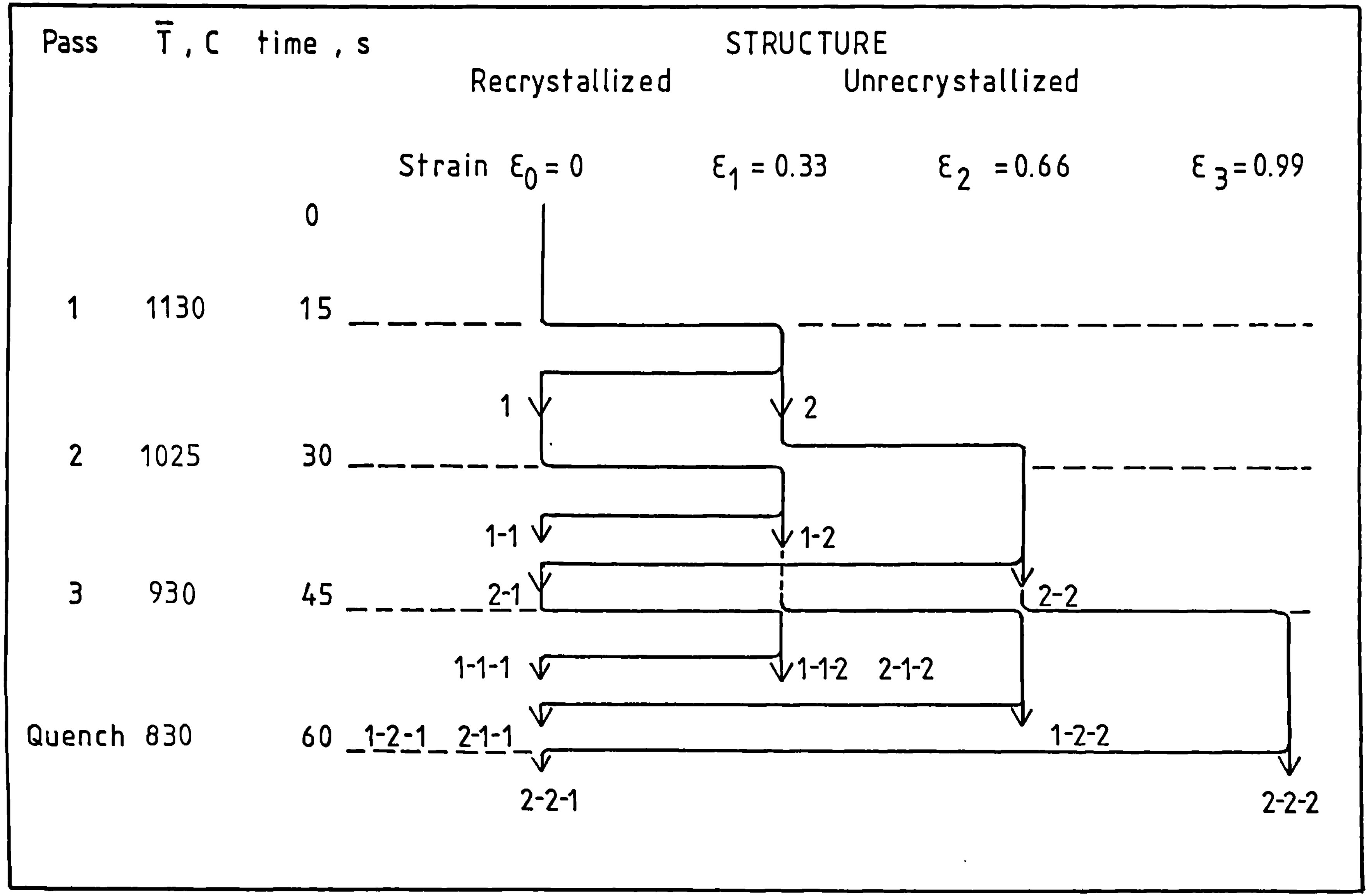

Pass
T̄ , C
time , s
STRUCTURE
Recrystallized
Unrecrystallized
Strain ε0 = 0
ε1 = 0.33
ε2 = 0.66
ε3 = 0.99
0
1 1130 15
2 1025 30
3 930 45
Quench 830 60
1
2
1-1
1-2
2-1
2-2
1-1-1
1-1-2
2-1-2
1-2-1
2-1-1
1-2-2
2-2-1
2-2-2

FIGURE 8.47 : Comparison between predicted grain growth given by equations (3.29) and (8.63).

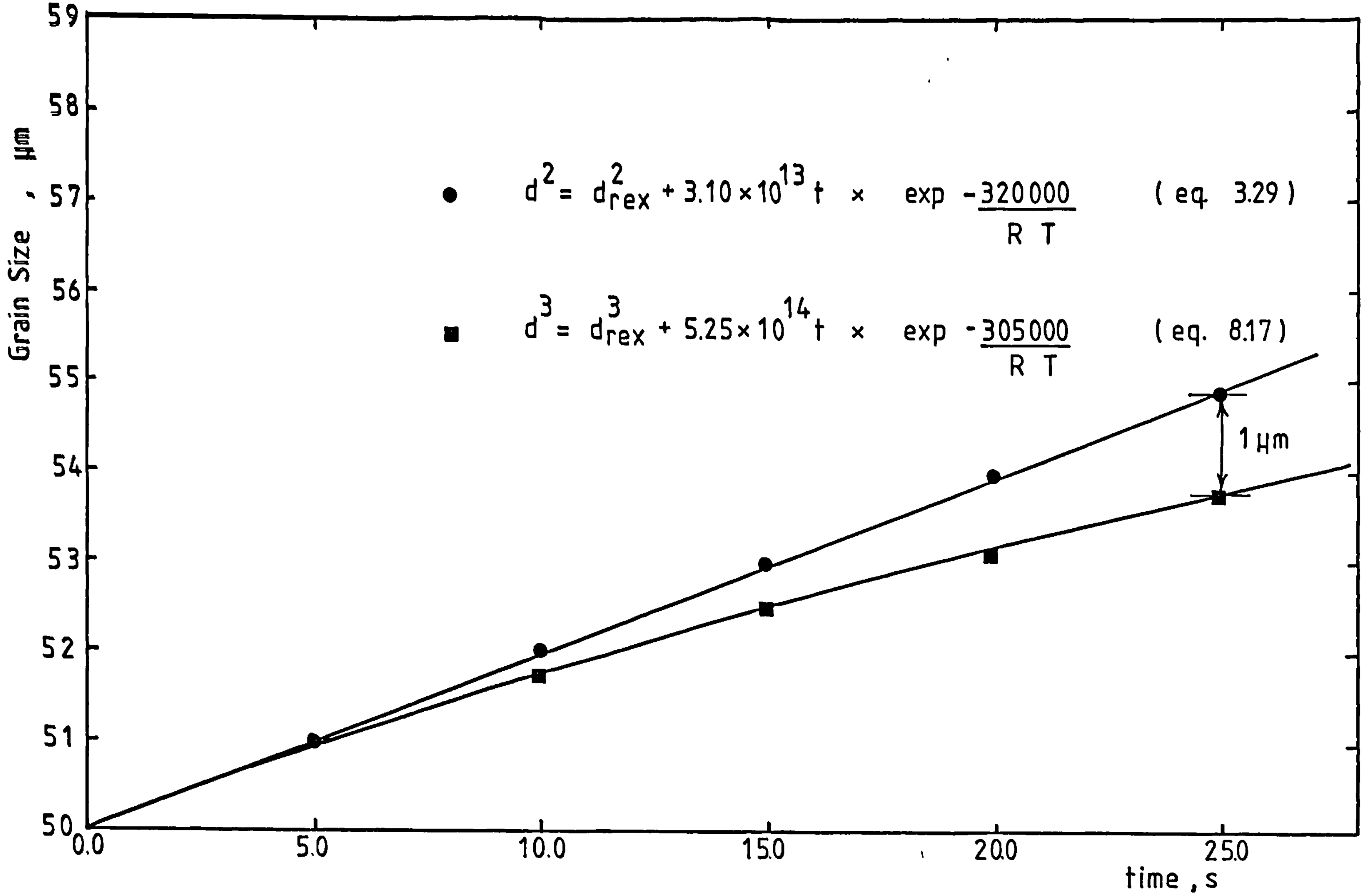

Grain Size , μm
59
58
57
56
55
54
53
52
51
50
0.0
5.0
10.0
15.0
20.0
25.0
time , s
● $d^2 = d_{rex}^2 + 3.10 \times 10^{13} t \times \exp -\frac{320000}{R T}$ (eq. 3.29)
■ $d^3 = d_{rex}^3 + 5.25 \times 10^{14} t \times \exp -\frac{305000}{R T}$ (eq. 8.17)
1 μm

FIGURE 9.1 : Stress-strain curves for AISI316L tested under axisymmetric compression tests.

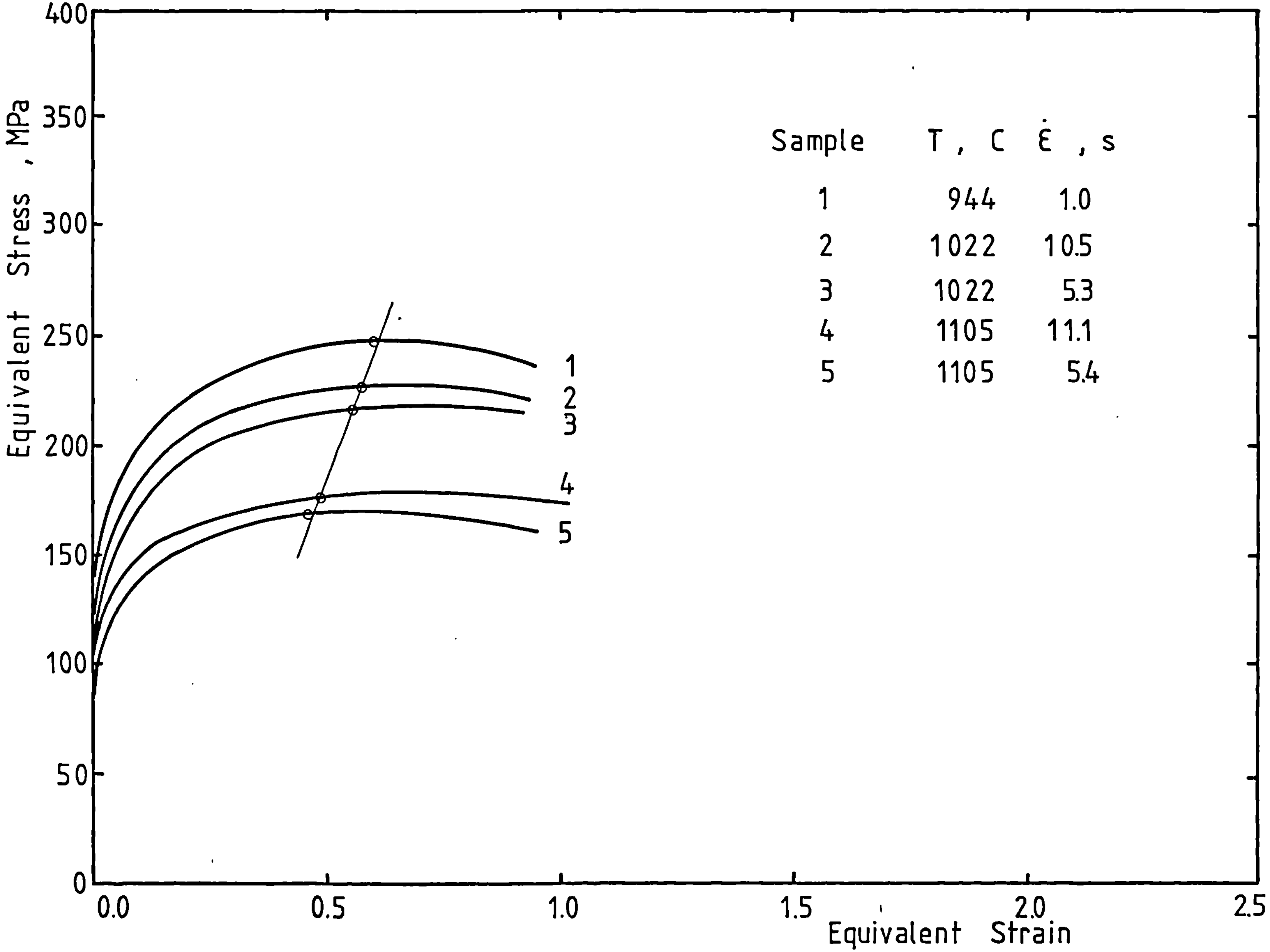

Equivalent Stress , MPa
0
50
100
150
200
250
300
350
400
0.0
0.5
1.0
1.5
2.0
2.5
Equivalent Strain
1
2
3
4
5
Sample T , C $\dot{\varepsilon}$, s
1 944 1.0
2 1022 10.5
3 1022 5.3
4 1105 11.1
5 1105 5.4

FIGURE 9.2 : Comparison between the strain to peak stress dependence on the Zener-Hollomon parameter for axisymmetric (full line) and plane strain compression tests (dotted line).

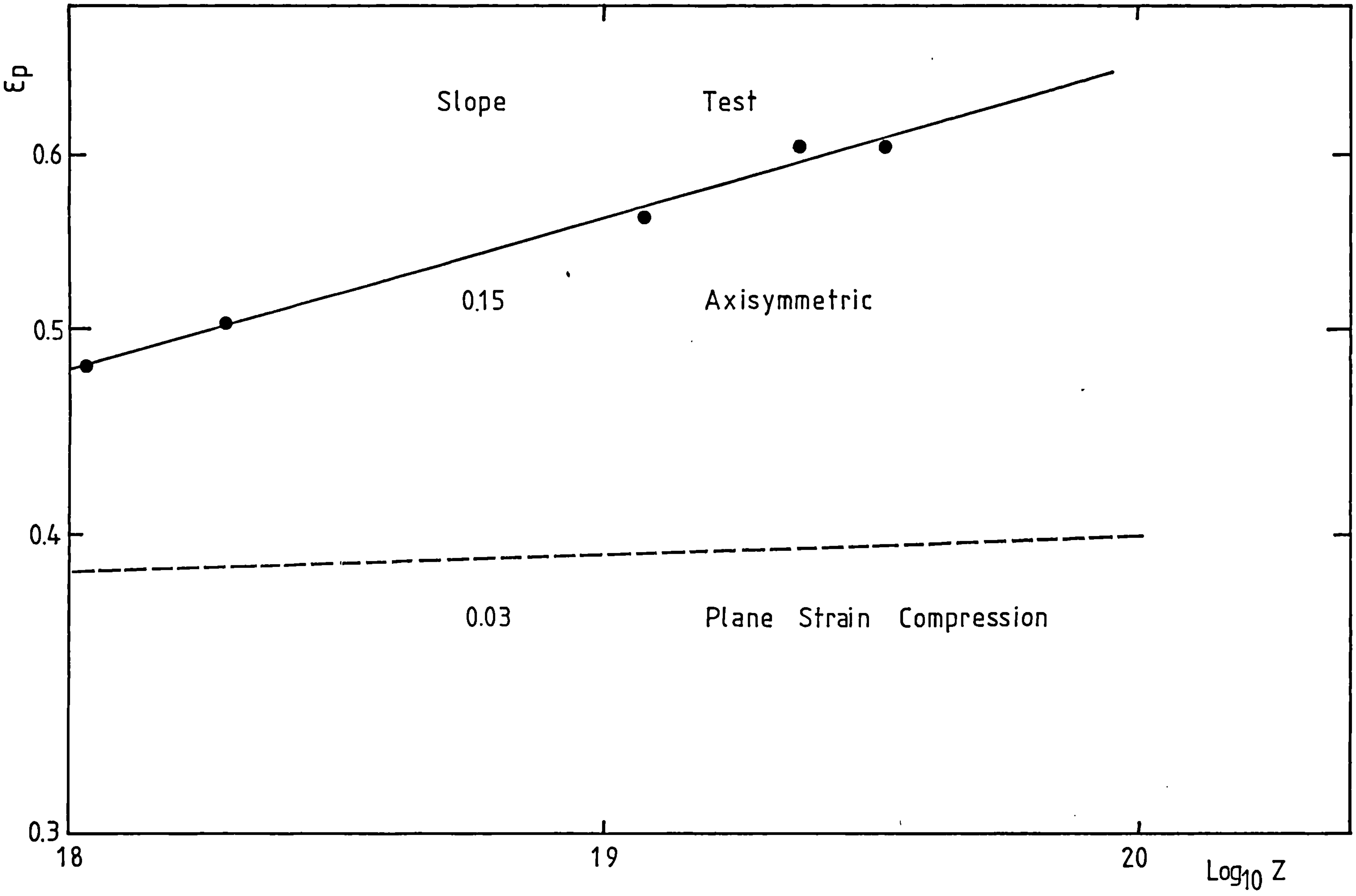
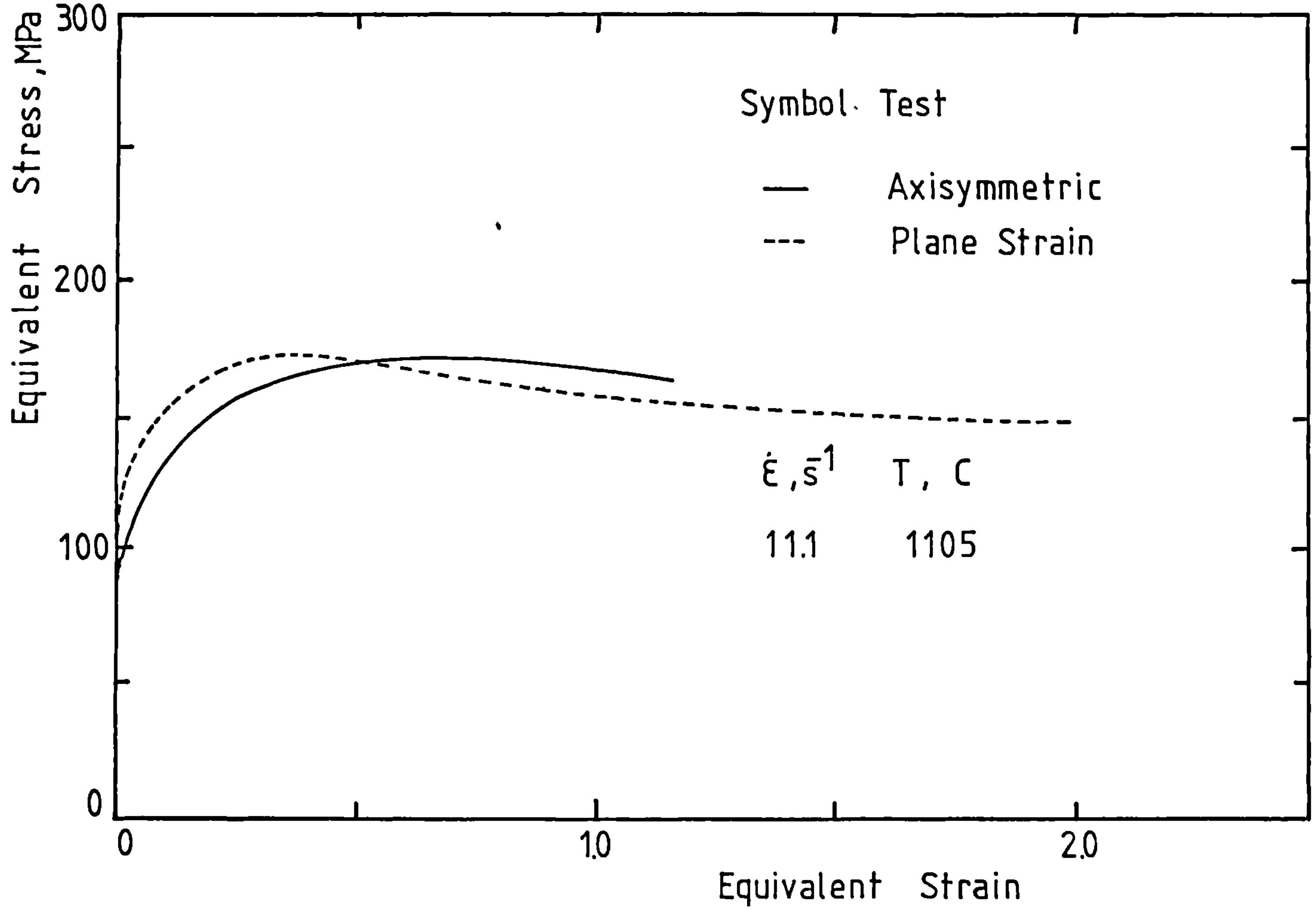

ε_p
0.6
0.5
0.4
0.3
18
19
20
$\mathrm{Log}_{10} Z$
Slope
Test
0.15
Axisymmetric
0.03
Plane Strain Compression

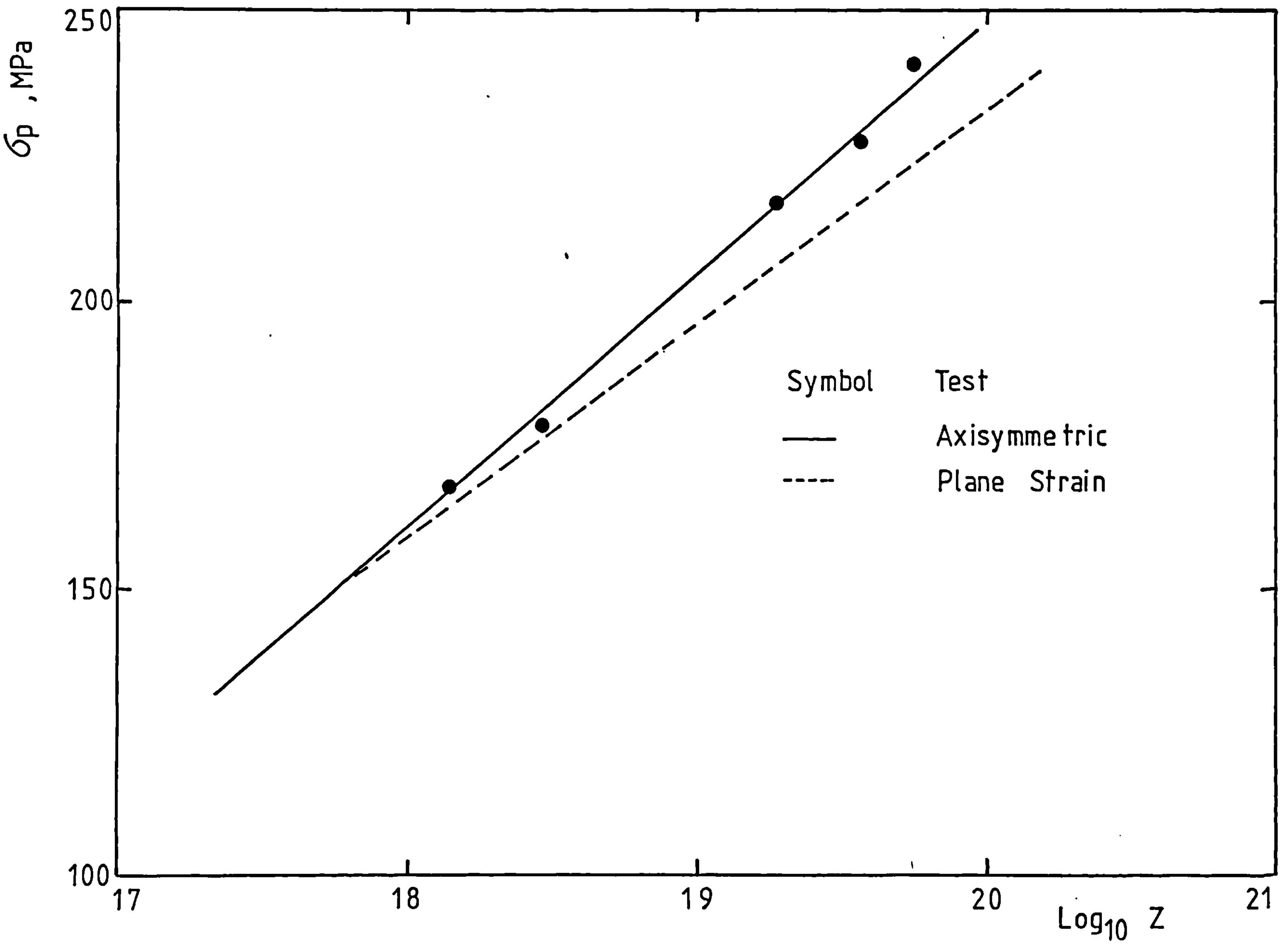
FIGURE 9.3 : Comparison between stress-strain curves.

Full line represents curve for sample tested under axisymmetric compression. Dotted line is a theoretical stress-strain curve for an isothermal plane strain compression test.



Equivalent Stress, MPa
300
200
100
0
0
1.0
2.0
Equivalent Strain
Symbol Test
— Axisymmetric
--- Plane Strain
$\dot{\varepsilon}, s^{-1}$ T, C
11.1 1105

FIGURE 9.4 : Comparison between maximum stress for axisymmetric (full line) and for plane strain compression tests (dotted line).



σ_p ,MPa
250
200
150
100
17
18
19
20
21
Log_{10} Z
Symbol
Test
Axisymmetric
Plane Strain

FIGURE 9.5 : Comparison between the stress at strain equal 0.1 for axisymmetric (full line) and for plane strain compression tests (dotted line).

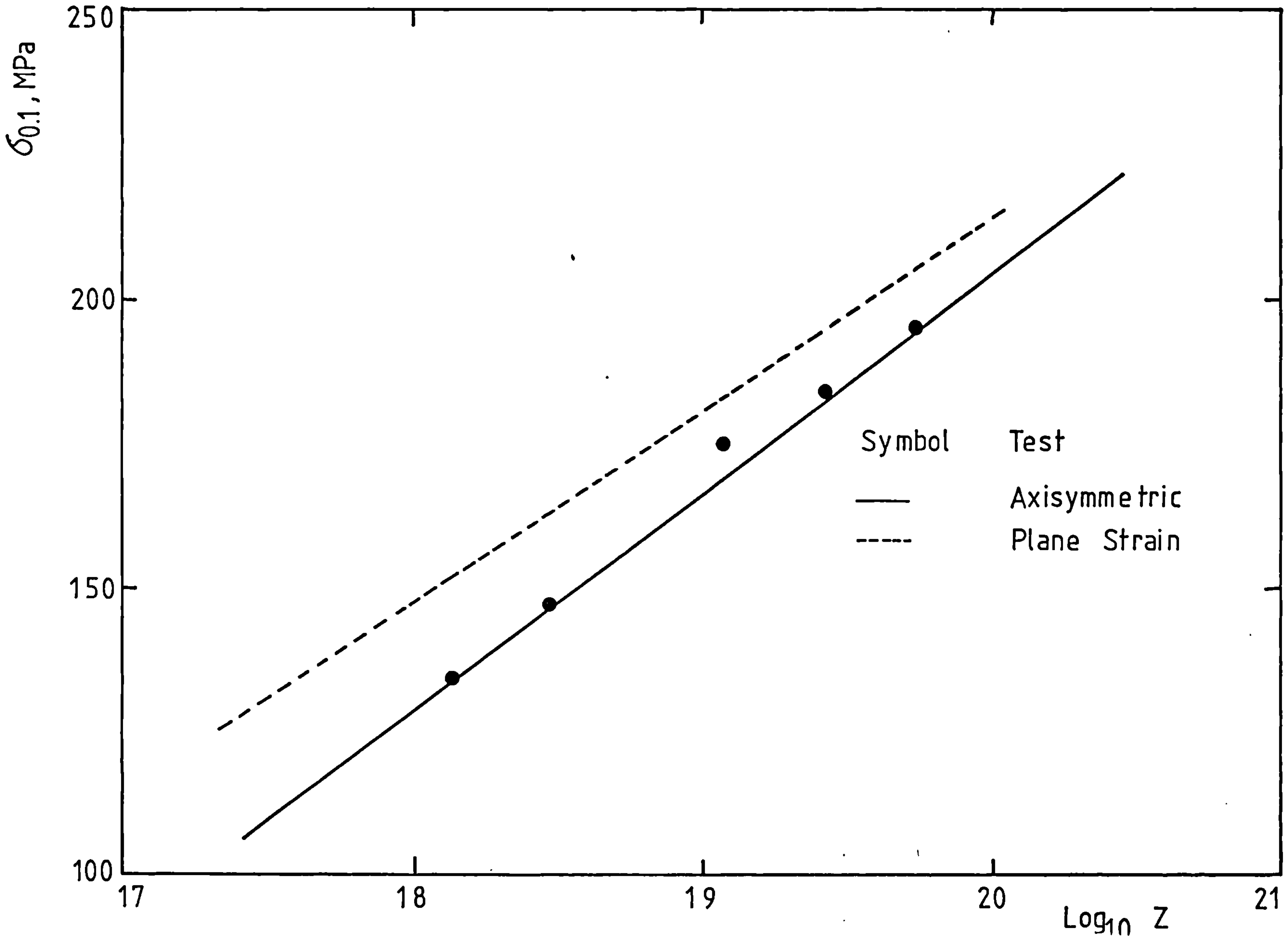
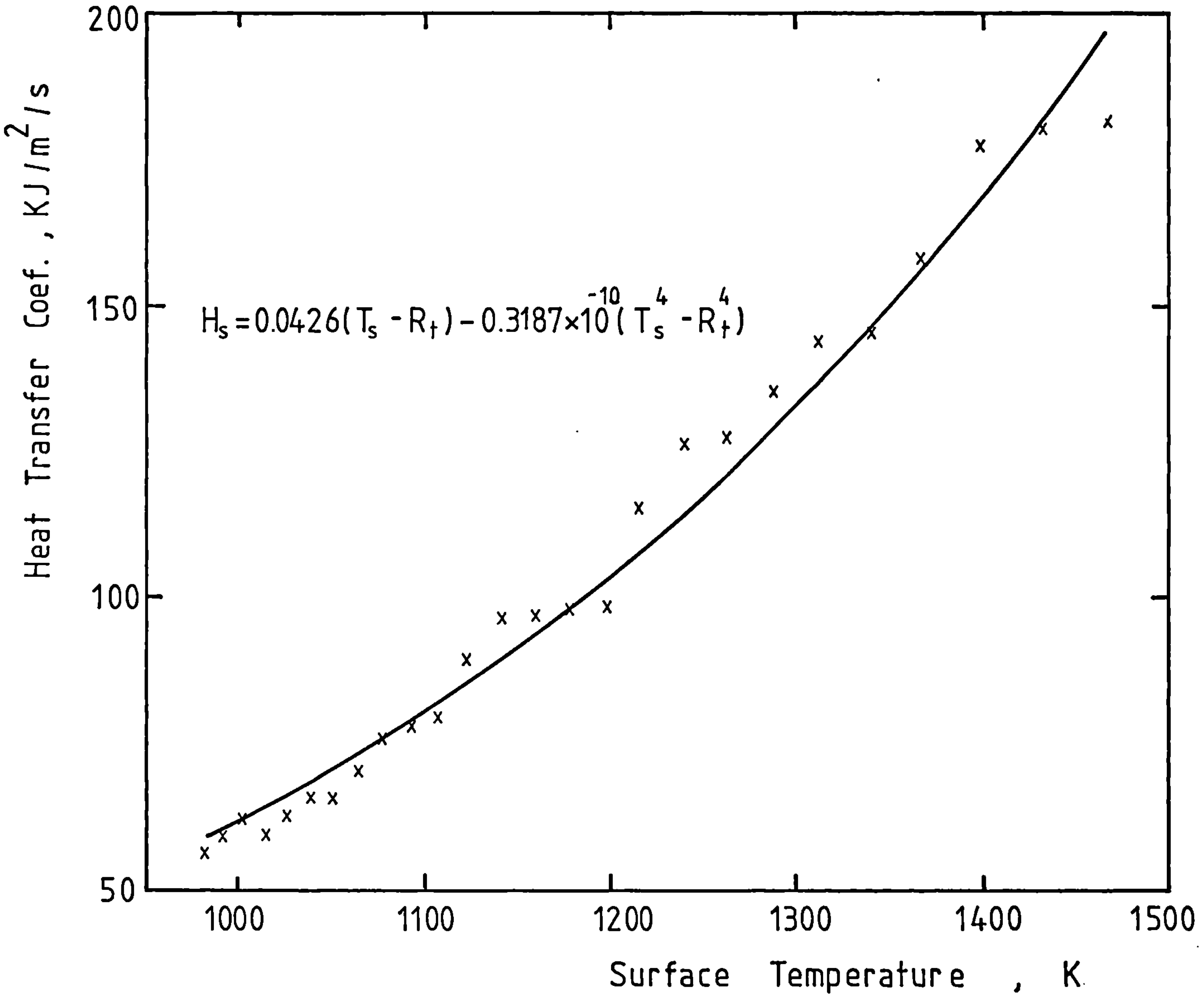

$\sigma_{0.1}$, MPa
250
200
150
100
17
18
19
20
21
Log_{10} Z
Symbol
Test
Axisymmetric
Plane Strain

FIGURE 9.6 : The surface heat transfer coefficient dependence on the sample surface temperature. Specimen was held air cooling in the servo test machine conveyor arms.



200
150
100
50
1000
1100
1200
1300
1400
1500
Heat Transfer Coef. , KJ/m^2/s
Surface Temperature , K
$H_s = 0.0426(T_s - R_t) - 0.3187 \times 10^{-10}(T_s^4 - R_t^4)$

FIGURE 9.7 : Comparison between theoretical and experimental air cooling behaviour for a plane strain compression sample held in the Servotest machine conveyor arms.

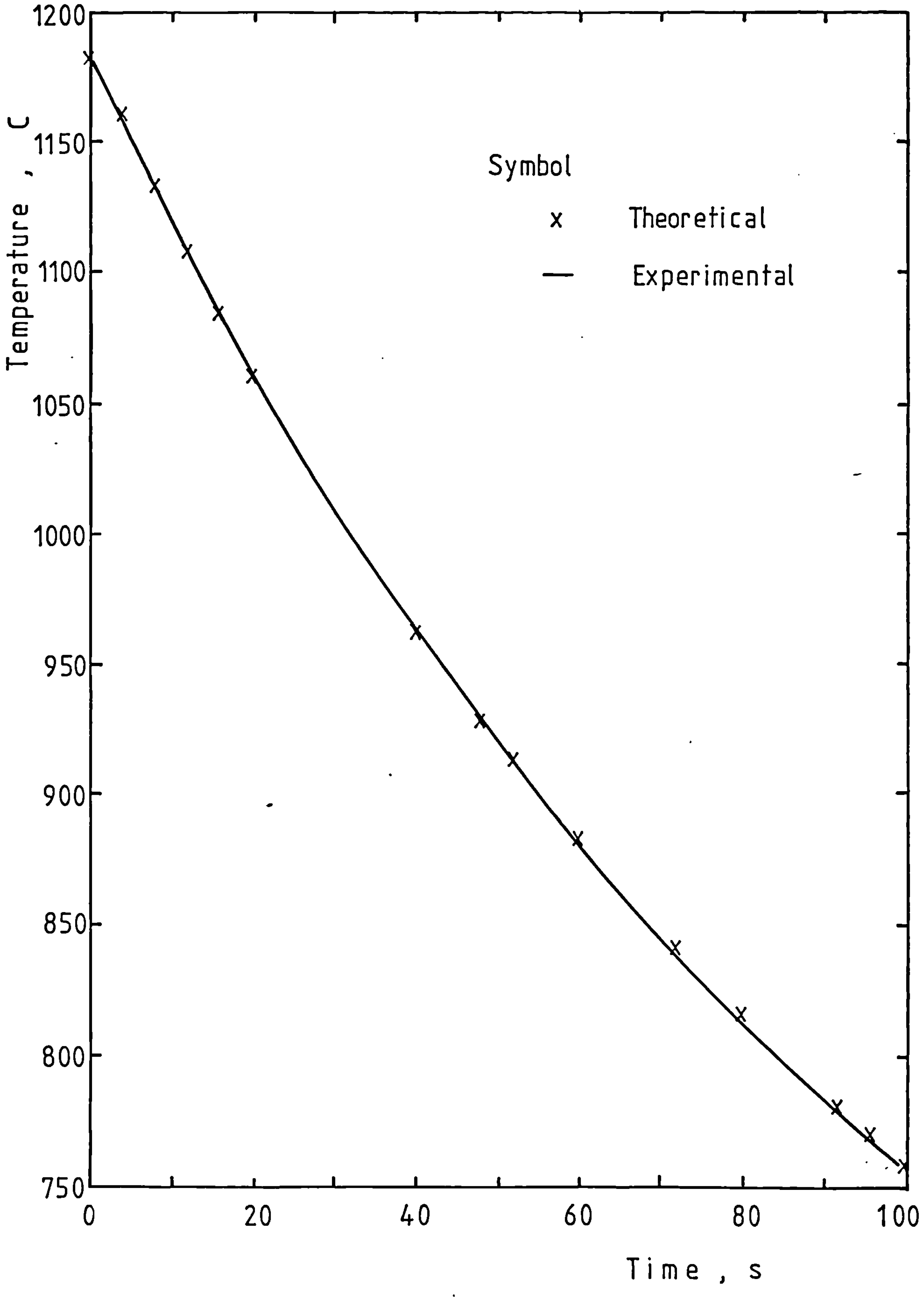

1200
1150
1100
1050
1000
950
900
850
800
750
Temperature , C
0
20
40
60
80
100
Time , s
Symbol
x Theoretical
— Experimental

FIGURE 9.8 : Comparison between experimental and theoretical furnace cooling behaviour for a plane strain compression sample.

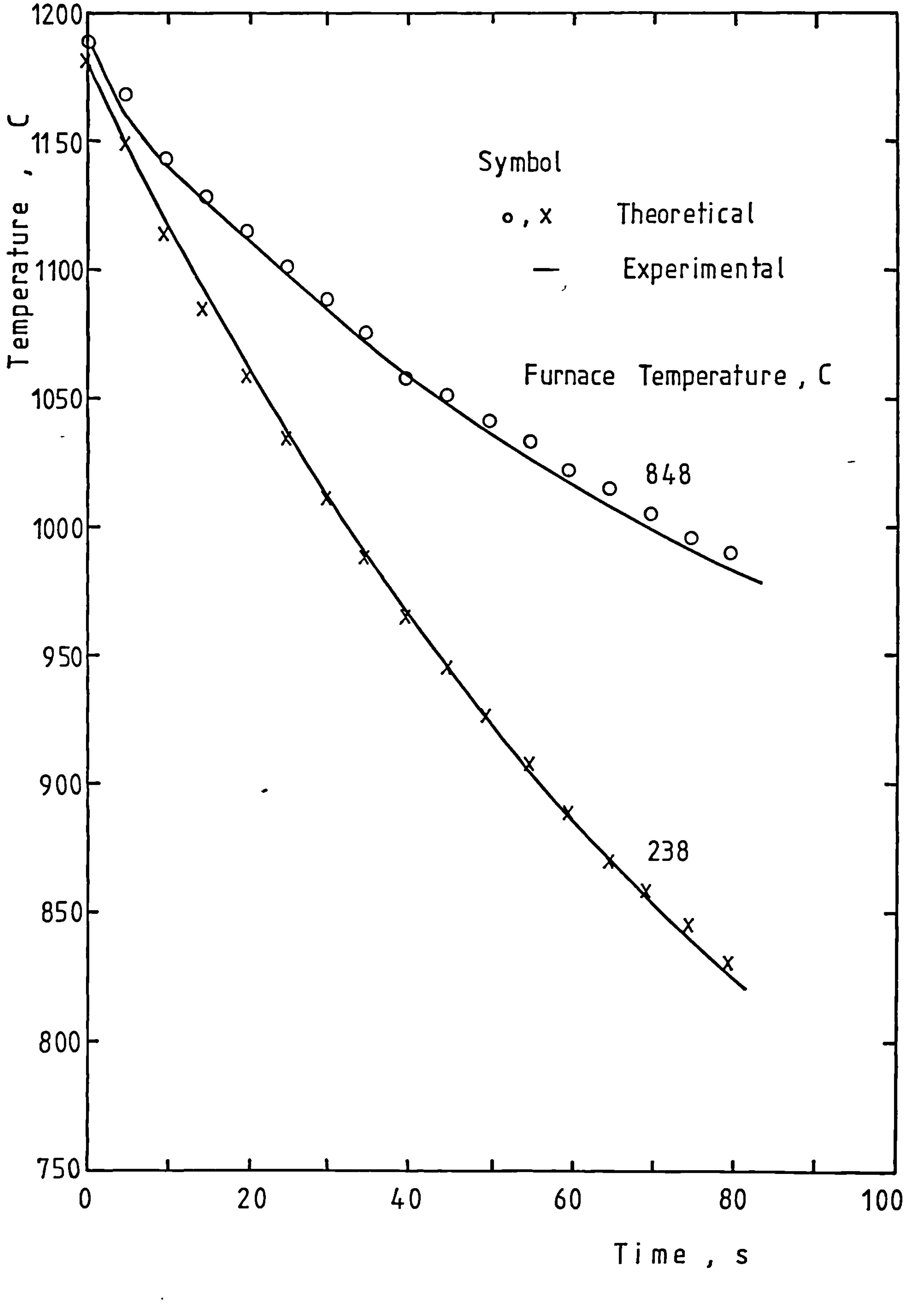

Temperature , C
1200
1150
1100
1050
1000
950
900
850
800
750
0
20
40
60
80
100
Time , s
Symbol
o , x Theoretical
— Experimental
Furnace Temperature , C
848
238

FIGURE 9.9 : Comparison between experimental and theoretical cooling behaviour of a sample being tested under plane strain compression. H is the sample surface heat transfer during a pass and DAG is a factor to reduce the cooling rate during test furnace cooling periods following a deformation (Foster,1981). The sample was given 3 passes of 25% reduction each.

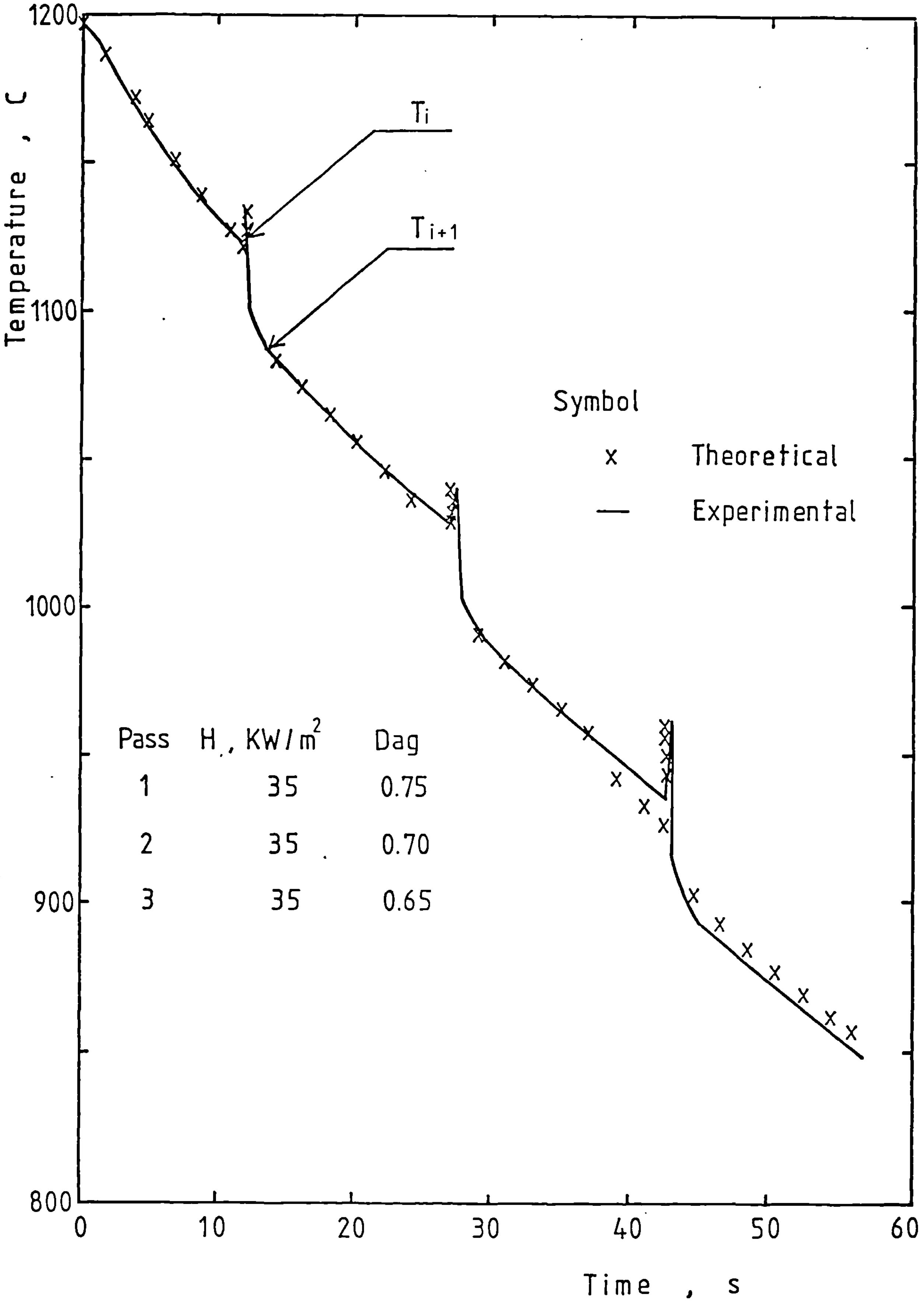

Temperature , C
Time , s
1200
1100
1000
900
800
0
10
20
30
40
50
60
Ti
Ti+1
Symbol
x Theoretical
— Experimental
Pass H , KW/m² Dag
1 35 0.75
2 35 0.70
3 35 0.65

FIGURE 9.10 : Comparison between computed average pass temperature and estimated one for samples being tested under plane strain compression.

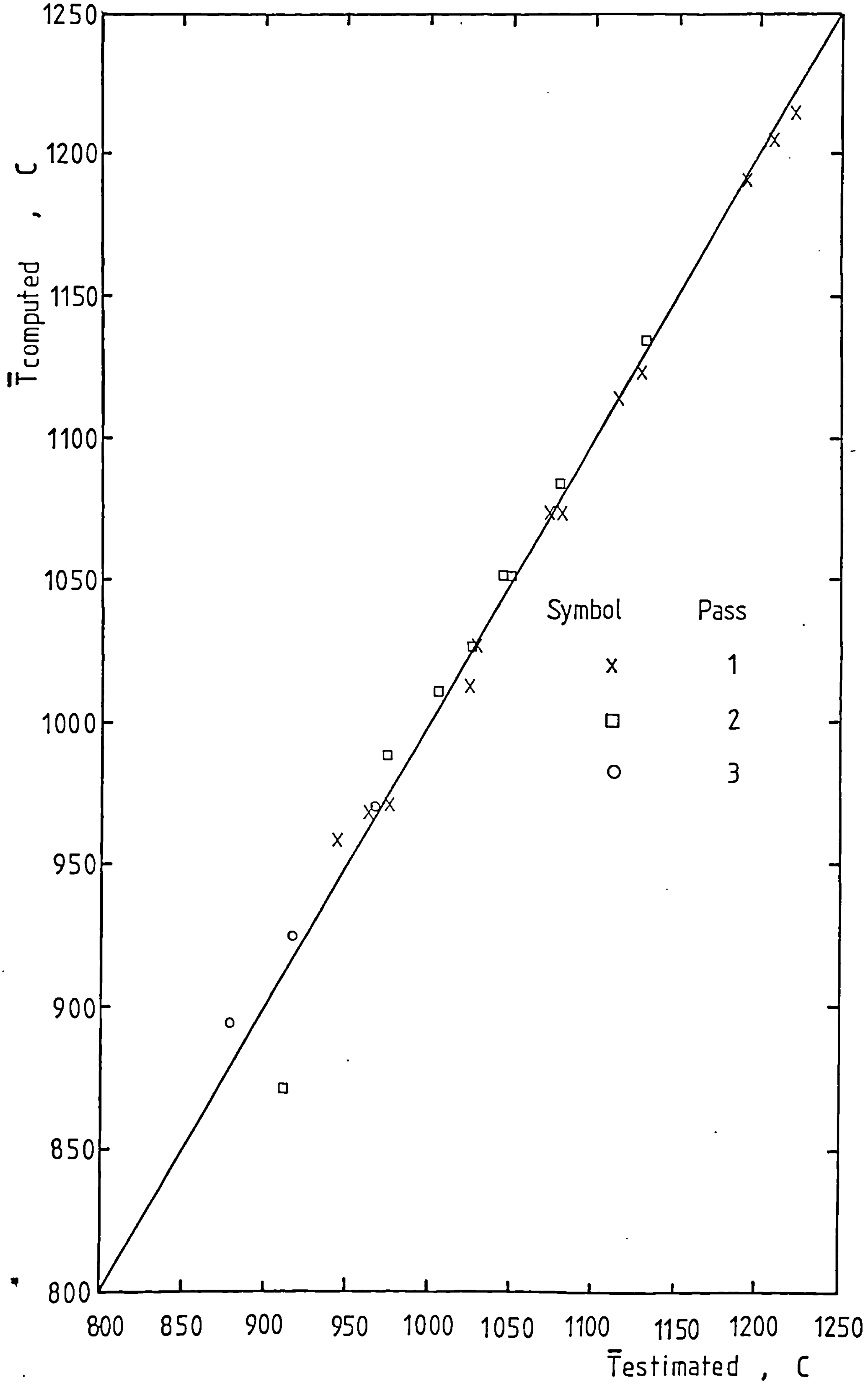
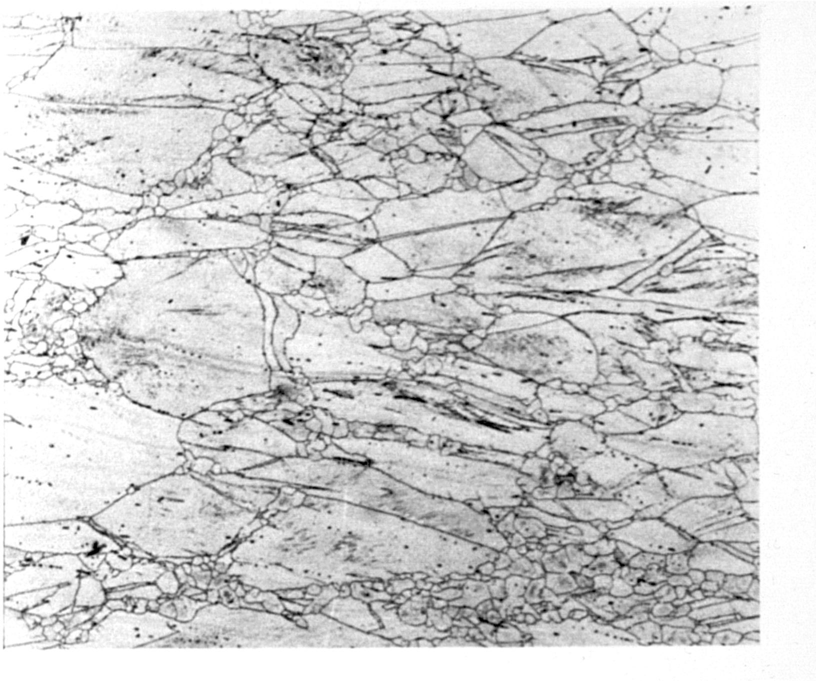
1250
1200
1150
1100
1050
1000
950
900
850
800
T̄computed , C
800
850
900
950
1000
1050
1100
1150
1200
1250
T̄estimated , C
Symbol
Pass
x
1
□
2
o
3

FIGURE 9.11 : Microstructure evolution after the first pass.

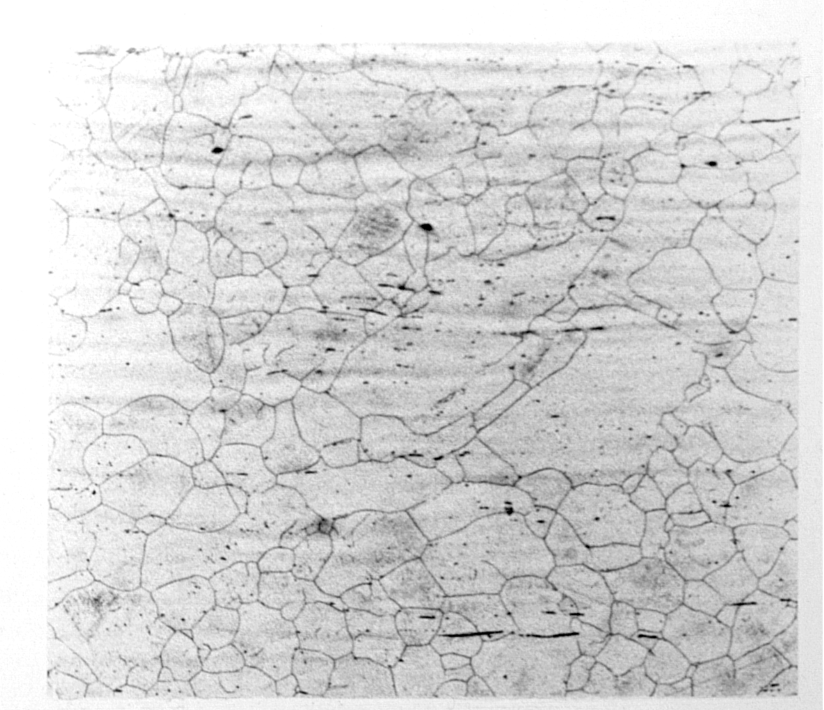
Mag. x100

a- $X=20\%$; $\overline{T}=1084$ C

b- $X=90\%$; $\overline{T}=1206$ C



(a)



(b)

FIGURE 9.12 : The fraction recrystallized dependence on the first pass average temperature for samples tested under plane strain compression. Samples were given a single 25% reduction pass.

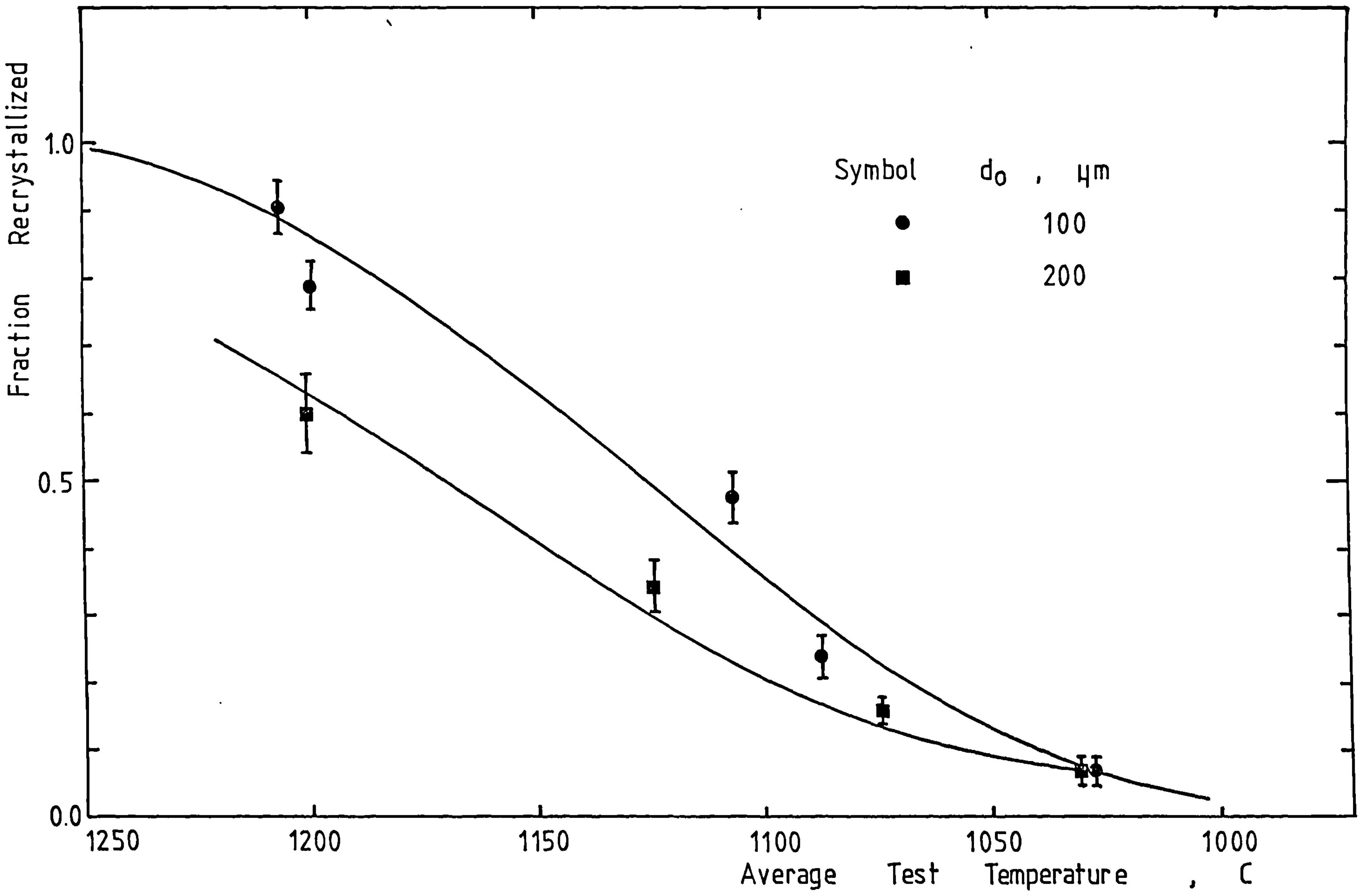

Fraction Recrystallized
1.0
0.5
0.0
1250
1200
1150
1100
1050
1000
Average Test Temperature , C
Symbol d_o , μm
● 100
■ 200

FIGURE 9.13 : The average grain size during recrystallization dependence on the fraction recrystallized after the first pass.

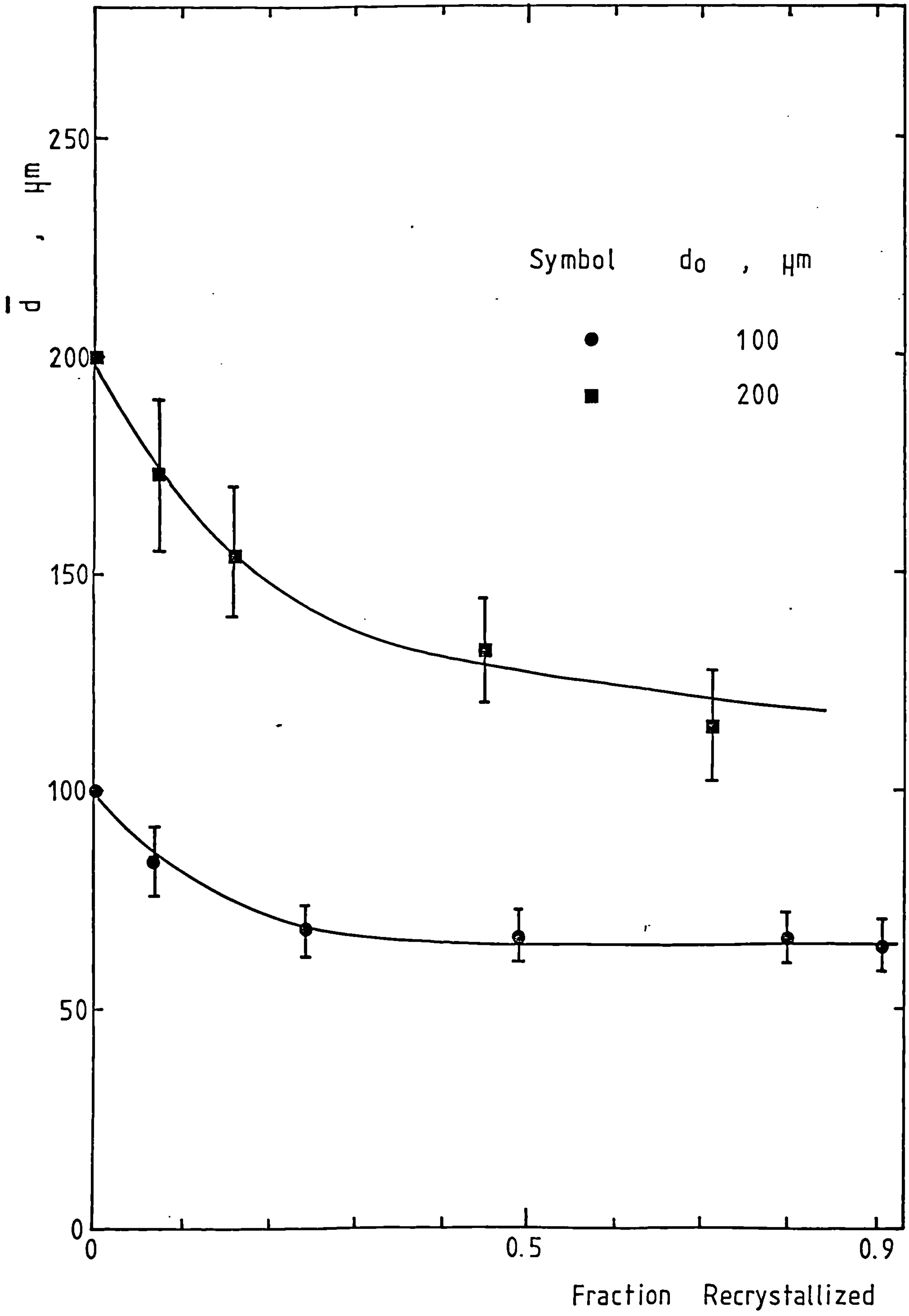

$\bar{d}$, μm
250
200
150
100
50
0
0
0.5
0.9
Fraction Recrystallized
Symbol d_0 , μm
● 100
■ 200

FIGURE 9.14 : The average grain size during recrystallization as a function of the first pass average test temperature.

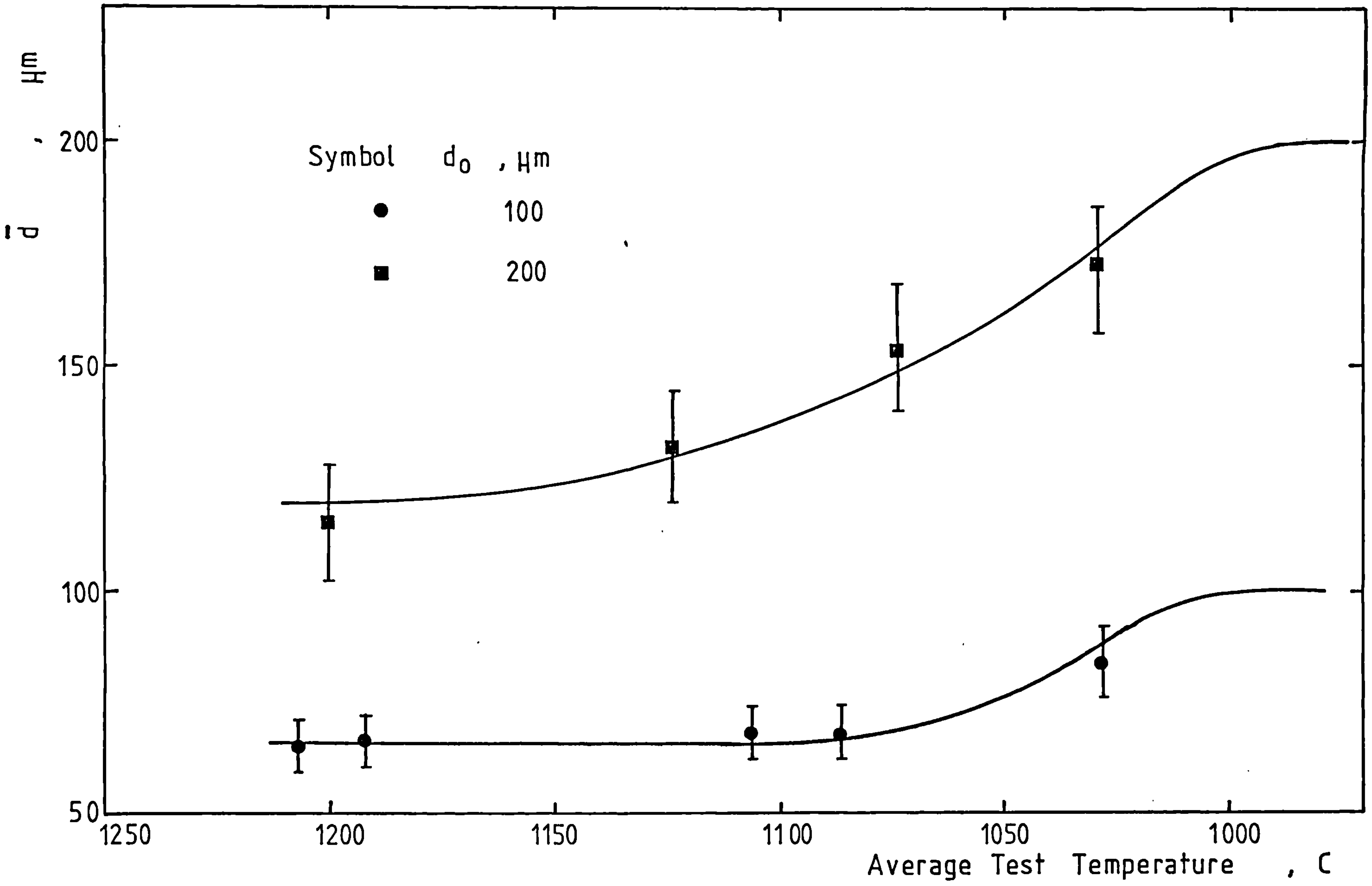

$\bar{d}$, µm
200
150
100
50
Symbol
d_o , µm
● 100
■ 200
1250
1200
1150
1100
1050
1000
Average Test Temperature , C

FIGURE 9.15 : Comparison between plane strain compression fraction recrystallized values with the ones obtained from hot rolling samples. Samples were deformed in a single 25% reduction pass.

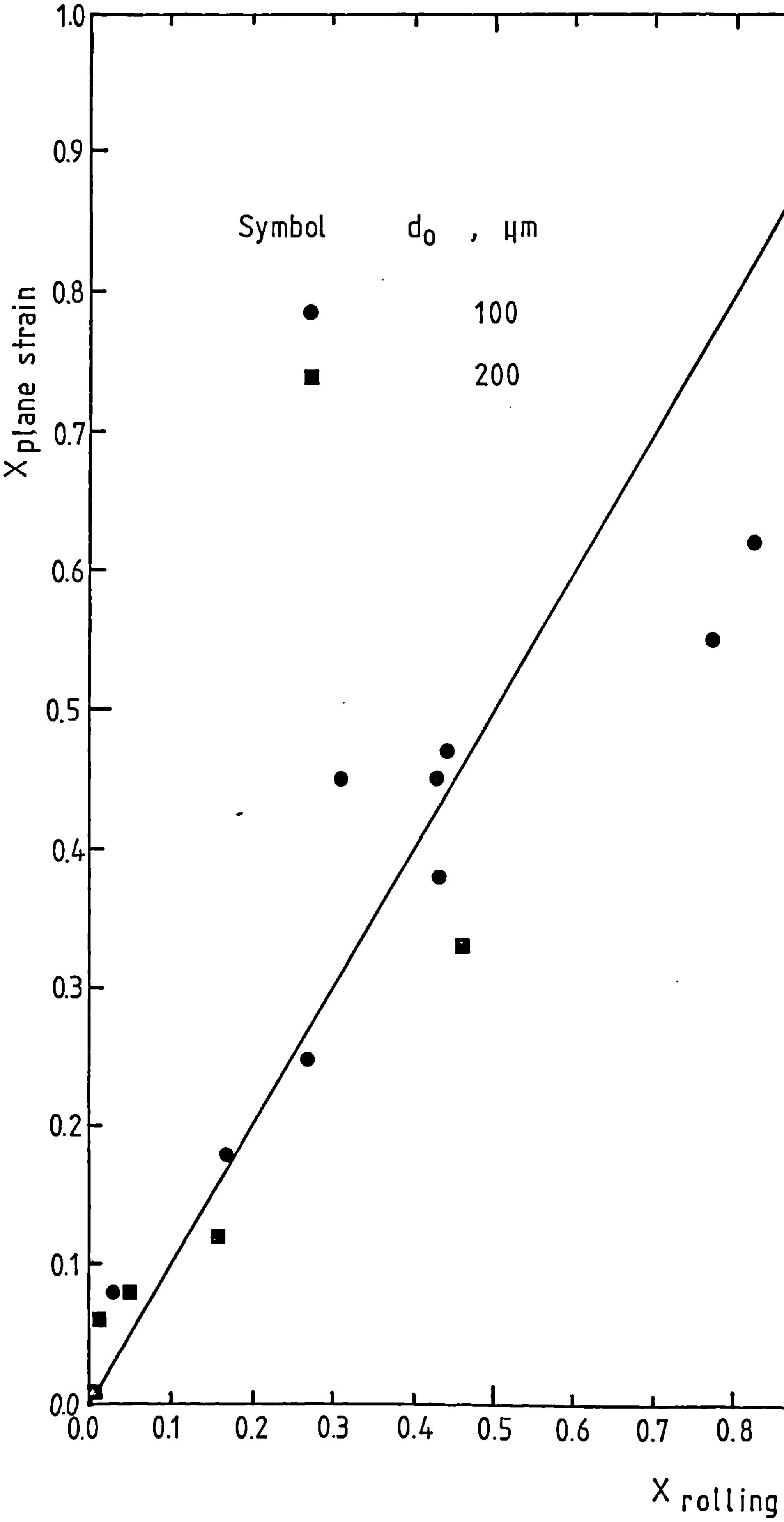
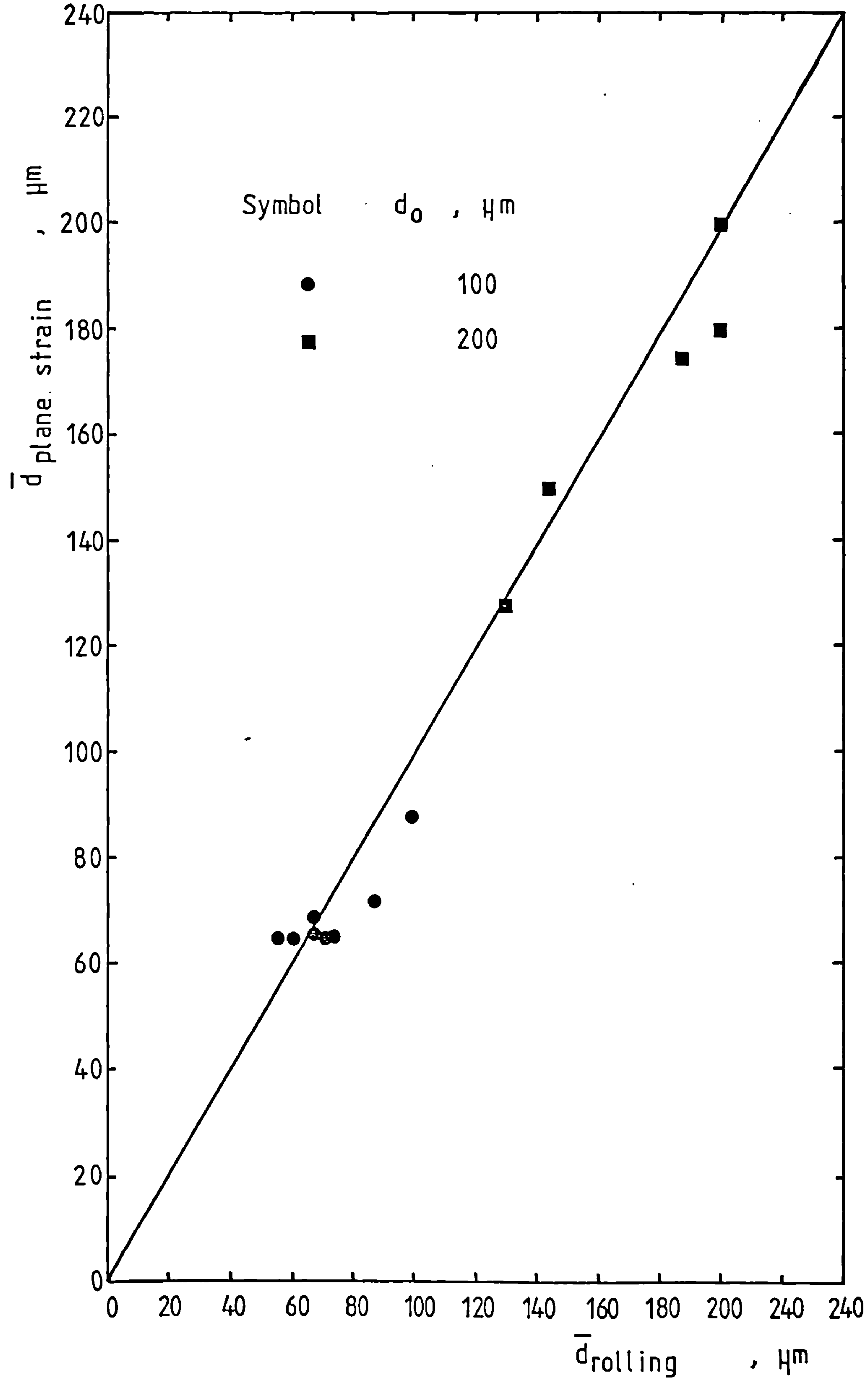

Symbol
d$_0$, µm
● 100
■ 200
X$_{plane\ strain}$
X$_{rolling}$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

FIGURE 9.16 : Comparison between average grain size during recrystallization measured from plane strain compression samples and the one measured from hot rolling samples.



Symbol
d_0 , µm
● 100
■ 200
$\bar{d}_{plane\ strain}$, µm
$\bar{d}_{rolling}$, µm
0
20
40
60
80
100
120
140
160
180
200
220
240
0
20
40
60
80
100
120
140
160
180
200
240
240

FIGURE 9.17 : The mean plane strain strength dependence on the Zener-Hollomon parameter for hot rolled specimens (full line) and plane strain compression ones.

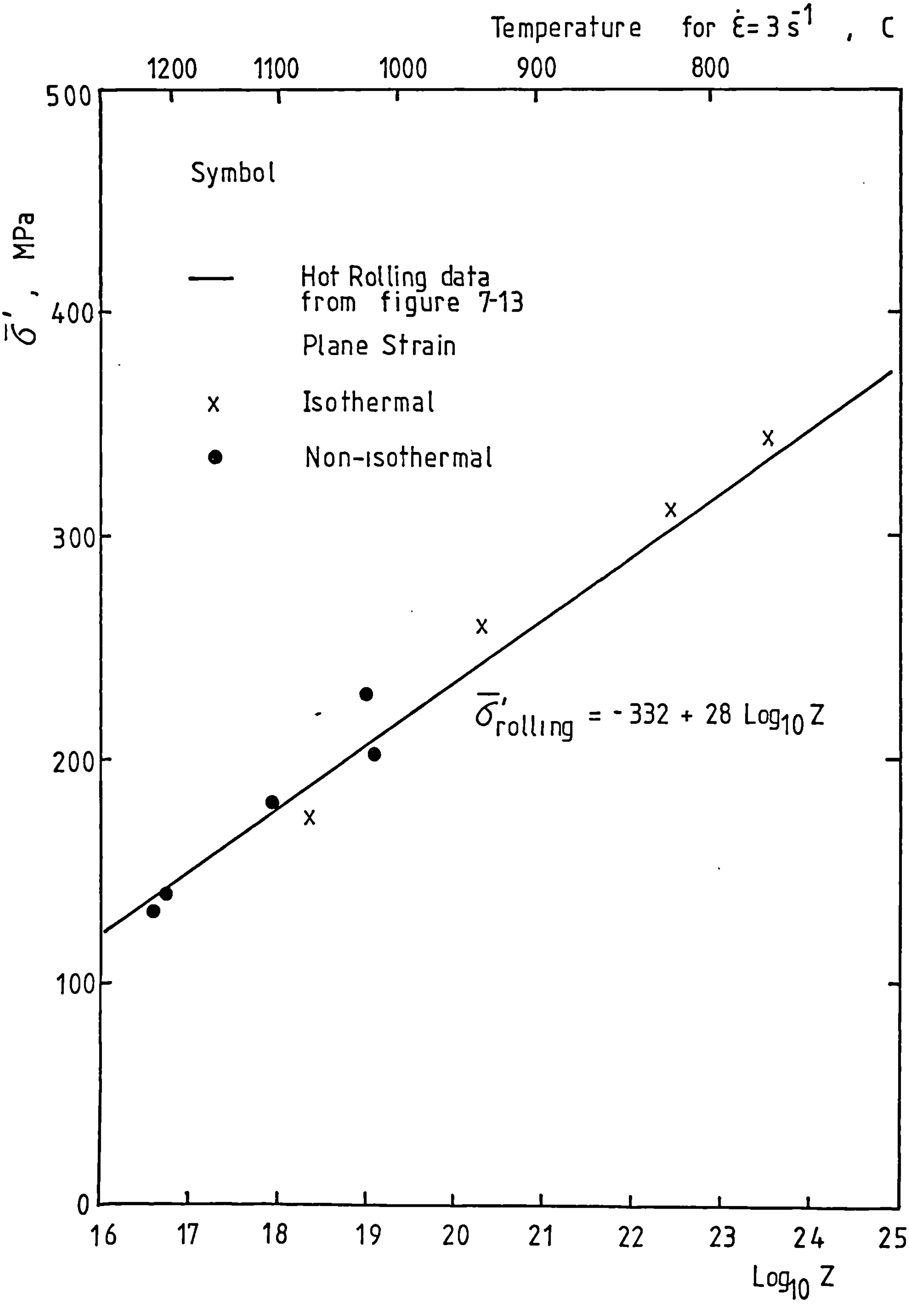
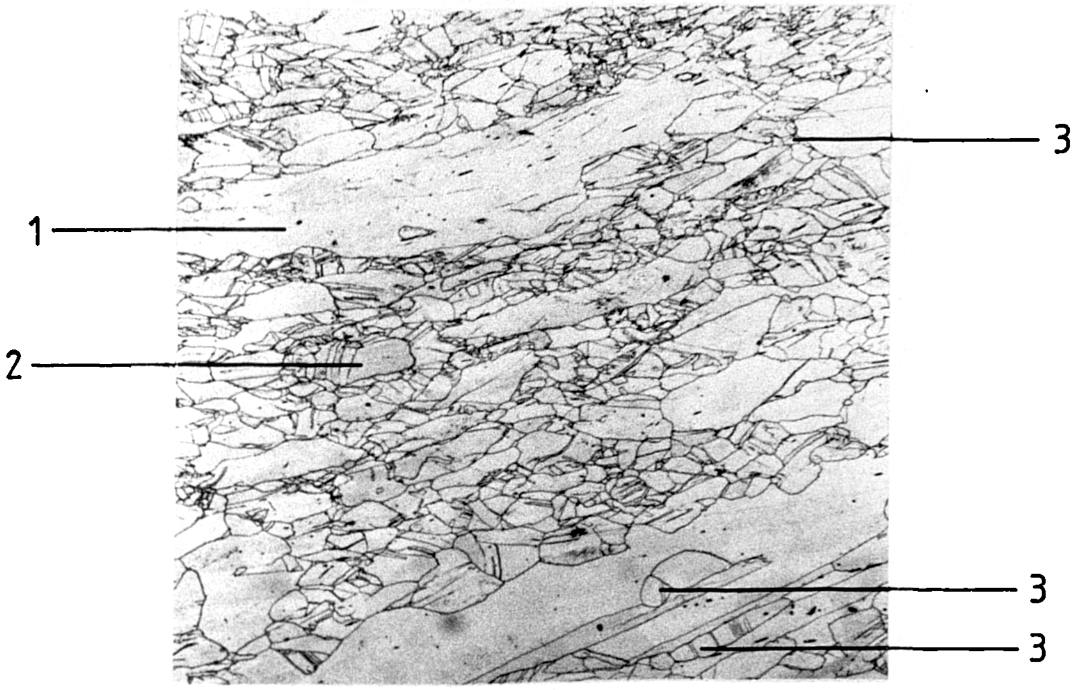

Temperature for $\dot{\varepsilon} = 3\ s^{-1}$, C
1200
1100
1000
900
800
$\bar{\sigma}'$, MPa
500
400
300
200
100
0
Symbol
Hot Rolling data from figure 7-13
Plane Strain
x Isothermal
● Non-isothermal
$\bar{\sigma}'_{rolling} = -332 + 28\ \mathrm{Log}_{10} Z$
16
17
18
19
20
21
22
23
24
25
$\mathrm{Log}_{10} Z$

FIGURE 9.18 : Microstructural evolution after the second pass. Numbers mean a structure entering a pass i.

Mag. x100

a- X=20% ; $\overline{T}$=989 C

b- X=46% ; $\overline{T}$=1084 C


3
1
2
3
3

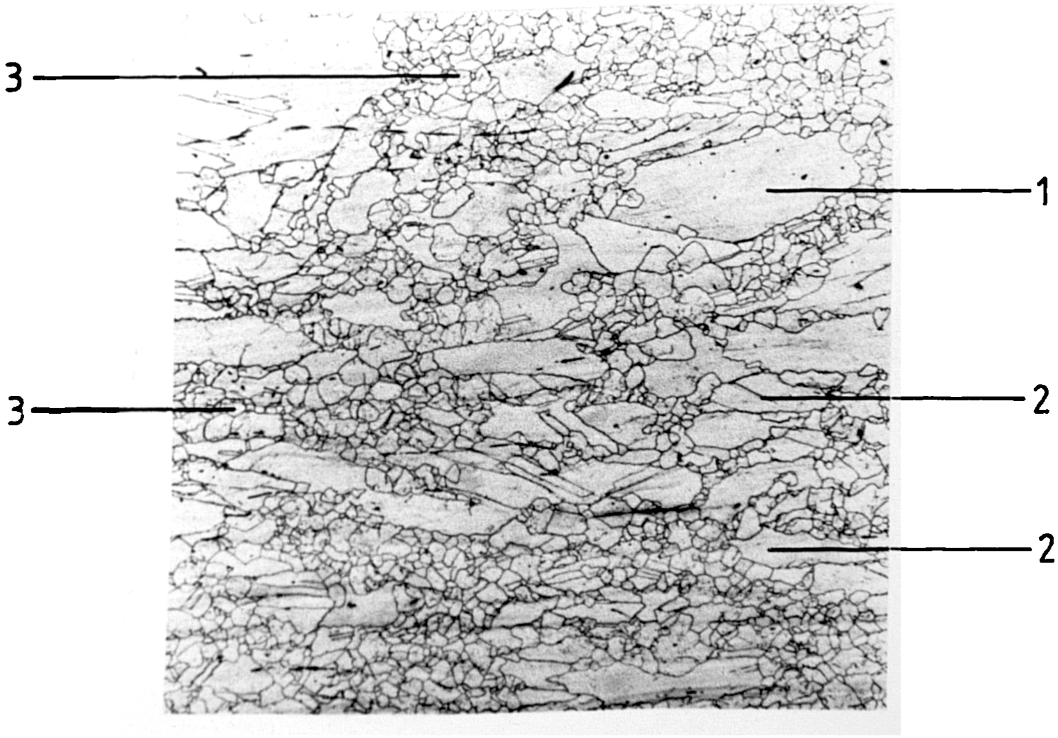

3
1
3
2
2

FIGURE 9.19 : Dependence of the fraction recrystallized after the second pass on the pass average temperature. All samples were deformed in a 2x25% schedule with 15s 'furnace cooling' rest period.

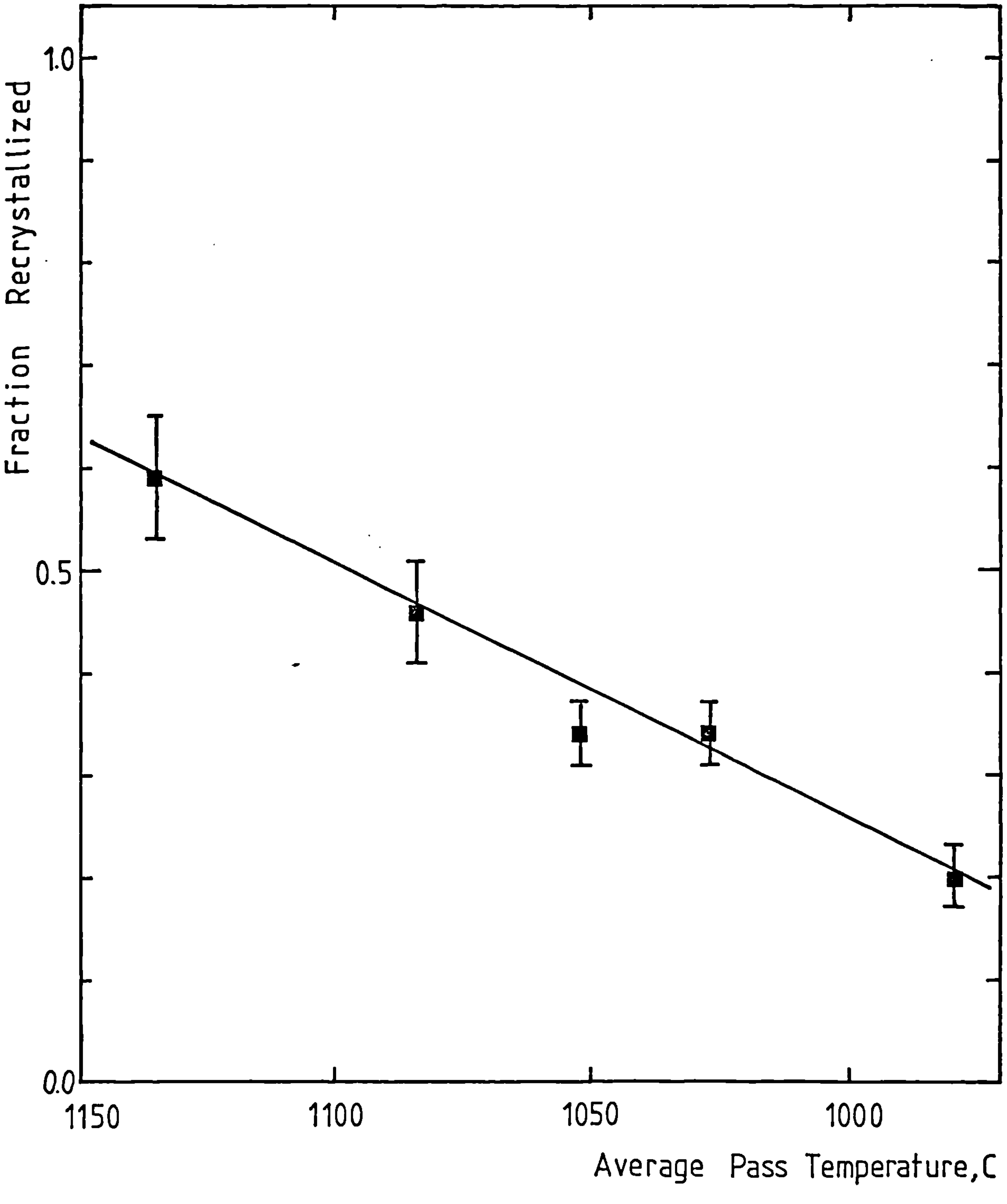

Fraction Recrystallized
1.0
0.5
0.0
1150
1100
1050
1000
Average Pass Temperature,C

FIGURE 9.20 : Dependence of the average grain size during recrystallization on the second pass average test temperature.

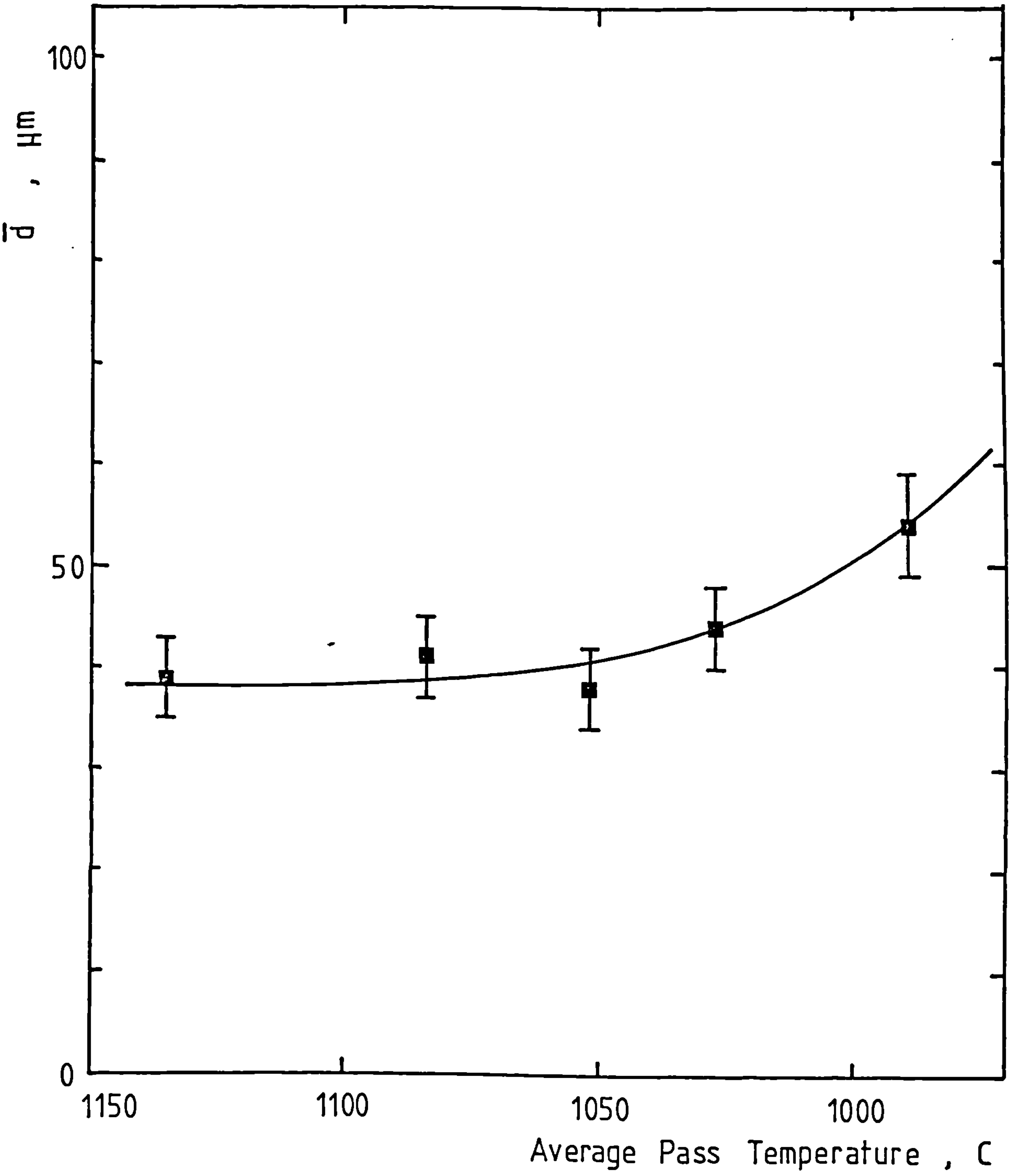

100
50
0
d̄ , μm
1150
1100
1050
1000
Average Pass Temperature , C

FIGURE 9.21 : Comparison between measured fraction recrystallized from hot rolling samples and plane strain compression ones. Samples were deformed in a 2x25% reduction schedule.

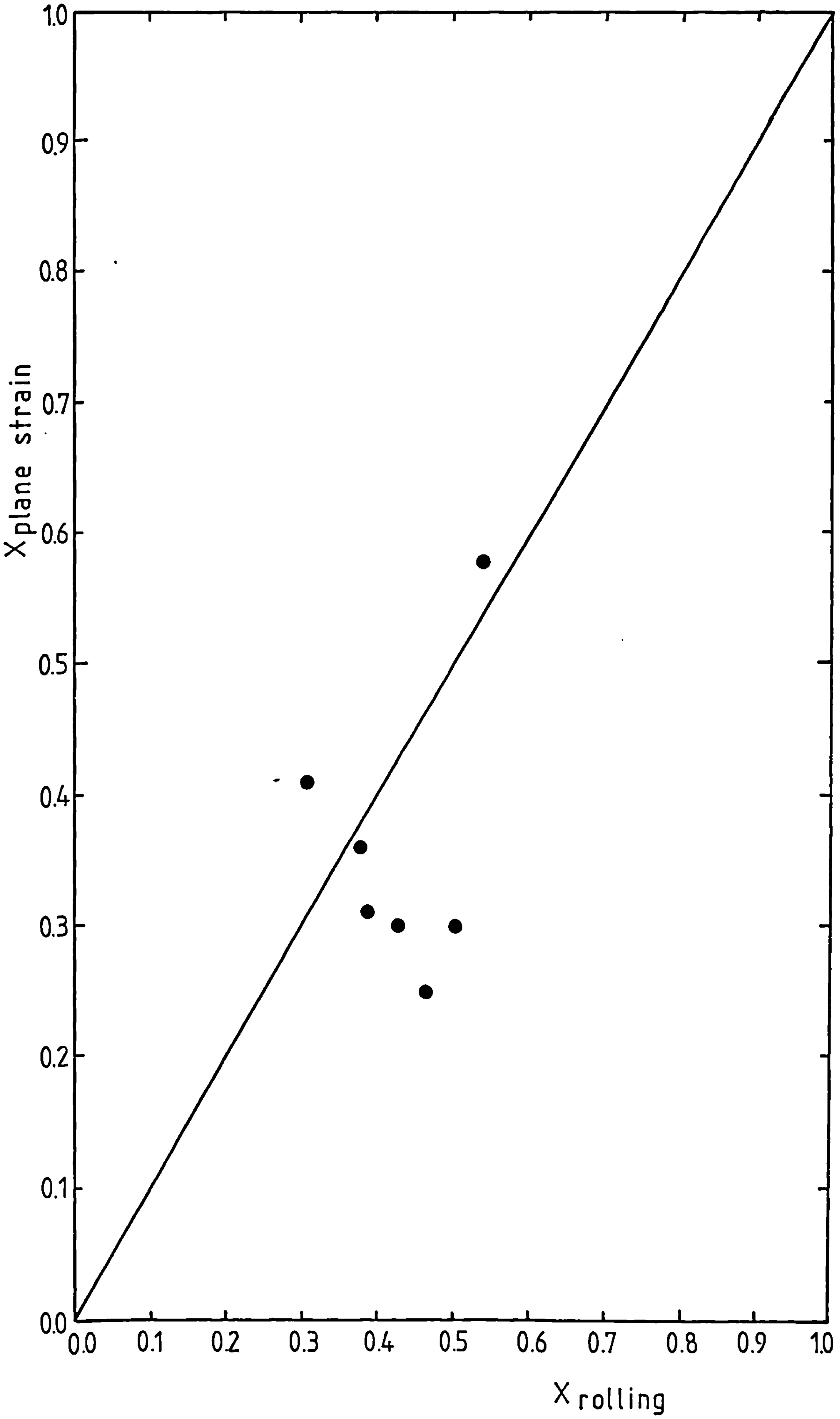

0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$X_{\text{plane strain}}$
X_{rolling}

FIGURE 9.22 : Comparison between measured average grain size during recrystallization from hot rolling samples and from plane strain compression ones.

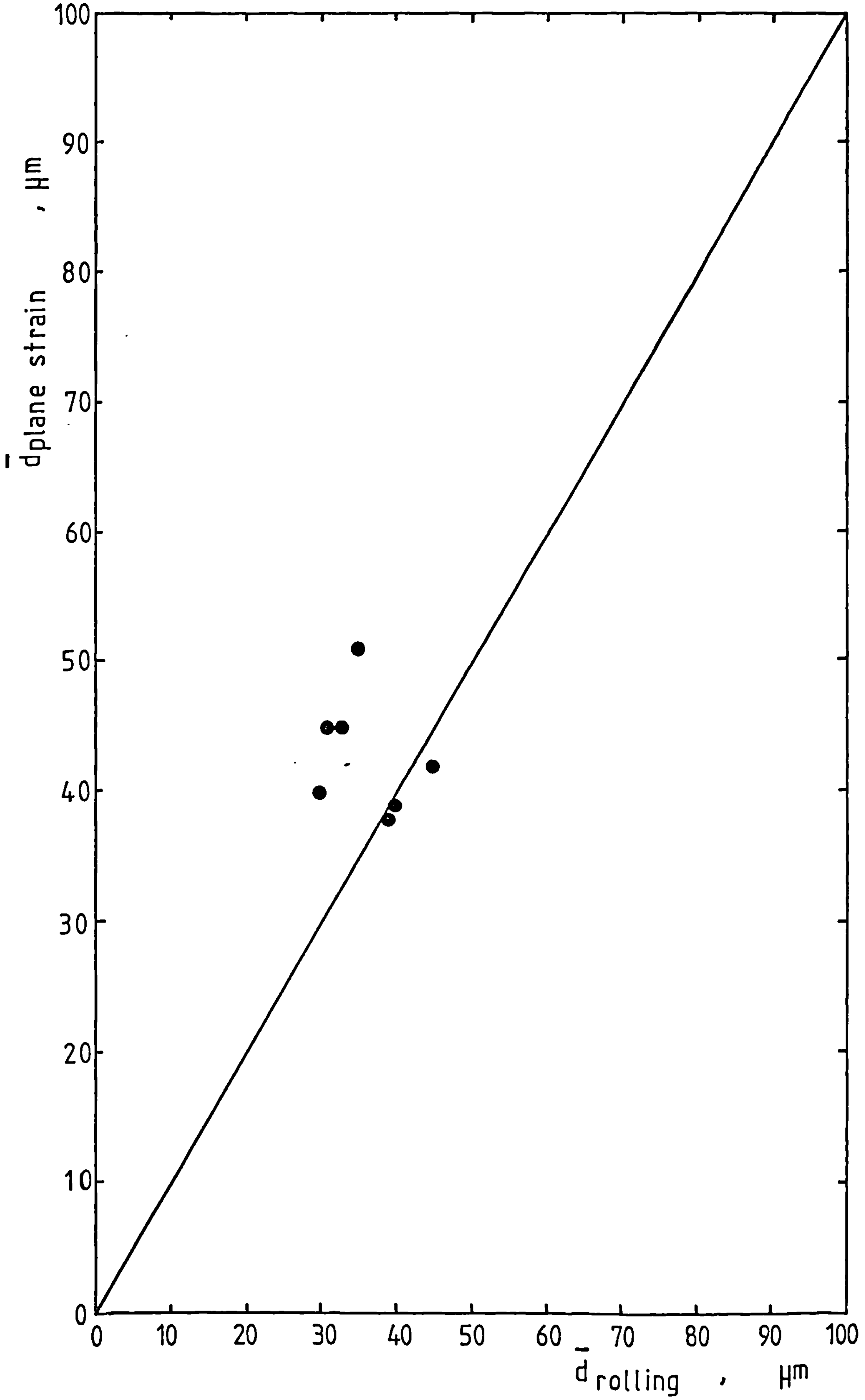

$\bar{d}_{plane\ strain}$, μm
$\bar{d}_{rolling}$, μm
0
10
20
30
40
50
60
70
80
90
100

FIGURE 9.23 : Microstructure after the third pass:

a- general view

Mag. x100

b- Coexisting types of structure. Numbers mean structure entering a given pass number i.

Mag. x350

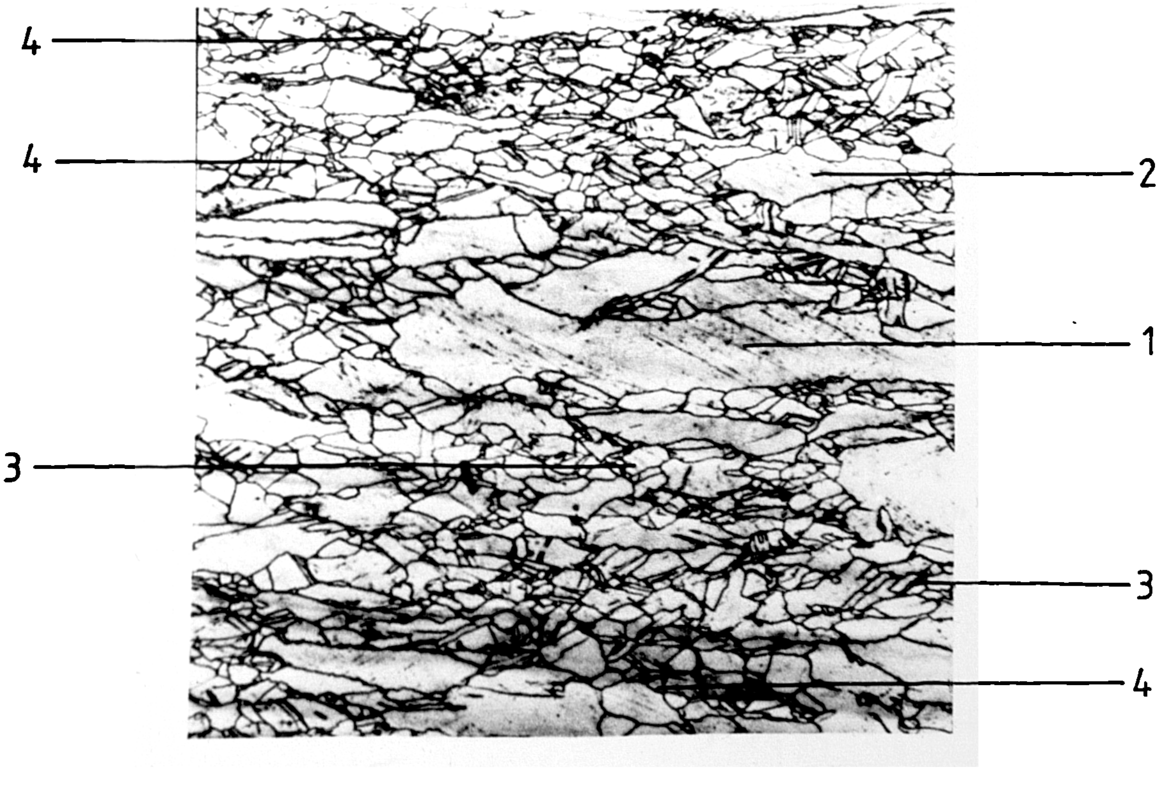
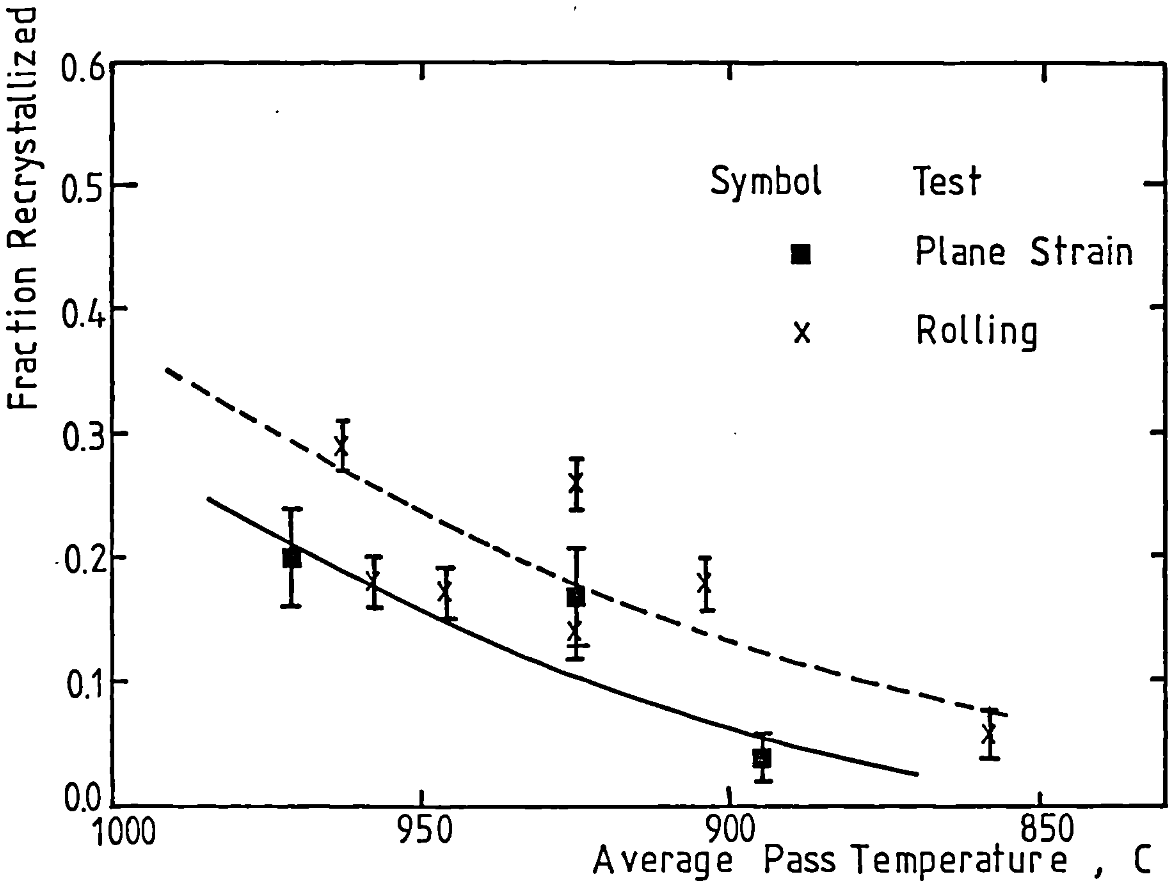

4
4
2
1
3
3
4

FIGURE 9.24 : The fraction recrystallized dependence on the third pass average temperature for hot rolled and plane strain compression samples.

FIGURE 9.25 : The average grain size during recrystallization as a function of the third pass average temperature for hot rolled and plane strain compression samples.


Fraction Recrystallized
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1000
950
900
850
Average Pass Temperature , C
Symbol
Test
■
Plane Strain
x
Rolling

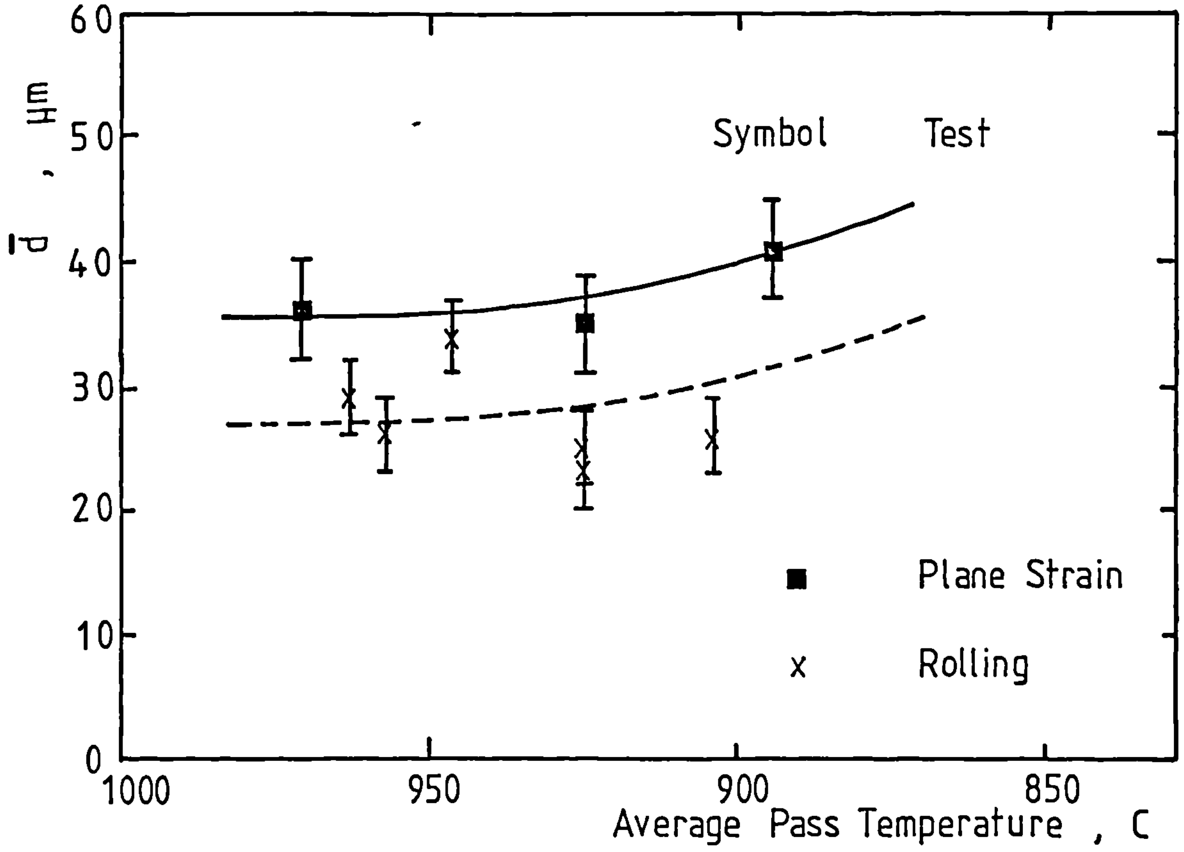
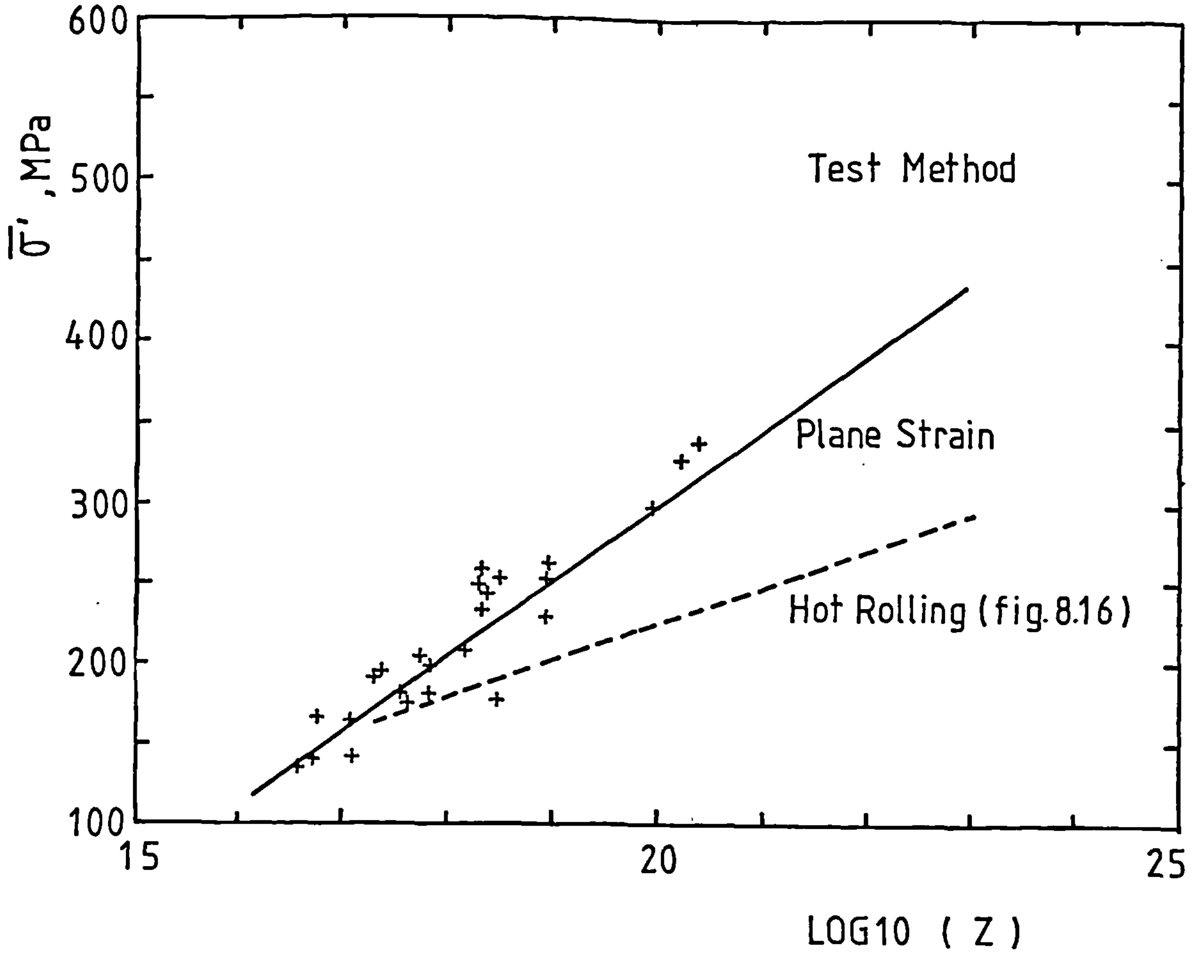

$\bar{d}$, μm
60
50
40
30
20
10
0
1000
950
900
850
Average Pass Temperature , C
Symbol
Test
■
Plane Strain
x
Rolling

FIGURE 9.26 : The dependence of the mean plane strain strength during non-isothermal plane strain compression test on the Zener-Hollomon parameter. Samples were deformed in a single 25% reduction pass schedule.

FIGURE 9.27 : The dependence of the mean plane strain strength during non-isothermal plane strain compression test on the Zener-Hollomon parameter.


600
500
400
300
200
100
σ̄' , MPa
15
20
25
LOG10 (Z)
Test Method
Plane Strain
Hot Rolling (fig. 8.16)

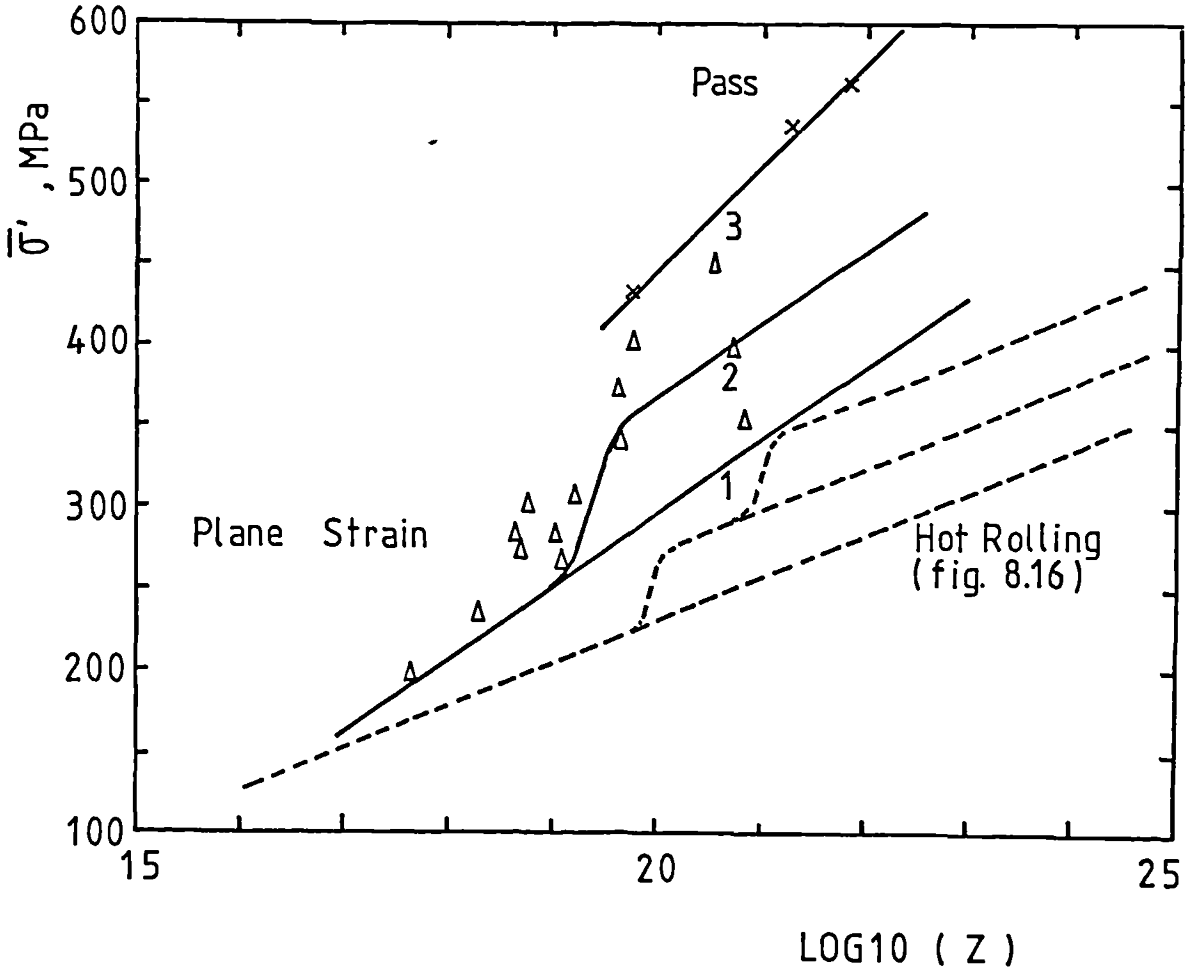
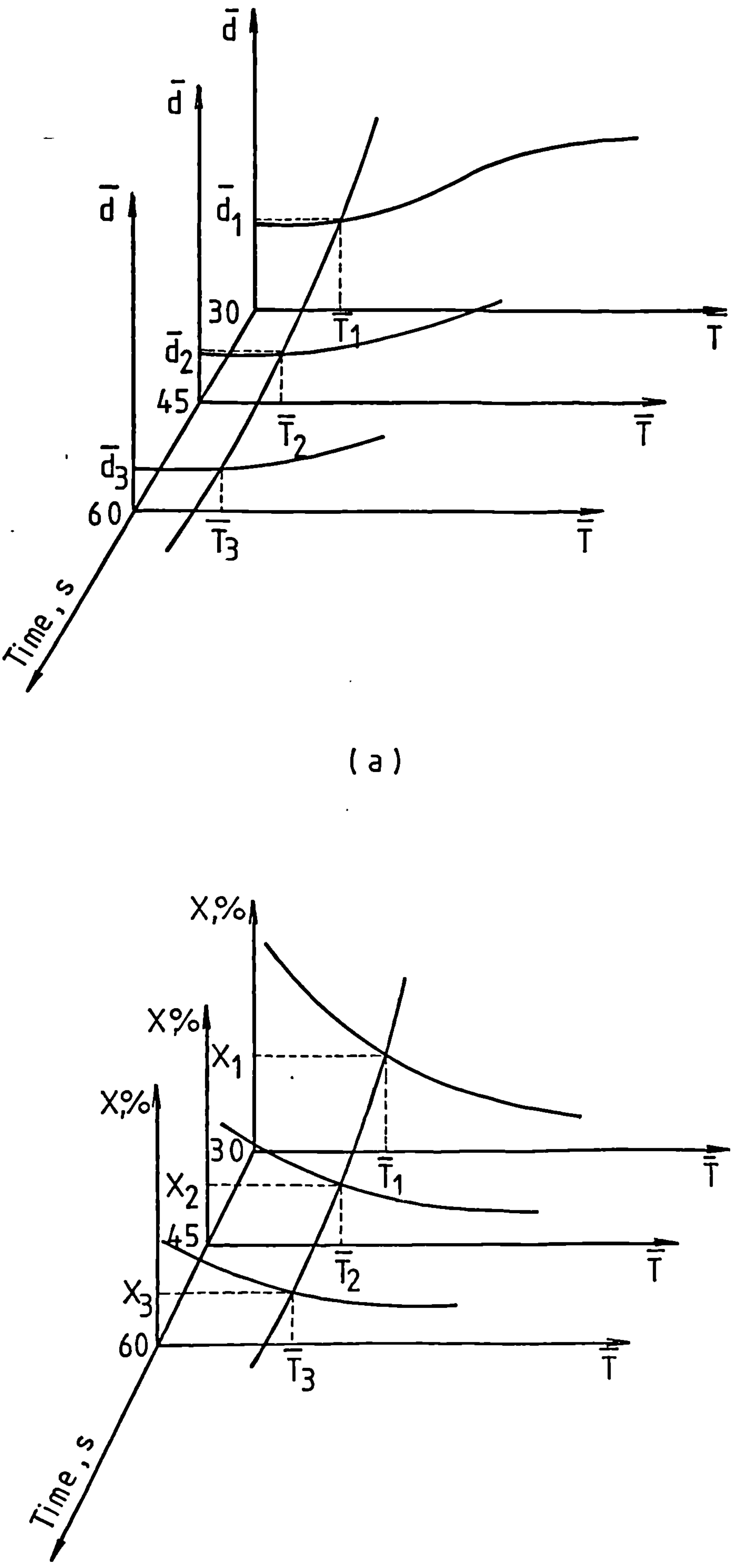

600
500
400
300
200
100
σ̄' , MPa
15
20
25
LOG10 (Z)
Pass
3
2
1
Plane Strain
Hot Rolling
(fig. 8.16)

FIGURE 9.28 : Schematic representation of the method used to interpolate values of:

a- average grain size during recrystallization,

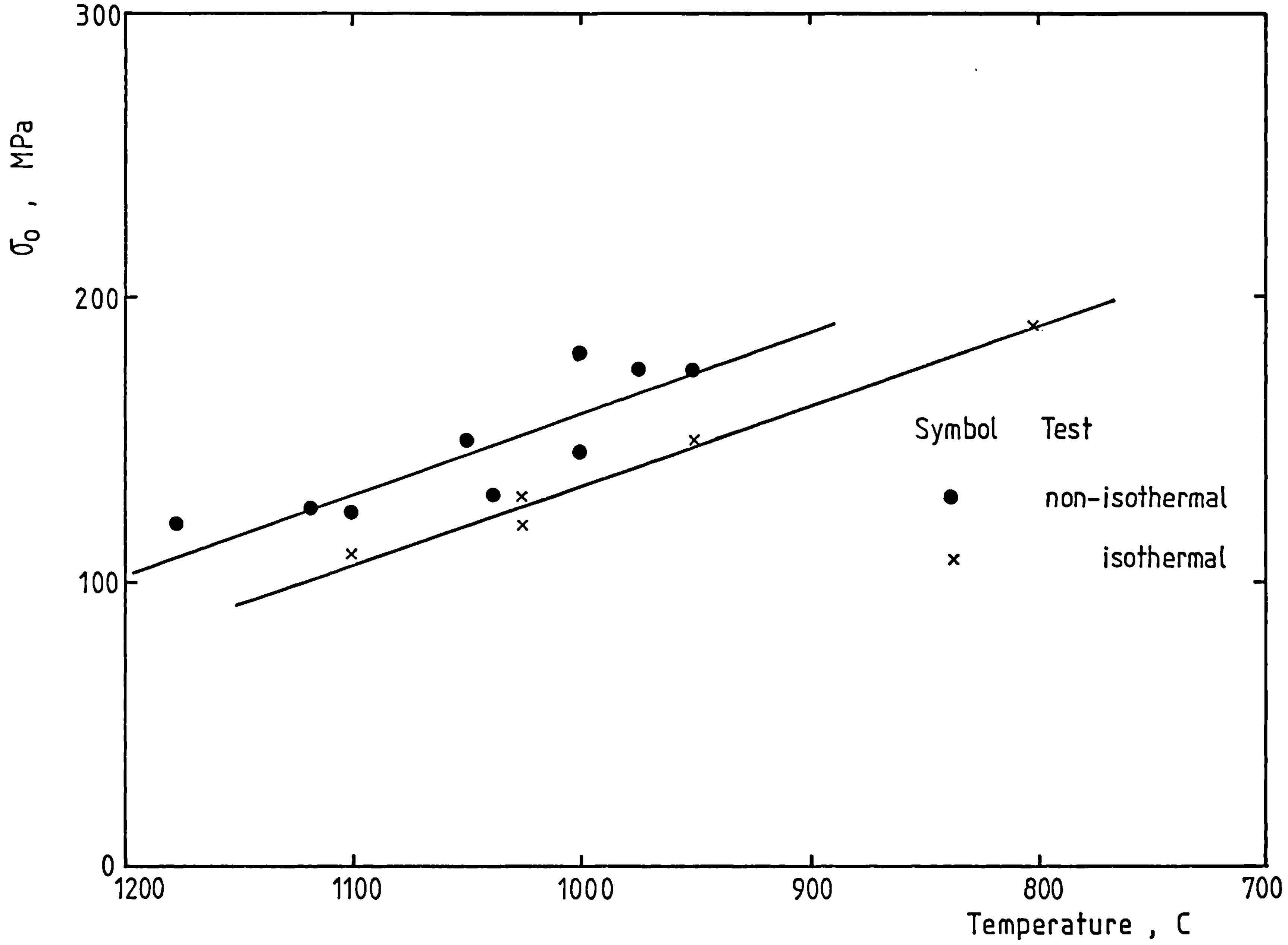
b- fraction recrystallized.


d̄
d̄
d̄
d̄1
30
T̄1
T
d̄2
45
T̄2
T̄
d̄3
60
T̄3
T̄
Time, s
X,%
X%
X,%
X1
30
T̄1
T̄
X2
45
T̄2
T̄
X3
60
T̄3
T̄
Time, s

(a)

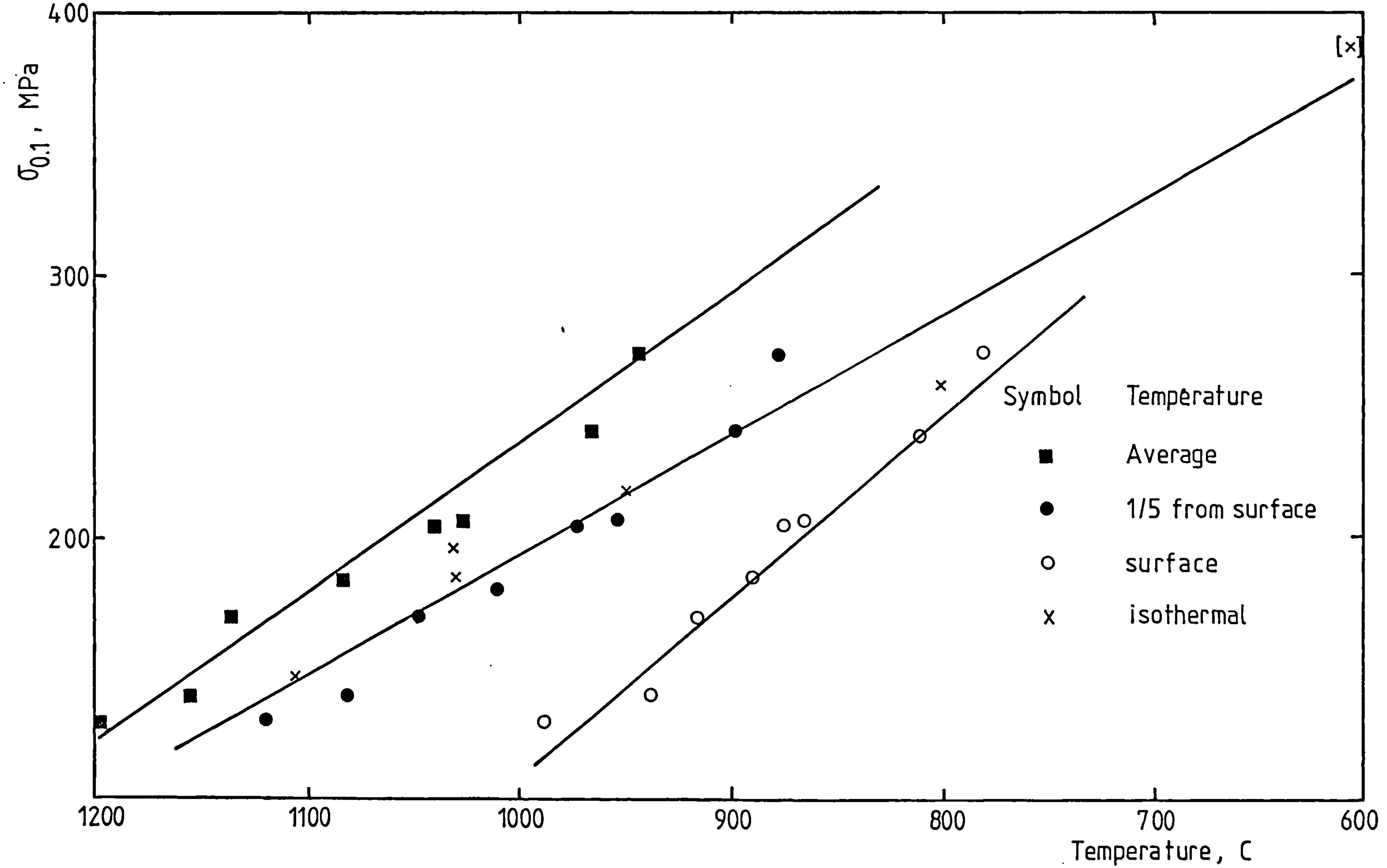
(b)

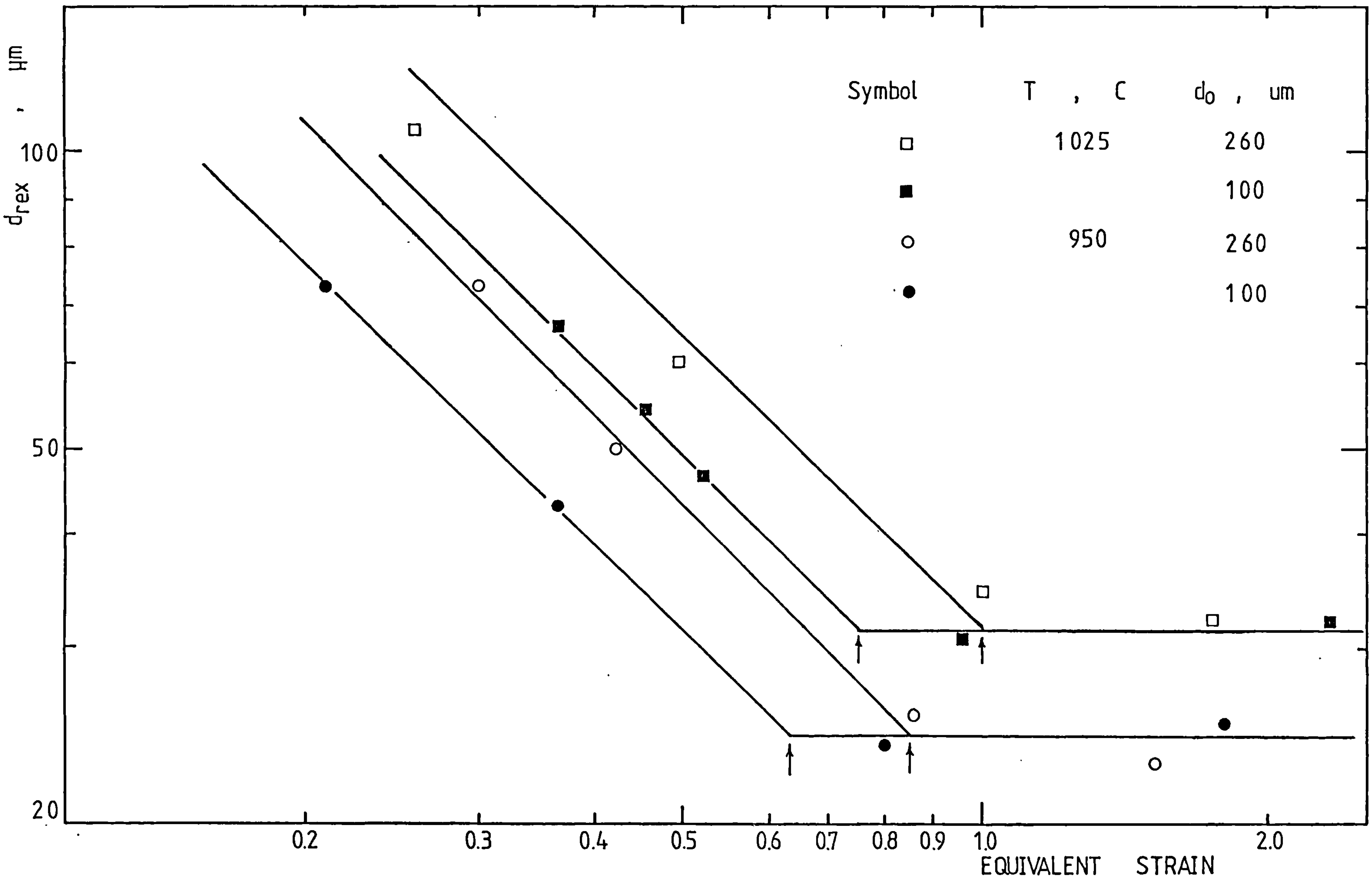
FIGURE 9.29 : Dependence of σ_0 on the temperature for samples tested in plane strain compression under isothermal and non-isothermal conditions.

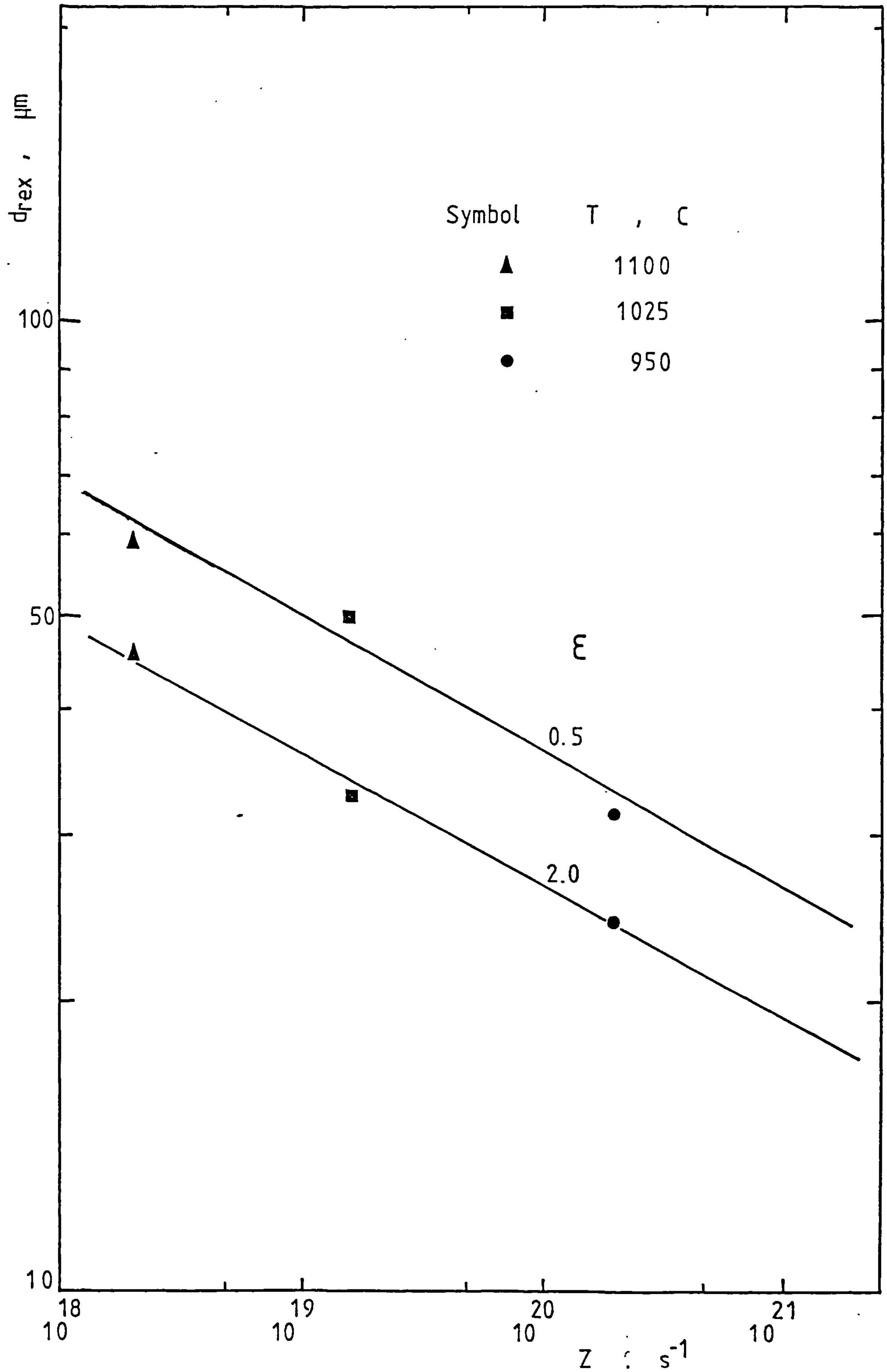


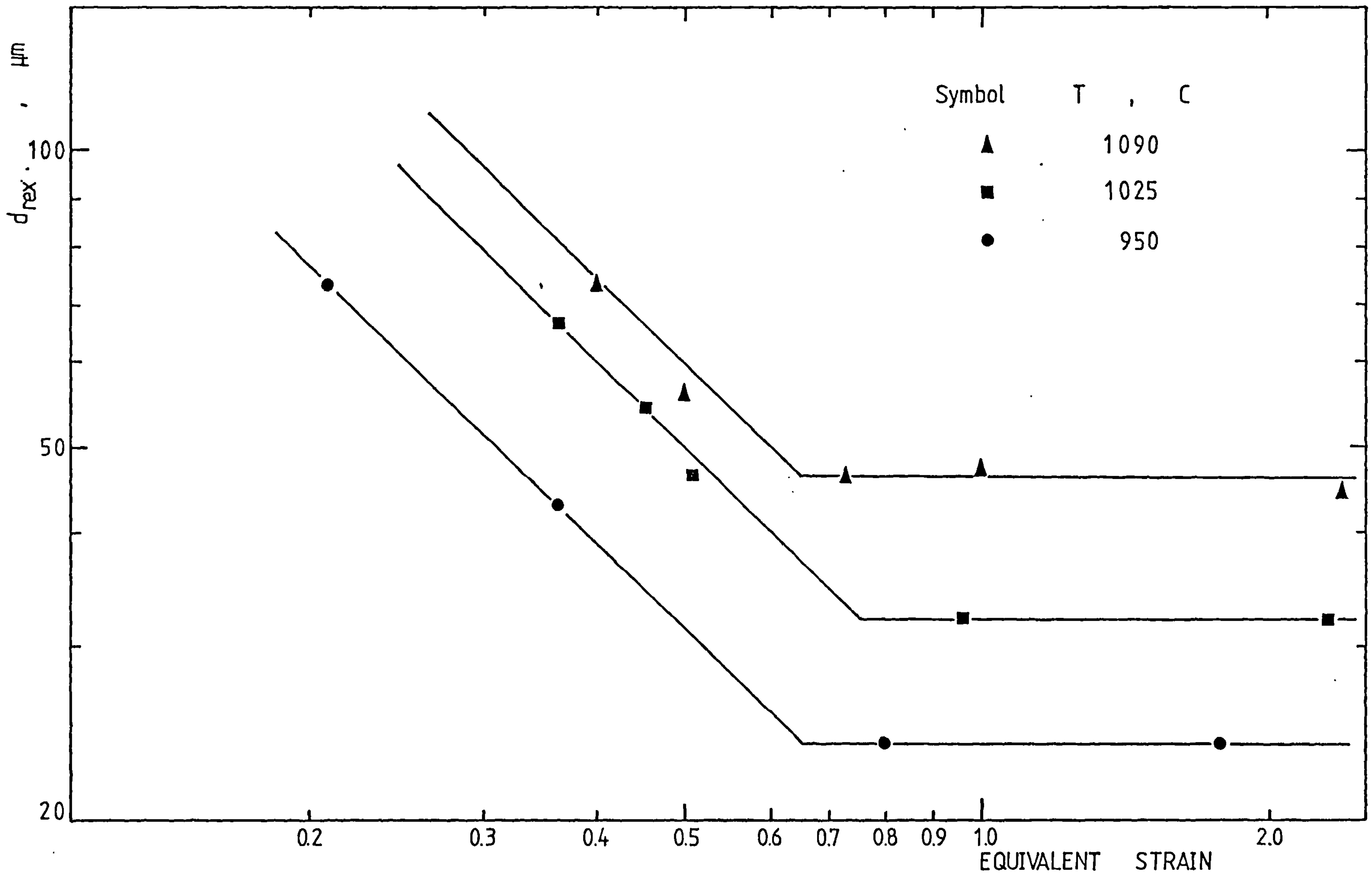
σ_0 , MPa
300
200
100
0
1200
1100
1000
900
800
700
Temperature , C
Symbol
Test
●
non-isothermal
×
isothermal

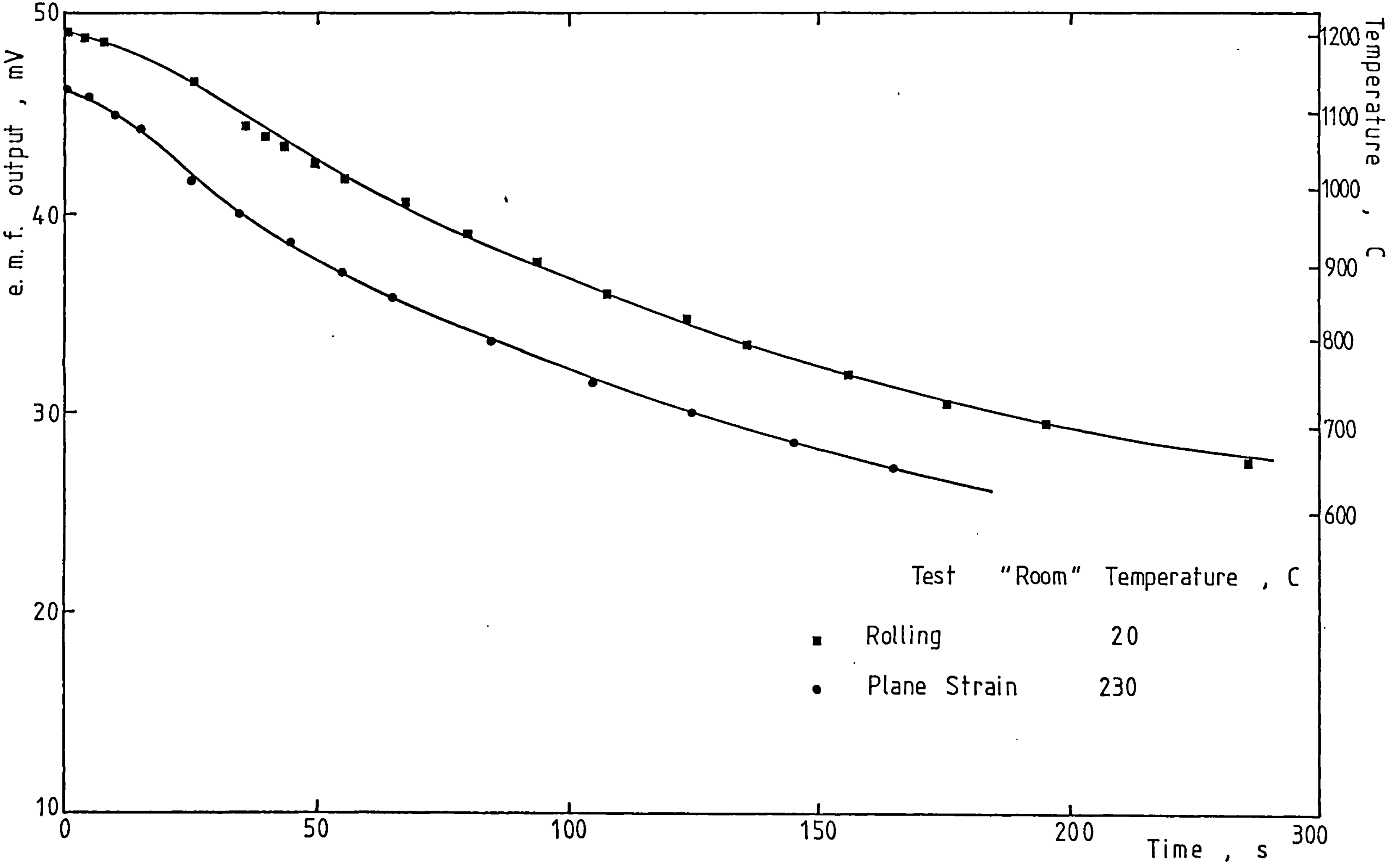
FIGURE 9.30 : Dependence of the $\sigma_{0.1}$ on the temperature for samples tested in plane strain compression under isothermal and non-isothermal conditions.


400
300
200
$\sigma_{0.1}$, MPa
1200
1100
1000
900
800
700
600
Temperature, C
[x]
Symbol
Temperature
■
Average
●
1/5 from surface
○
surface
x
isothermal


d_{rex} , μm
100
50
20
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2.0
EQUIVALENT STRAIN
Symbol T , C d_0 , um
□ 1025 260
■ 100
○ 950 260
● 100


d_rex , μm
Symbol T , C
▲ 1100
■ 1025
● 950
ε
0.5
2.0
100
50
10
10^18
10^19
10^20
10^21
Z , s^-1


d_rex , μm
100
50
20
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2.0
EQUIVALENT STRAIN
Symbol T , C
▲ 1090
■ 1025
● 950


e. m. f. output , mV
50
40
30
20
10
0
50
100
150
200
300
Time , s
Temperature , C
1200
1100
1000
900
800
700
600
Test "Room" Temperature , C
■ Rolling 20
● Plane Strain 230