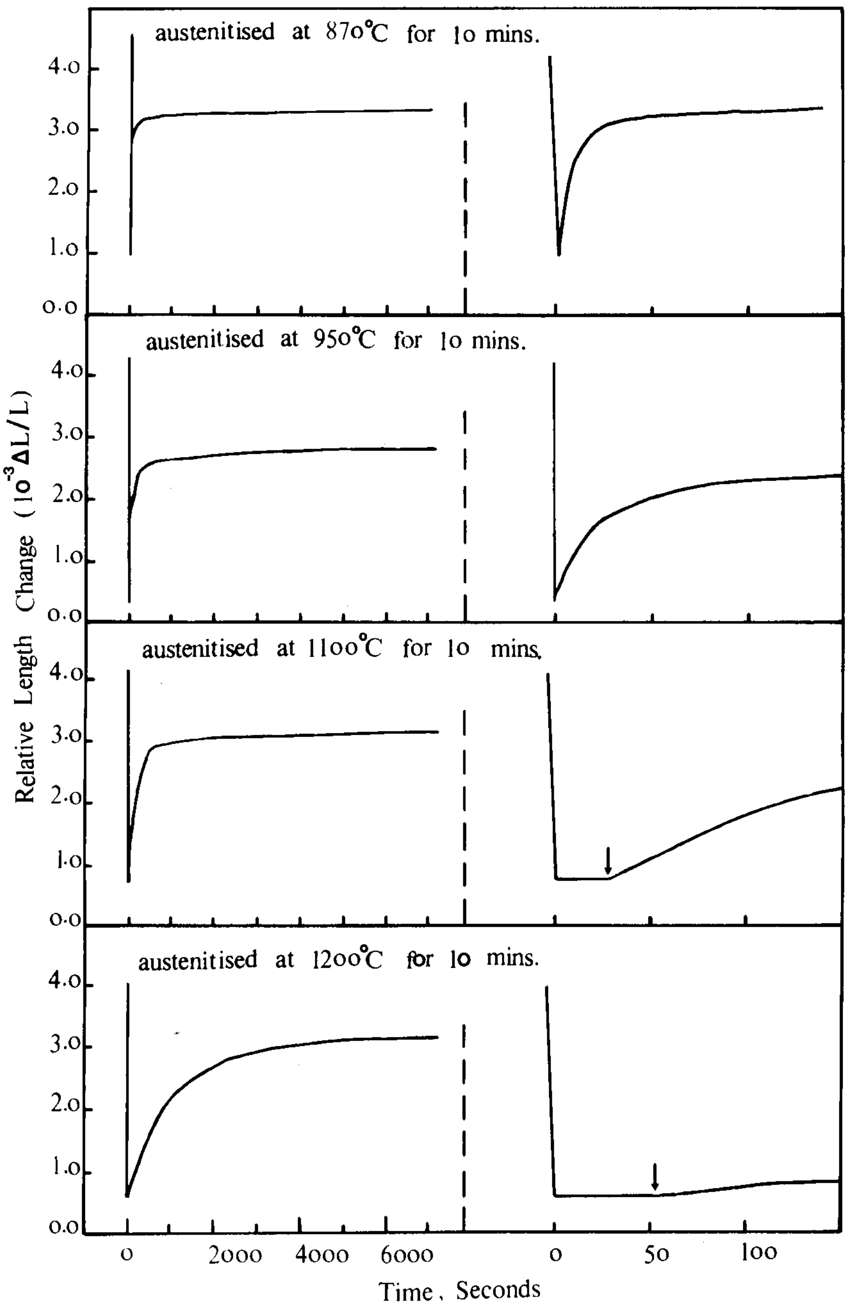


Figure VIII.7(e) - Dilatometric curves shows isothermal transformation at 680°.

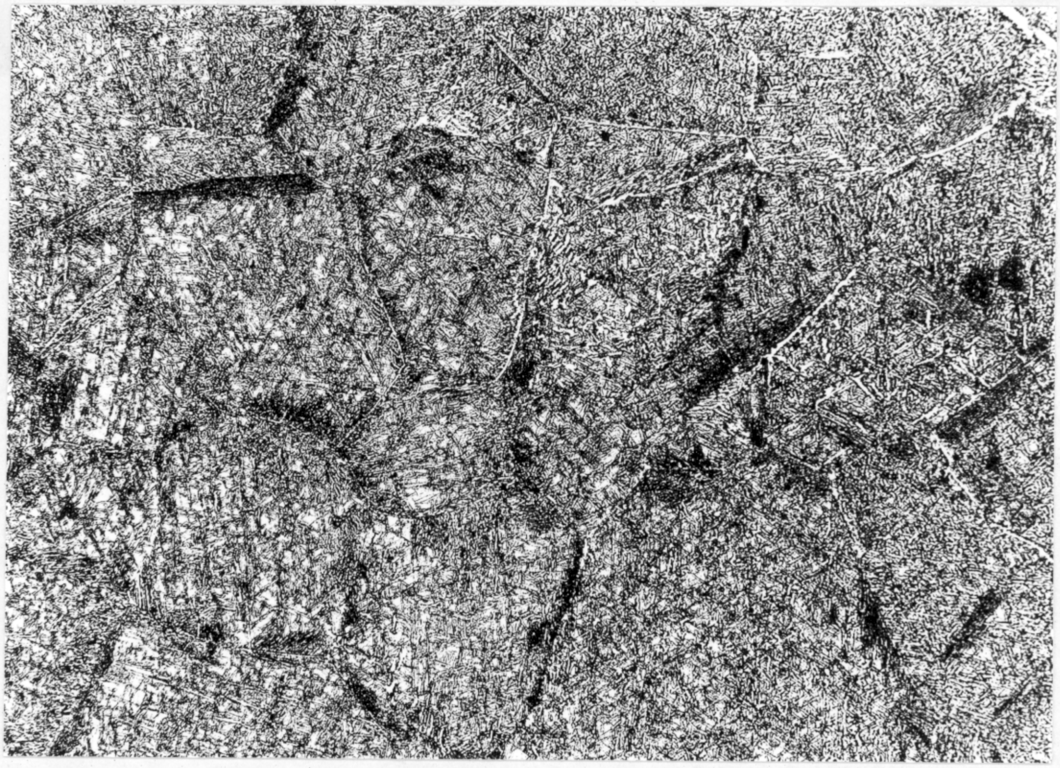

Figure VIII.8(a) - 10 mins @ 1200°C → 2 hrs @ 760°C → quenched by helium gas. 100 μm

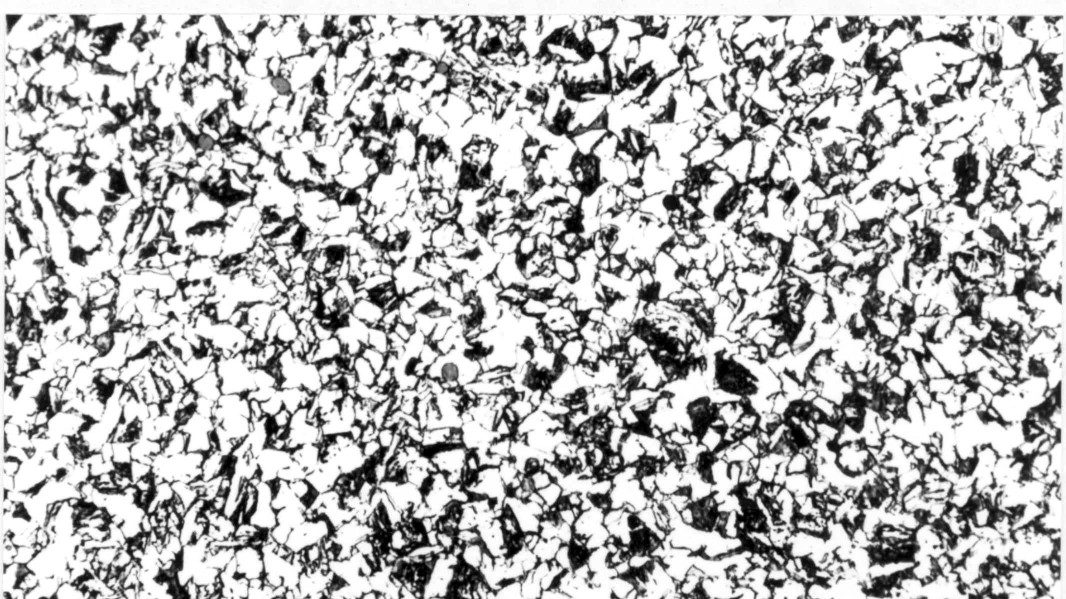

Figure VIII.8(b) - 10 mins @ 870°C → 2 hrs @ 760°C → quenched by helium gas. 20 μm

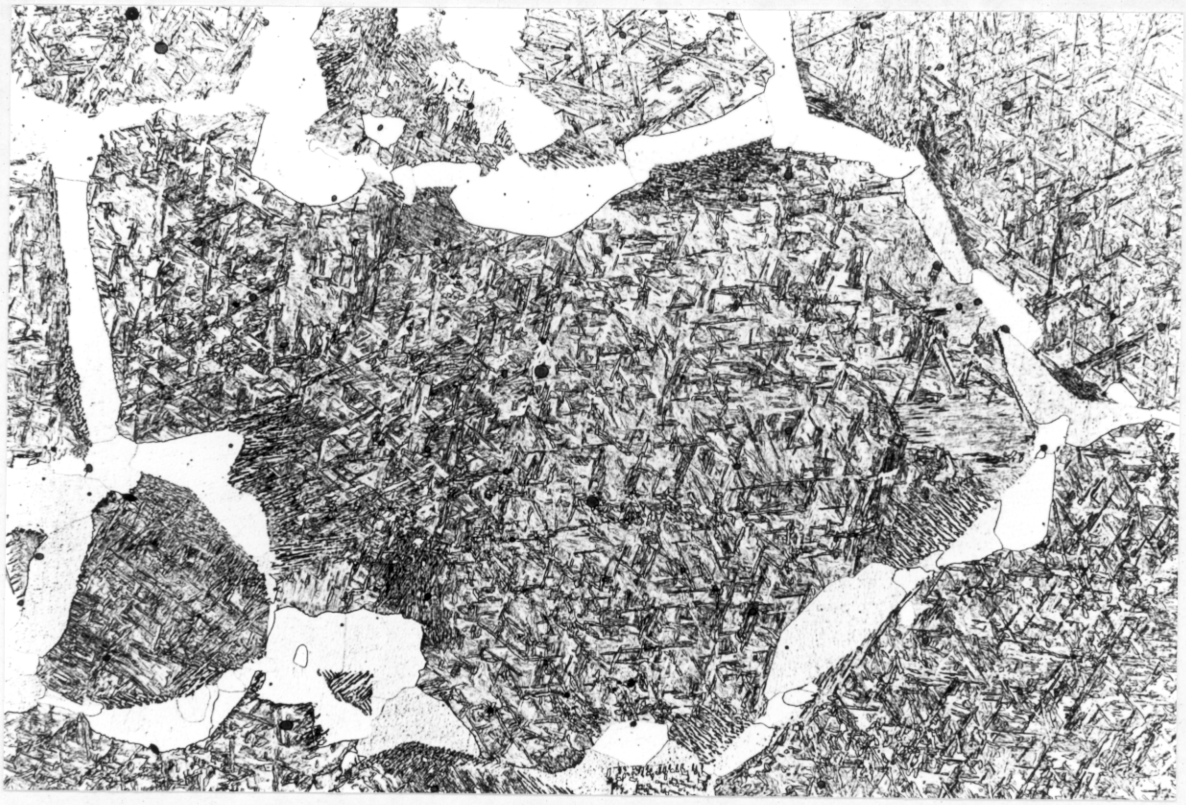

Figure VIII.8(c) - 10 mins @ 1200°C → 2 hrs @ 720°C → quenched by helium gas. 50μm

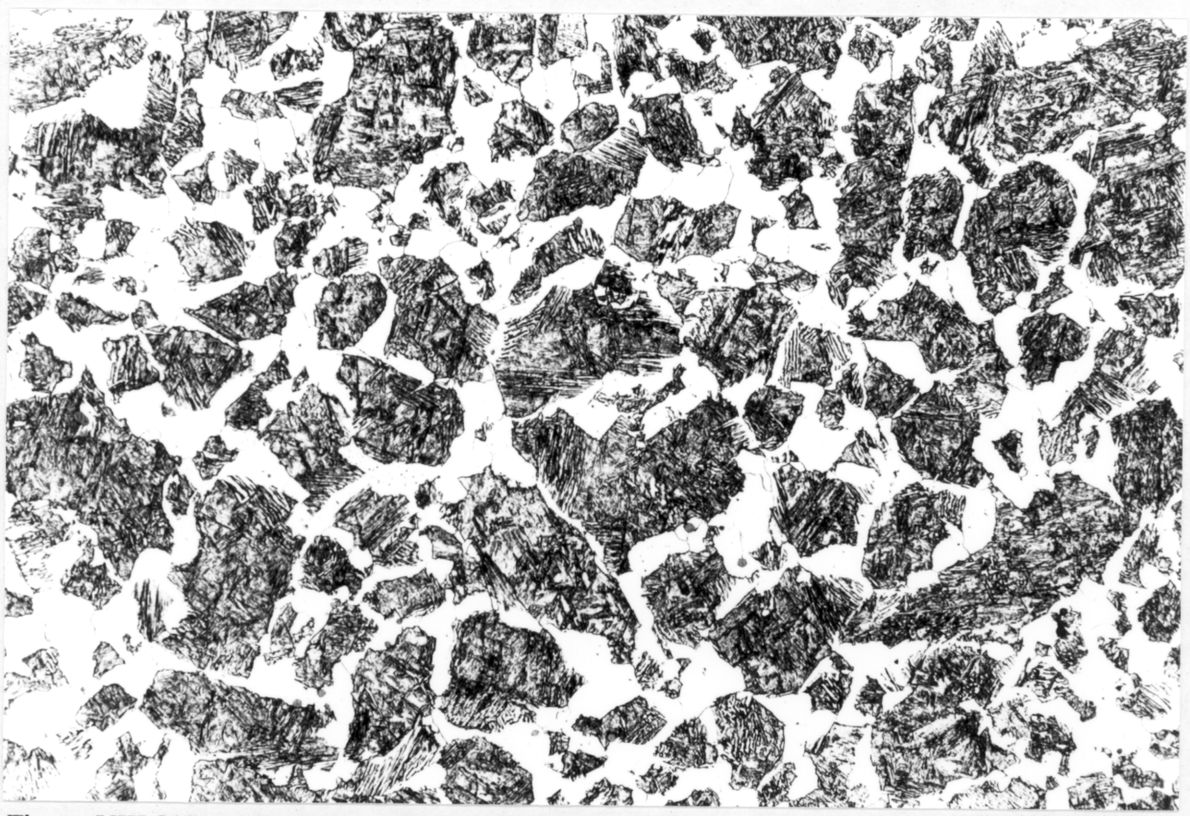

Figure VIII.8(d) - 10 mins @ 1100°C → 2 hrs @ 720°C → quenched by helium gas. 50μm

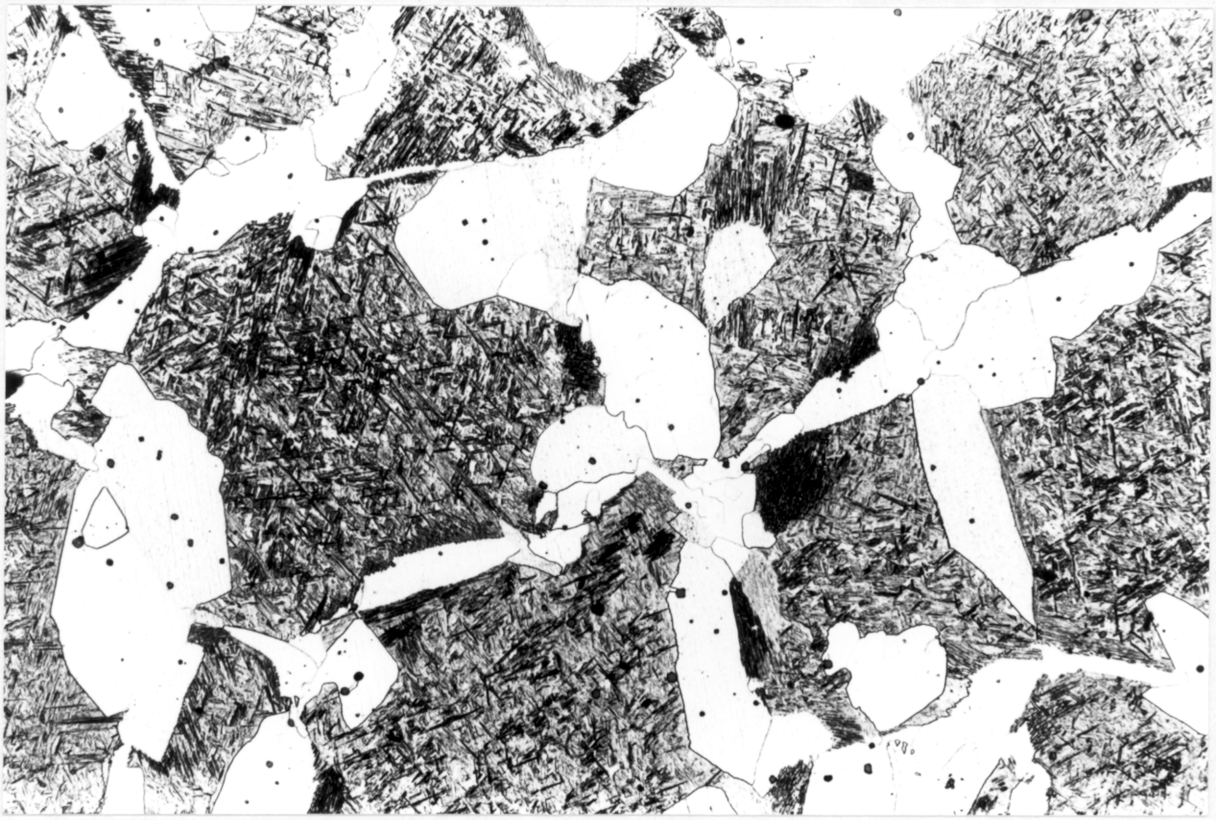

Figure VIII.8(e) - 10 mins @ 1200°C → 2 hrs @ 700°C → quenched by helium gas. 50μm

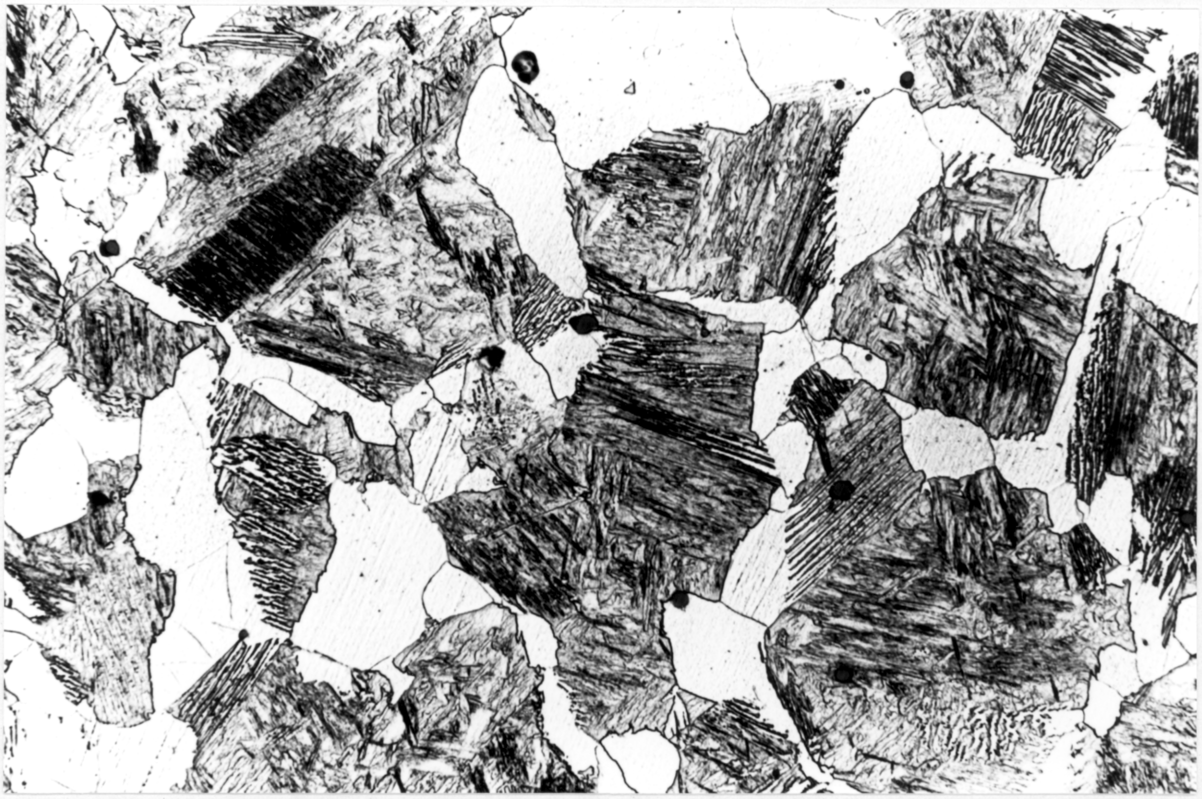

Figure VIII.8(f)-10 mins @ 1100°C → 2 hrs @ 700°C → quenched by helium gas. 20μm

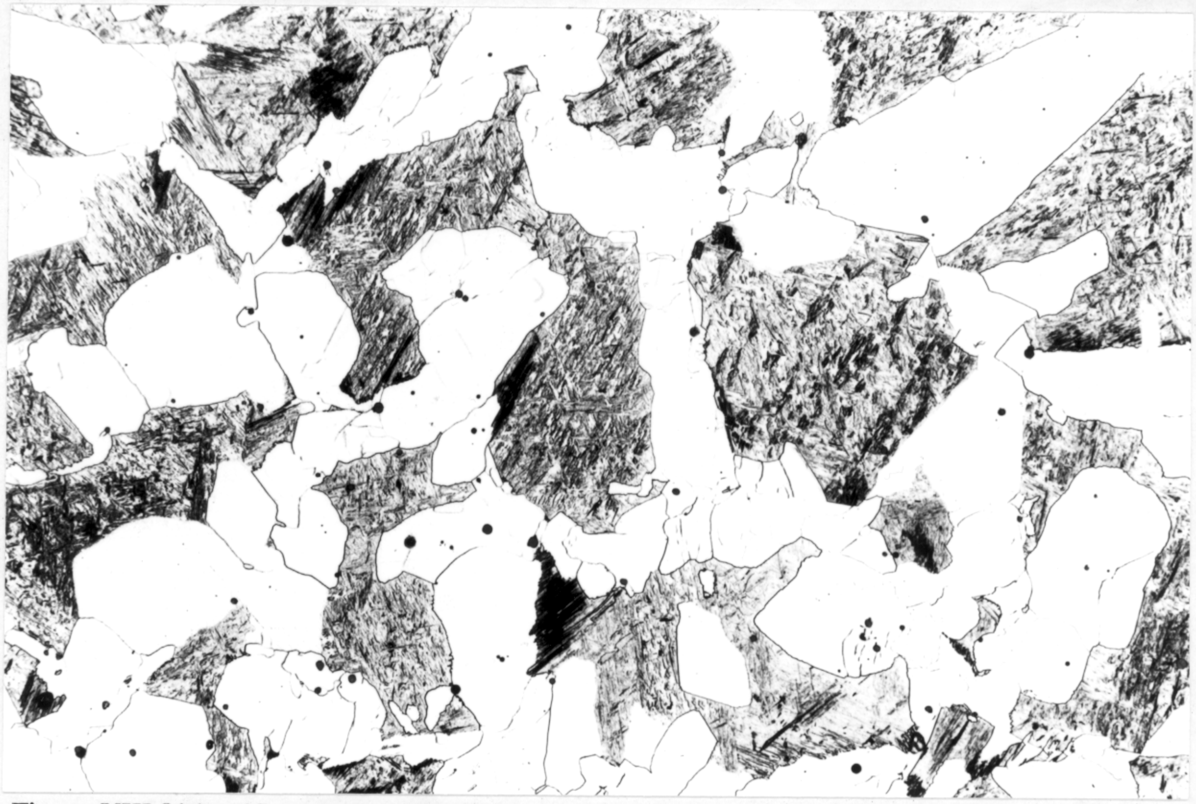

Figure VIII.8(g) - 10 mins @ 1200°C → 2 hrs @ 680°C → quenched by helium gas. 50 μm

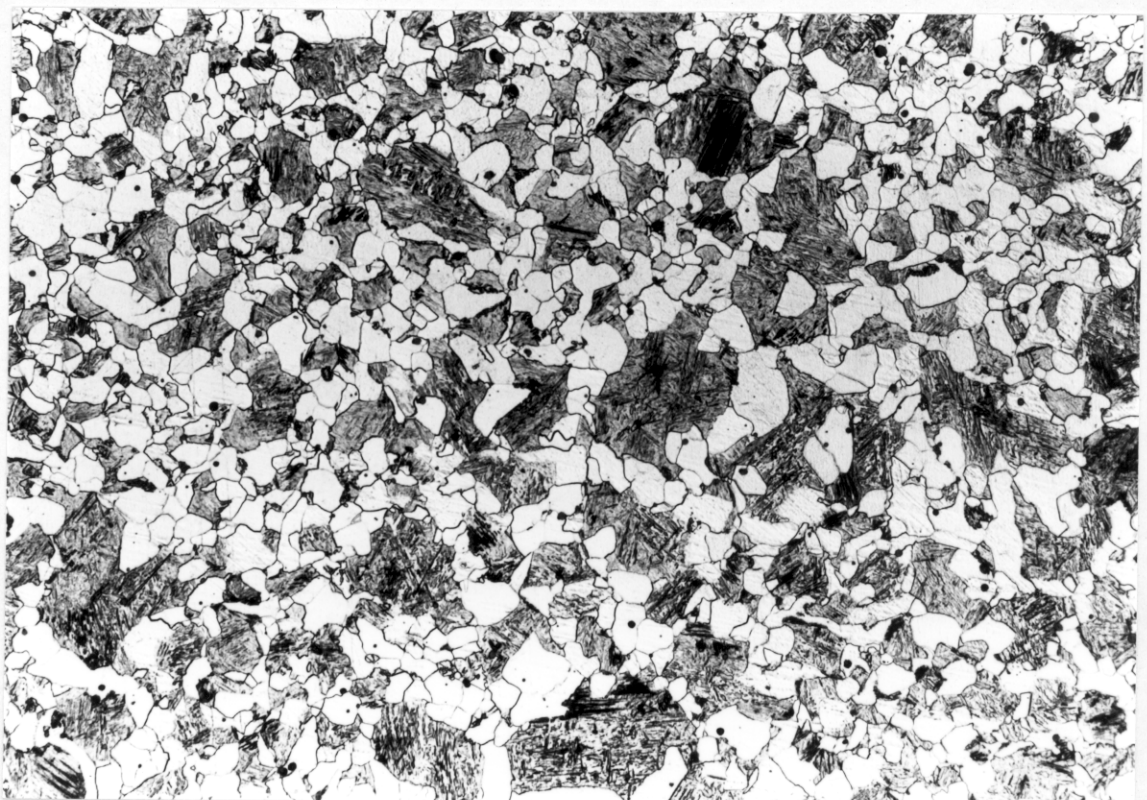

Figure VIII.8(h) - 10 mins @ 1100°C → 2 hrs @ 680°C → quenched helium gas. 50 μm

# Chapter Nine

## Further Research

The present work has gone some way towards an understanding of the mechanism of acicular ferrite formation. This is of importance in placing the reaction in the context of other reactions that arise in steels, in computing the effects of alloying elements and thermomechanical treatments on the design of steel microstructures and ultimately in the improvement of weld quality. However, much further work needs to be carried out to ensure that the thermodynamic description can be extended to permit detailed calculations of the nucleation and growth kinetics of acicular ferrite. Measurements of the nucleation and growth kinetics seem vital. The mechanism by which acicular ferrite improves mechanical properties is not established although very qualitative relationships can be found in the literature. In particular, the micromechanisms of fracture resistance of acicular ferrite should be most interesting to investigate.

The model developed for reaustenitisation already permits a calculation of the TTT curves for the growth of austenite from a specified starting microstructure. However, this is only the tip of the iceberg and to adapt the work to industrially relevant situations it is necessary to address complications such as the nucleation rate of austenite, and reaustenitisation from a variety of possibly mixed microstructures.

# APPENDIX 1

```
C ******************************************************************
C PROGRAM FOR THE CALCULATION OF LENGTH CHANGE
C ACCOMANYING REAUSTENTISATION FROM A MIXTURE OF
C AUSTENITE AND BAINITIC FERRITE
C ******************************************************************

   IMPLICIT REAL*8(A-H,K-Z)

   DOUBLE PRECISION A(8),WT0(8),WF(8),WAE3(8),W4(8)
C AG=AUSTENITE LATTICE PARAMETER AS A FUNCTION OF COMP, TEMP
C AF=FERRITE LATTICE PARAMETER AS A FUNCTION OF COMP, TEMP
C AGF AND AFF ARE CORRESPONDING FUNCTIONS TO GIVE THESE
PARAMETERS
C XBAR=AVERAGE ALLOY CARBON, MOLE FRACTION
C XAE3=CARBON, MOL FRAC CORRESPONDING TO AE3 CURVE
C XF=CARBON CONTENT OF ALPHA
C XT0= CARBON, MOL FRAC, CORRESPONDING TO T0 CURVE
C T=TEMPERATURE, CENTIGRADE
C EG,EF EXPANSIVITIES OF GAMMA AND FERRITE
C TBAIN,TAUST=CENTIGRADE, ISOTHERMAL TRANSF TEMPS FOR
BAINITE,AUSTENITISATION
C COMPOSITIONS READ IN WT.PCT.
C VB=VOLUME FRACTION OF BAINITE AT TBAIN
C V1=VOLUME OF GAMMA+ALPHA MIX,BEFORE TRANSFORMATION, AT
TAUST
C V2=VOLUME OF GAMMA+ALPHA MIX,AFTER TRANSFORMATION, AT
TAUST
C DELTAL=RELATIVE LENGTH CHANGE,AFTER TRANSFORMATION, AT
TAUST
C DEL5V=RELATIVE LENGTH CHANGE DUE TO INCREASING THE VOLUME
FRACTION
C OF AUSTENITE BY 0.05, DURING TRANSFORMATION, AT TAUST
C ******************************************************************

   READ(5,*)C,SI,MN,NI,MO,CR,V,EG,EF,TBAIN

   CALL ATOM(A,C,SI,MN,NI,MO,CR,V)

   WRITE(6,1)C,SI,MN,NI,MO,CR,V,A(1),A(2),A(3),A(4),A(5),A(6),

   &A(7),EG,EF,TBAIN

   XBAR=A(1)/100.0

   XF=0.0D+00

   XT0=XT0F(TBAIN)

   VB=(XT0-XBAR)/(XT0-XF)

   WRITE(6,2)VB,XT0,XF,XBAR
C VOLUME OF MIXTURE (V1) OF VB BAINITE AND (1-VB)GAMMA, AT TAUST

   WRITE(6,3)
```

```
      DO 5 I=600,850,5
      TAUST=I*1.0D+00
      CALL WEIGHT(WT0,XT0,C,SI,MN,NI,MO,CR,V)
      CALL WEIGHT(WF,XF,C,SI,MN,NI,MO,CR,V)
      CALL AFF(AF,EF,WF(1),SI,MN,NI,MO,CR,V,TAUST)
      CALL AGF(AG,EG,WT0(1),SI,MN,NI,MO,CR,V,TAUST)
      V1=VB*2.0D+00*AF**3 + (1.0D+00-VB)*AG**3
      XAE3=XAE3F(TAUST)
      IF(XAE3 .GT. XT0) GOTO 5
      IF(XAE3 .LT. XBAR) GOTO 6
      VF=(XAE3-XBAR)/(XAE3-XF)
      GOTO 7
    6 VF=0.0D+00
      XAE3=XBAR
    7 CALL WEIGHT(WAE3,XAE3,C,SI,MN,NI,MO,CR,V)
      CALL WEIGHT(WF,XF,C,SI,MN,NI,MO,CR,V)
      CALL AFF(AF,EF,WF(1),SI,MN,NI,MO,CR,V,TAUST)
      CALL AGF(AG,EG,WAE3(1),SI,MN,NI,MO,CR,V,TAUST)
      V2=VF*2.0D+00*AF**3 + (1.0D+00-VF)*AG**3
      DELTAL=(V2-V1)/(3.0D+00*V1)
      DEL5V=(0.05*AG**3-0.05*2*AF**3)/(3.0D+00*V1)
      WRITE(6,4)DELTAL,TAUST,VF,DEL5V
    5 CONTINUE
    1 FORMAT(' C SI MN NI MO CR V'/
     &7F8.4, ' WT.PCT'/7F8.4,' ATOMIC PCT'/
     &' EXPANSION COEFFICIENT OF AUSTENITE=',D10.4,
     &' EXPANSION COEFFICIENT OF FERRITE=',D10.4/
     &' TRANSFORMED TO BAINITE AT DEGREES CENTIGRADE=',F8.2)
    2 FORMAT(' VOLUME FRACTION OF BAINITIC FERRITE=',F8.3,
     &' MOL. FRAC. XT0=',F8.4/' MOL. FRAC. XF=',D10.4,
     &' AVERAGE ALLOY MOL. FRAC. XBAR=',F8.3)
    3 FORMAT(' DELTAL TAUST VF DEL5V ')
    4 FORMAT(D14.4,F8.0,F8.3,D14.4)
```

```
      STOP

      END
C ******************************************************************

      DOUBLE PRECISION FUNCTION XT0F(T)
C T01=INTERCEPT ON TEMP AXIS OF ST. LINE REPRESENTING T0 CURVE
C SLOPE=RECIPROCAL MAGNITUDE OF SLOPE OF T0 LINE

      XT0F=0.14885-6.4052D-04*T+1.2219D-06*T**2-9.2707D-10*T**3

      RETURN

      END
C ******************************************************************

      DOUBLE PRECISION FUNCTION XAE3F(T)
C T01=INTERCEPT ON TEMP AXIS OF ST. LINE REPRESENTING AE3 CURVE
C SLOPE=RECIPROCAL MAGNITUDE OF SLOPE OF AE3 LINE

      XAE3F=0.34227-3.5370D-04*T-6.7065D-07*T**2+7.2111D-10*T**3

      RETURN

      END
C ******************************************************************

      SUBROUTINE AGF(AG,EG,C,SI,MN,NI,MO,CR,V,T)

      IMPLICIT REAL*8(A-H,K-Z)
C   CONCENTRATIONS IN WT. PCT., PARAMETER IN ANGSTOMS,
EG=EXPANSIVITY
C TEMPERATURE IN CENTIGRADE

      AG=0.00095*MN-0.0002*NI+0.0006*CR+0.0031*MO+0.0018*V

      &+0.033*C+3.578

      AG=AG*(1.0D+00 + EG*(T-25))

      RETURN

      END
C ******************************************************************

      SUBROUTINE AFF(AF,EF,C,SI,MN,NI,MO,CR,V,T)

      IMPLICIT REAL*8(A-H,K-Z)
C   CONCENTRATIONS IN WT. PCT., PARAMETER IN ANGSTOMS,
EF=EXPANSIVITY
C TEMPERATURE IN CENTIGRADE
C SPEICH, P.111: CARBON, MO, V, NOT ACCOUNTED FOR

      DOUBLE PRECISION A(8)

      CALL ATOM(A,C,SI,MN,NI,CR,MO,V)
```

```
      AF=2.866-0.0003*A(2)+0.0005*A(6)+0.0006*A(3)+0.0007*A(4)

      AF=AF*(1.0D+00 + EF*(T-25))

      RETURN

      END
C***********************************************************************

      SUBROUTINE ATOM(A,C,SI,MN,NI,CR,MO,V)
C SUBROUTINE FOR CONVERTING WT.% TO ATOMIC %

      DOUBLE PRECISION A(8),C,SI,MN,NI,CR,MO,V,B

      A(1)=C/12.0115

      A(2)=SI/28.09

      A(3)=MN/54.94

      A(4)=NI/58.71

      A(5)=MO/95.94

      A(6)=CR/52.0

      A(7)=V/50.94

      A(8)=(100.0-C-SI-MN-NI-MO-CR-V)/55.84

      B=A(1)+A(2)+A(3)+A(4)+A(5)+A(6)+A(7)+A(8)

      DO 1 I=1,8

      A(I)=A(I)*100.0/B
1 CONTINUE

      RETURN

      END
C***********************************************************************

      SUBROUTINE WEIGHT(A,XMOL,C,SI,MN,NI,MO,CR,V)
C SUBROUTINE FOR CONVERTING MOL.FRACTION OF CARBON TO WT.%
CARBON
C C READ IN AS MOL.FRAC, AND AS AVERAGE ALLOY WT.%, REST AS
AVERAGE ALLOY WT.%

      DOUBLE PRECISION A(8),B(8),C,SI,MN,NI,CR,MO,V,B1

      B(2)=SI/28.09

      B(3)=MN/54.94

      B(4)=NI/58.71

      B(5)=MO/95.94
```

```
      B(6)=CR/52.0
      B(7)=V/50.94
      B(8)=(100.0-C-SI-MN-NI-MO-CR-V)/55.84
      B(1)=XMOL*(B(2)+B(3)+B(4)+B(5)+B(6)+B(7)+B(8))/(1.0D+00-XMOL)
      B1=B(1)+B(2)+B(3)+B(4)+B(5)+B(6)+B(7)+B(8)
      DO 2 I=1,8
      B(I)=B(I)*100.0D+00/B1
    2 CONTINUE
      A(1)=B(1)*12.0115
      A(2)=B(2)*28.09
      A(3)=B(3)*54.94
      A(4)=B(4)*58.71
      A(5)=B(5)*95.94
      A(6)=B(6)*52.0
      A(7)=B(7)*50.94
      A(8)=B(8)*55.84
      B1=A(1)+A(2)+A(3)+A(4)+A(5)+A(6)+A(7)+A(8)
      DO 1 I=1,8
      A(I)=A(I)*100.0/B1
    1 CONTINUE
      RETURN
      END
```

# APPENDIX 2

```
C ***********************************************************
C PROGRAM FOR ANALYSIS OF DATA FROM BBC/DILATOMETER
C ***********************************************************
C Remember that the first line contains length in mm

   DIMENSION XX(6000), COEFF(6000), TIME(6000), X(6000), Y(6000)

   READ(5,*)ALEN

   AMAG=4.9162

   J1=40

   N1=0

   NMAX = 6000
C ALEN=original length of specimen at ambient
C J1=number of data over which expansivity is averaged
C AMAG= magnification, with dilatometer set at 10000
C COEFF contain expansion coefficients at temperatures XX
C YY contains length change per unit length at temps X, centigrage

   N = 0

   10 N = N + 1
C X IS TEMPERATURE AND Y IS LENGTH. A IS TIME/100, SES

   READ (5, *, END=20) X(N)

   X(N)=10.01836*X(N)+0.0187719

   B=X(N)

   IF(B .LT. 0.643) GOTO 300

   IF(B .LT. 1.78)GOTO 301

   IF(B .LT. 4.221)GOTO 302

   IF(B .LT. 7.656)GOTO 303

   IF(B .LT. 10.74)GOTO 304

   IF(B .LT. 12.06)GOTO 306
300 B=0.3677+176.4*B-33.57*B*B

   GOTO 305
301 B=10.26+146.0*B-9.573*B*B

   GOTO 305
302 B=32.33+121.2*B-2.485*B*B

   GOTO 305
303 B=44.79+114.7*B-1.591*B*B
```

```
   GOTO 305
304 B=68.41+108.0*B-1.117*B*B
   GOTO 305
306 B=205+83.33*B+8.385E-05*B*B
305 X(N)=B
   READ (5, *, END=20) Y(N)
   Y(N)=Y(N)/(ALEN*AMAG)
   READ (5, *, END=20) TIME(N)
   TIME(N)=TIME(N)/100.0
   IF (N .EQ. NMAX) GOTO 30
   GOTO 10
   20 N = N - 1
C GRST2S(ASPECT) - initialise package and specify the aspect ratio
30 DO 310 I1=1,2000
   IF(I1*J1 .GT. N) GOTO 312
   B1=0.0
   B2=0.0
   B3=0.0
   B4=0.0
   DO 311 J=1,J1
   N1=N1+1
   B1=B1+Y(N1)*X(N1)
   B2=B2+X(N1)
   B3=B3+Y(N1)
   B4=B4+X(N1)*X(N1)
311 CONTINUE
   COEFF(I1)=(J1*B1-B2*B3)/(J1*B4-B2*B2)
   XX(I1)=B2/J1
310 CONTINUE
312 I1=I1-1
   CALL GRST3S(1.0,150.0)
   CALL GRLM2S(0.3,0.9,0.1,0.6)
   CALL GRTY5S(-1,1)
```

```
      CALL GRFT3S(2.5,1.0,0,190,0.0,20)
C GRGR6S(X,Y,N) - draw linear graph of N (X,Y) values

      CALL GRGR6S (X, Y, N)

      CALL GRAN6S('A',0,'Centigrade',10,'Relative Length Change',22)

      CALL GRMS3S(1.0)

      CALL GRLM2S(0.3,0.9,0.1,0.6)

      CALL GRTY5S(-1,1)

      CALL GRFT3S(2.5,1.0,0,190,0.0,20)

      CALL GRGR6S(XX,COEFF,I1)

      CALL GRAN6S('A',0,'Centigrade',10,'Exp. Coeff.',11)

      CALL GRMS3S(1.0)

      CALL GRLM2S(0.3,0.9,0.1,0.6)

      CALL GRTY5S(-1,1)

      CALL GRFT3S(2.5,1.0,0,190,0.0,20)

      CALL GRGR6S(TIME,Y,N)

      CALL GRAN6S('A',0,'Time, Seconds',13,'Relative Length Change',22)

      CALL GRMS3S(1.0)

      CALL GRLM2S(0.3,0.9,0.1,0.6)

      CALL GRTY5S(-1,1)

      CALL GRFT3S(2.5,1.0,0,190,0.0,20)

      CALL GRGR6S(TIME,X,N)

      CALL GRAN6S('A',0,'Time, Seconds',13,'Centigrade',10)
C GRST9S - close package

      CALL GRST9S

      STOP

      END
```

# APPENDIX 3

```
C *****************************************************************
C  PROGRAM  TO  CALCULATE  THE  MAGNIFICATION  FACTOR  FOR
DILATOMETER
C *****************************************************************
C Platinum specimen calibration
C ANOT is the Pt length, ALPHA +BETA*T=expansivity of Pt
C T is temperature in centigrade, initial data from BBC/dilatometer

   DIMENSION YY(1200), X(1200), Y(1200)

   REAL ALPHA, BETA, ANOT, T0, A1, A2

   INTEGER N

   A3=0.0

   NMAX = 1200

   ALPHA=8.8631E-06

   BETA=0.0026E-06

   ANOT=15.24

   T0=26.21

   N = 0

   10 N = N + 1
C X IS TEMPERATURE AND Y IS AAAGTH. A IS TIME/100, SES

   READ (5, *, END=20) X(N)

   X(N)=10.01836*X(N)+0.0187719

   B=X(N)

   IF(B .LT. 0.643) GOTO 300

   IF(B .LT. 1.78)GOTO 301

   IF(B .LT. 4.221)GOTO 302

   IF(B .LT. 7.656)GOTO 303

   IF(B .LT. 10.74)GOTO 304
300 B=0.3677+176.4*B-33.57*B*B

   GOTO 305
301 B=10.26+146.0*B-9.573*B*B

   GOTO 305
302 B=32.33+121.2*B-2.485*B*B

   GOTO 305
303 B=44.79+114.7*B-1.591*B*B
```

```
      GOTO 305
304 B=68.41+108.0*B-1.117*B*B
305 X(N)=B
      READ (5, *, END=20) Y(N)
      IF (N .EQ. 1) GOTO 306
      A1=AAA(X(1),ALPHA,BETA,ANOT)
      A2=AAA(X(N),ALPHA,BETA,ANOT)
      YY(N)=(Y(N)-Y(1))/(A2-A1)
      GOTO 307
306 YY(N)=5.0
307 WRITE(6,311)YY(N),X(N)
311 FORMAT(F8.4,F8.2)
      READ (5, *, END=20)A
      IF (N .EQ. NMAX) GOTO 30
      GOTO 10
      20 N = N - 1
C GRST2S(ASPECT) - initialise package and specify the aspect ratio
30 DO 312 I=1,N
      A3=A3+YY(I)
312 CONTINUE
      A3=A3/N
      WRITE(6,313)A3
313 FORMAT(' AVERAGE MAGNIFICATION=', F12.6)
      CALL GRST3S(1.0,300.0)
      CALL GRLM2S(0.1,0.9,0.1,0.6)
      CALL GRTY5S(-1,1)
      CALL GRFT3S(2.5,1.0,0,190,0.0,50)
C GRGR6S(X,Y,N) - draw linear graph of N (X,Y) values
      CALL GRGR6S (X, YY, N)
C GRST9S - close package
      CALL GRST9S
      STOP
      END
      FUNCTION AAA(T,A,B,ANOT)
```

```
TT=26.21
AAA=A*T + B*T*T/2 + A*A*T*T/2 - A*A*TT*T + A*B*T**3/2
&-A*B*T*T*TT + A*B*TT*TT*T/2 + B*B*T**4/8 -
&B*B*T**3*TT/3 + B*B*T*T*TT*TT/4
AAA=ANOT*AAA
RETURN
END
```

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