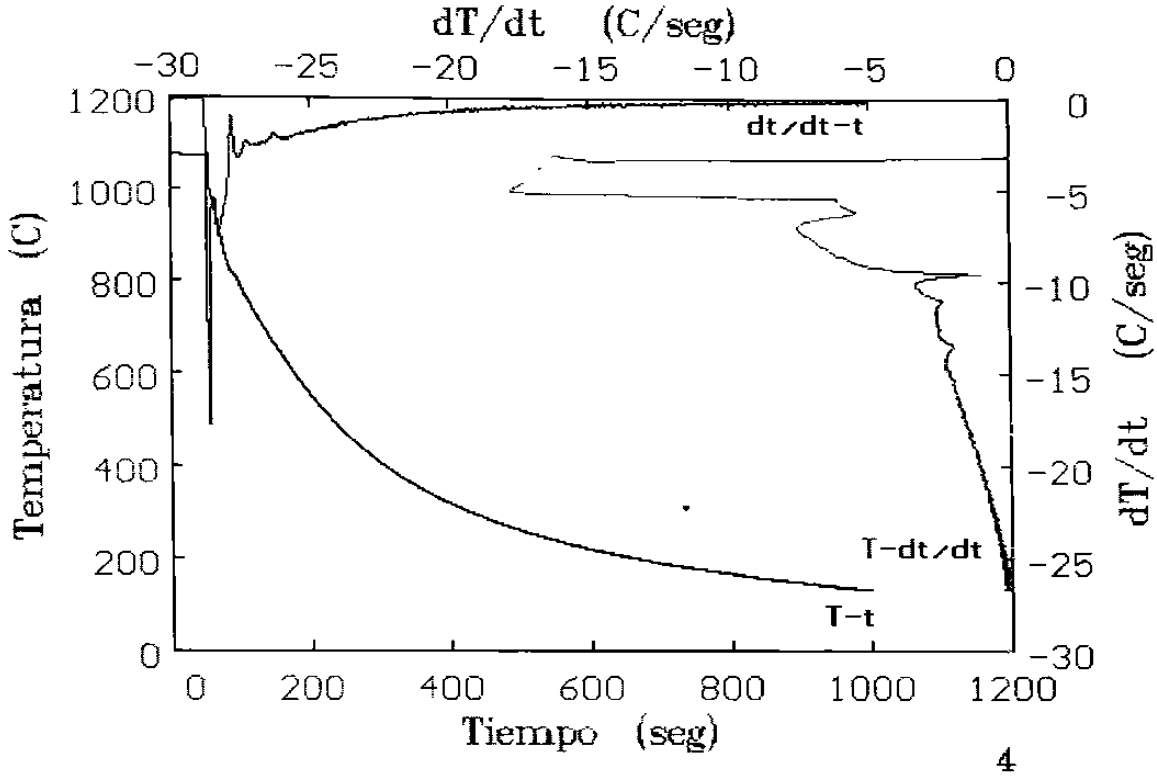
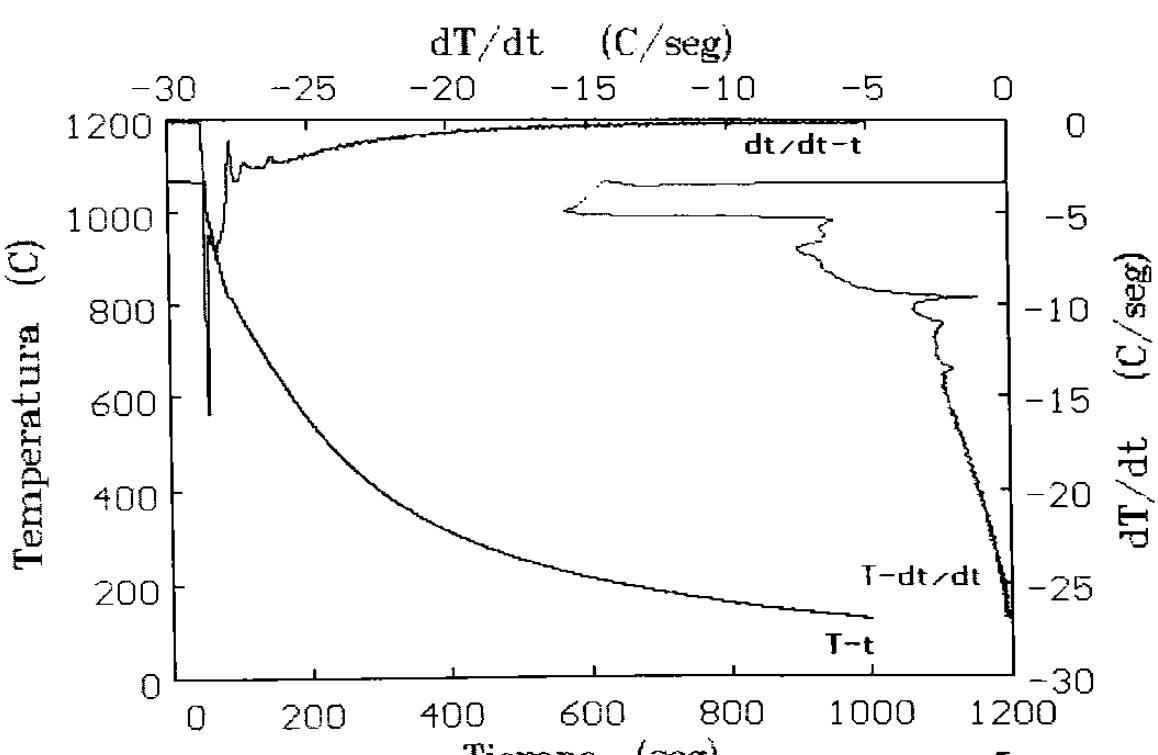
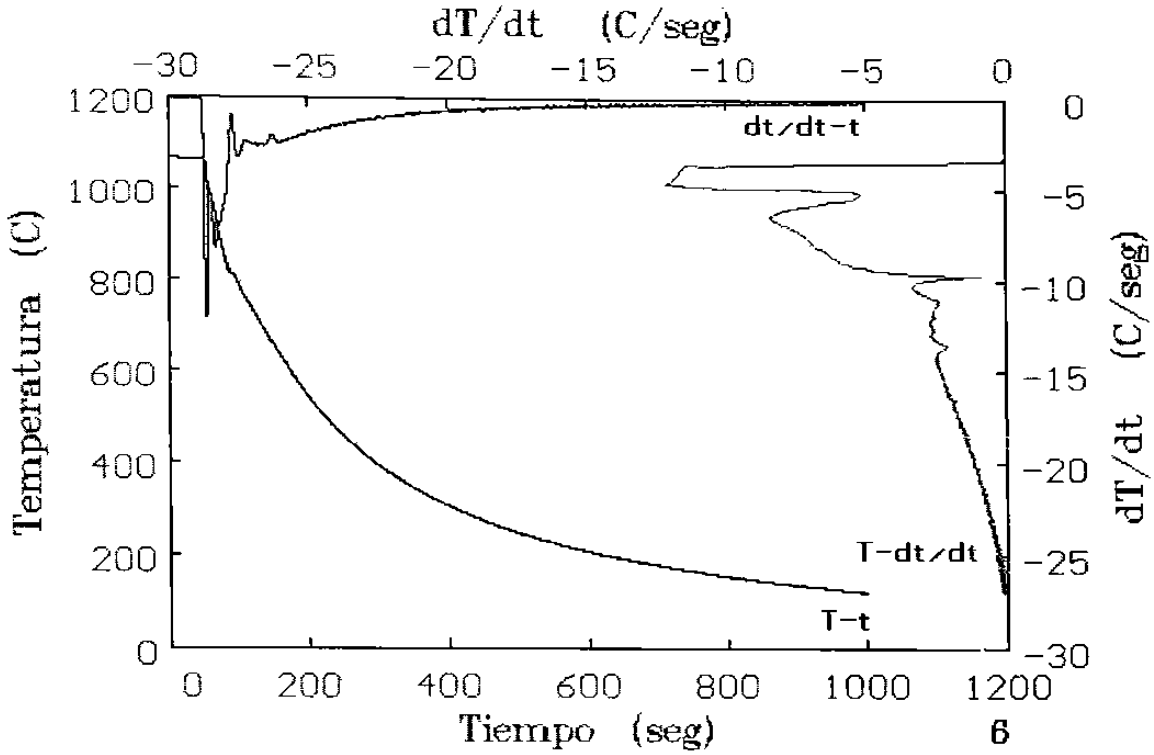

dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt-t
T-dt/dt
T-t
0 -5 -10 -15 -20 -25 -30
dT/dt (C/seg)
0 200 400 600 800 1000 1200
Tiempo (seg)

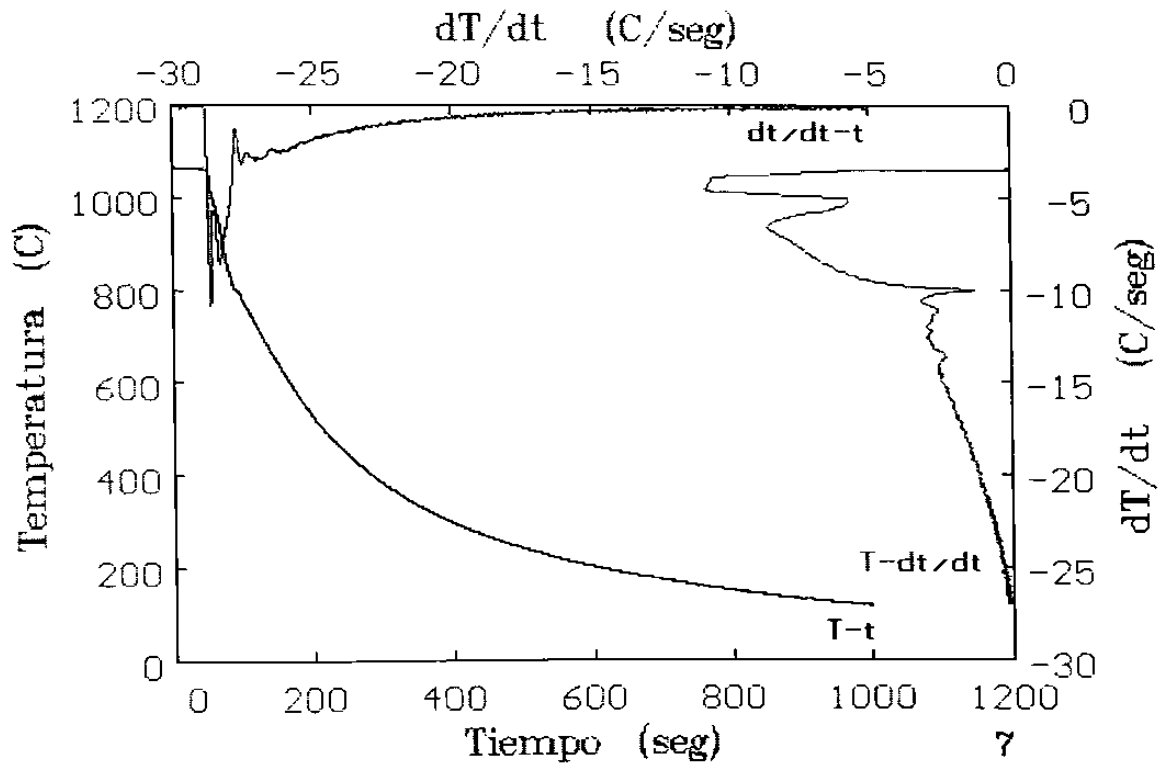
4


dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt-t
T-dt/dt
T-t
0 -5 -10 -15 -20 -25 -30
dT/dt (C/seg)
0 200 400 600 800 1000 1200
Tiempo (seg)

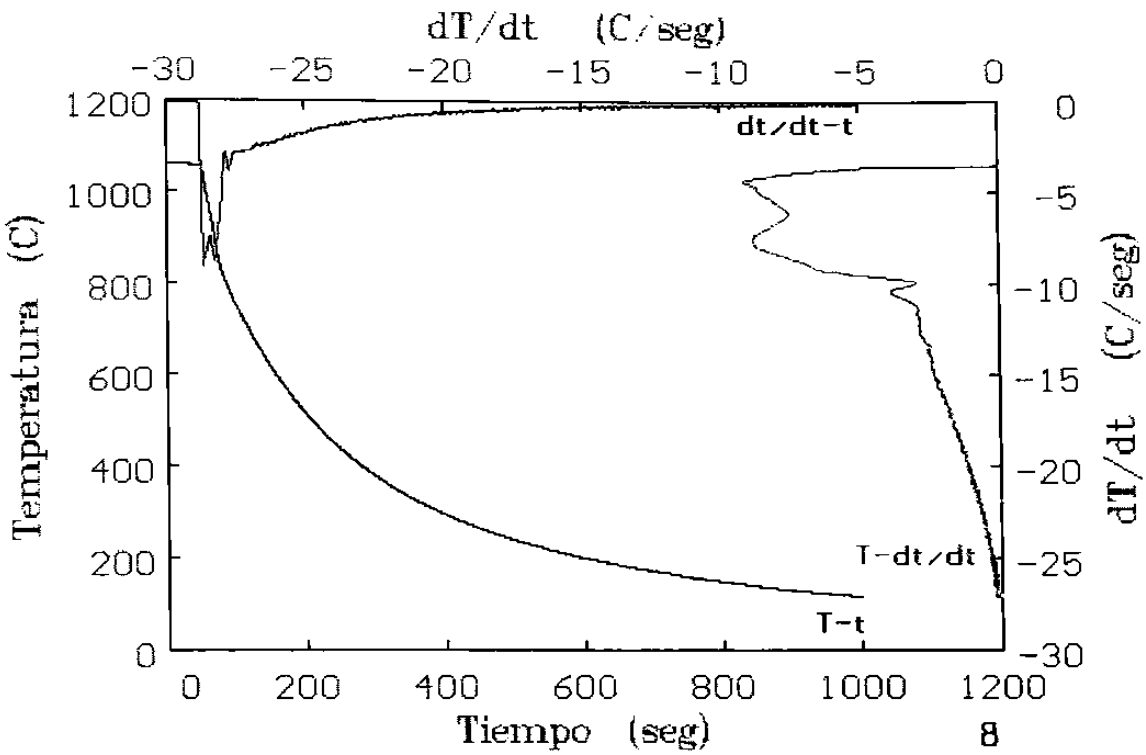
5


dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt-t
T-dt/dt
T-t
0 -5 -10 -15 -20 -25 -30
dT/dt (C/seg)
0 200 400 600 800 1000 1200
Tiempo (seg)

6

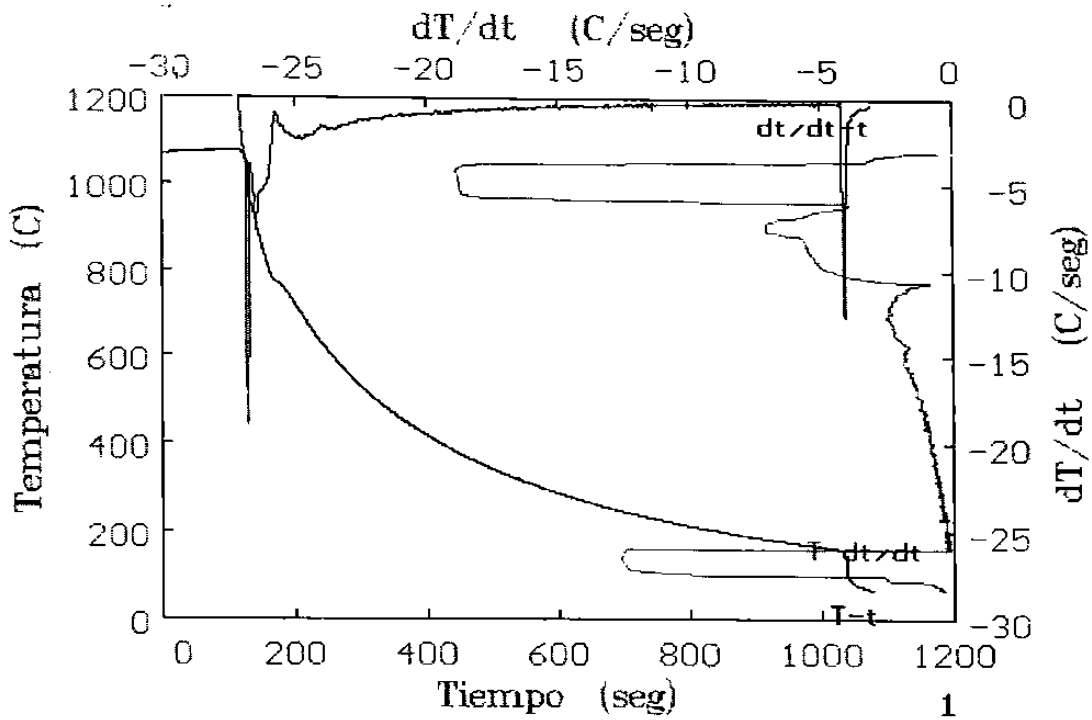

dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt-t
T-dt/dt
T-t
0 -5 -10 -15 -20 -25 -30
dT/dt (C/seg)
0 200 400 600 800 1000 1200
Tiempo (seg)

7

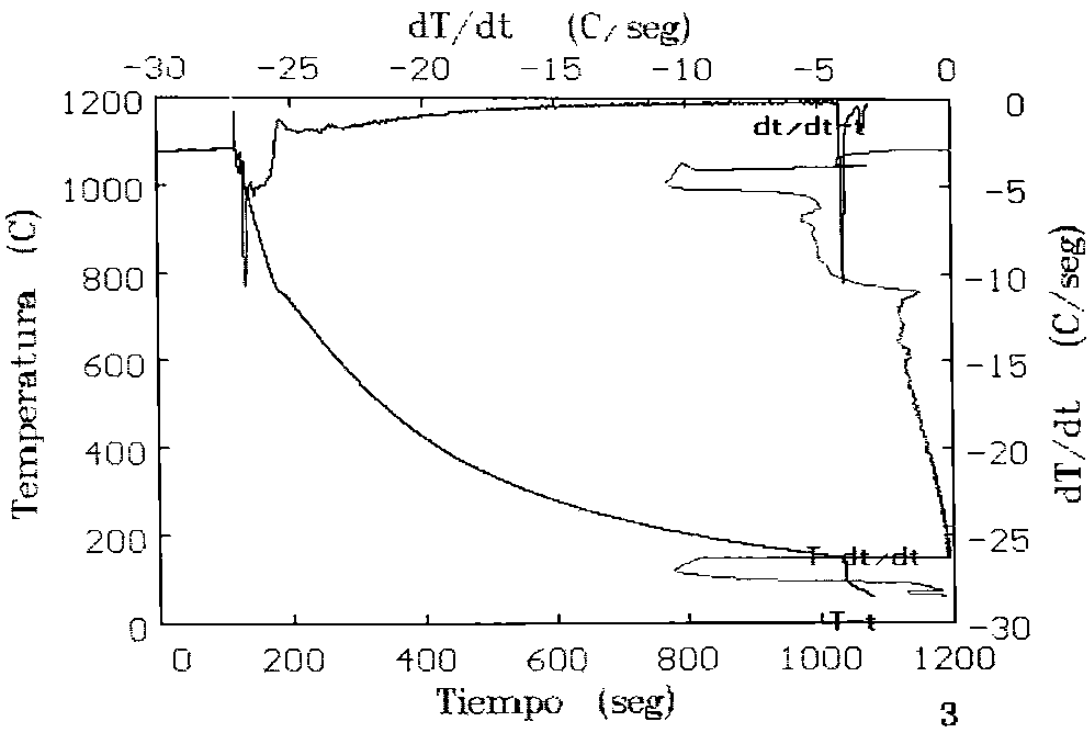

dT/dt (C/seg)
-30
-25
-20
-15
-10
-5
0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt-t
T-dt/dt
T-t
0
-5
-10
-15
-20
-25
-30
dT/dt (C/seg)
0
200
400
600
800
1000
1200
Tiempo (seg)

8

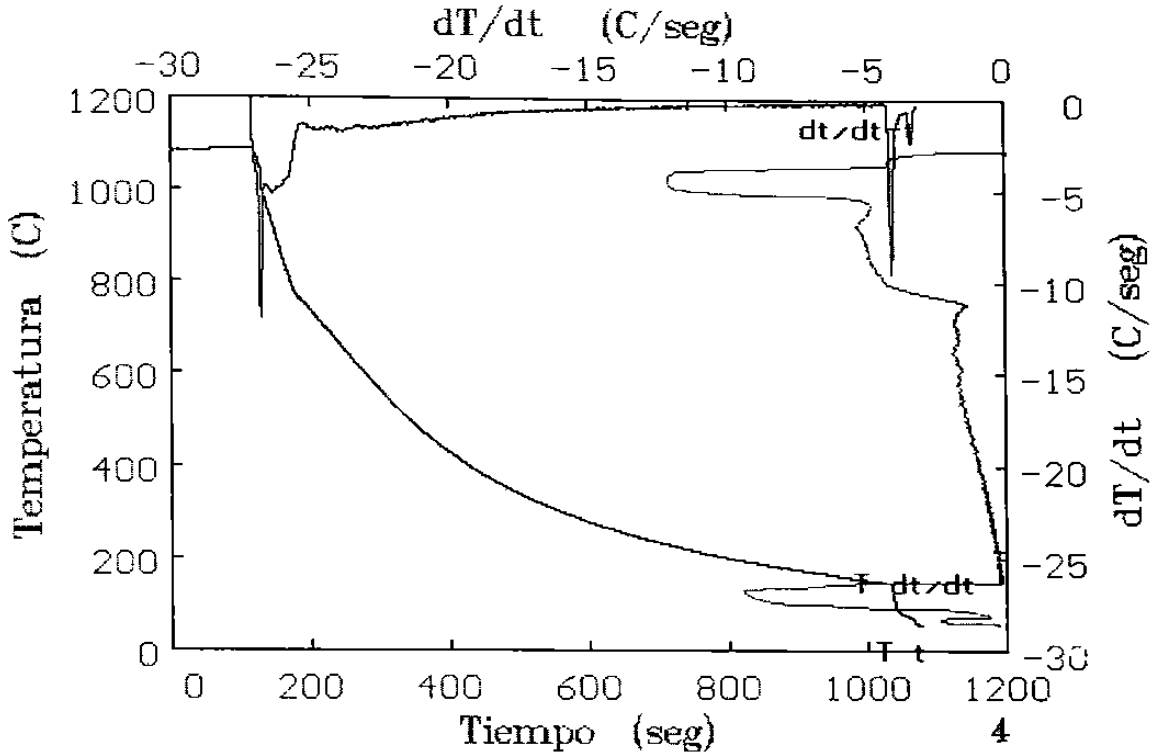
Acero "B"


dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200 1000 800 600 400 200 0
Temperatura (C)
0 -5 -10 -15 -20 -25 -30
dT/dt (C/seg)
dt/dt-t
T-dt/dt
T-t
0 200 400 600 800 1000 1200
Tiempo (seg)

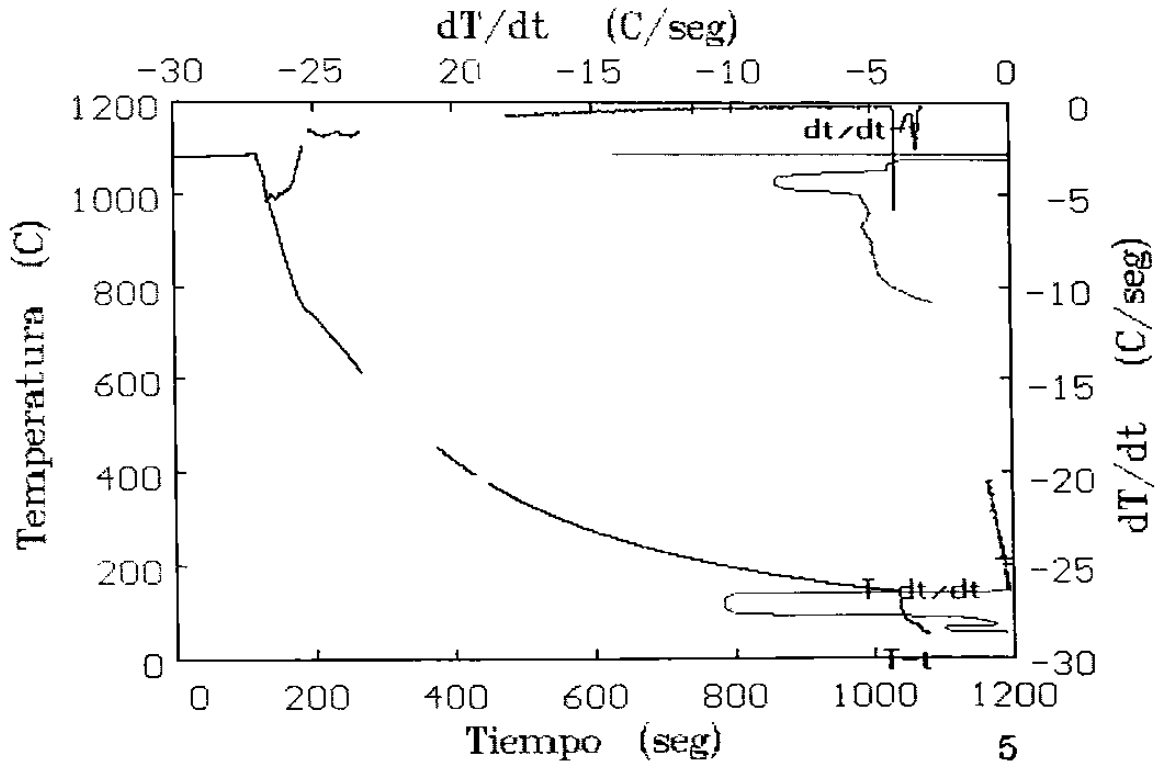
1


dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200 1000 800 600 400 200 0
Temperatura (C)
0 -5 -10 -15 -20 -25 -30
dT/dt (C/seg)
dt/dt-t
T-dt/dt
T-t
0 200 400 600 800 1000 1200
Tiempo (seg)

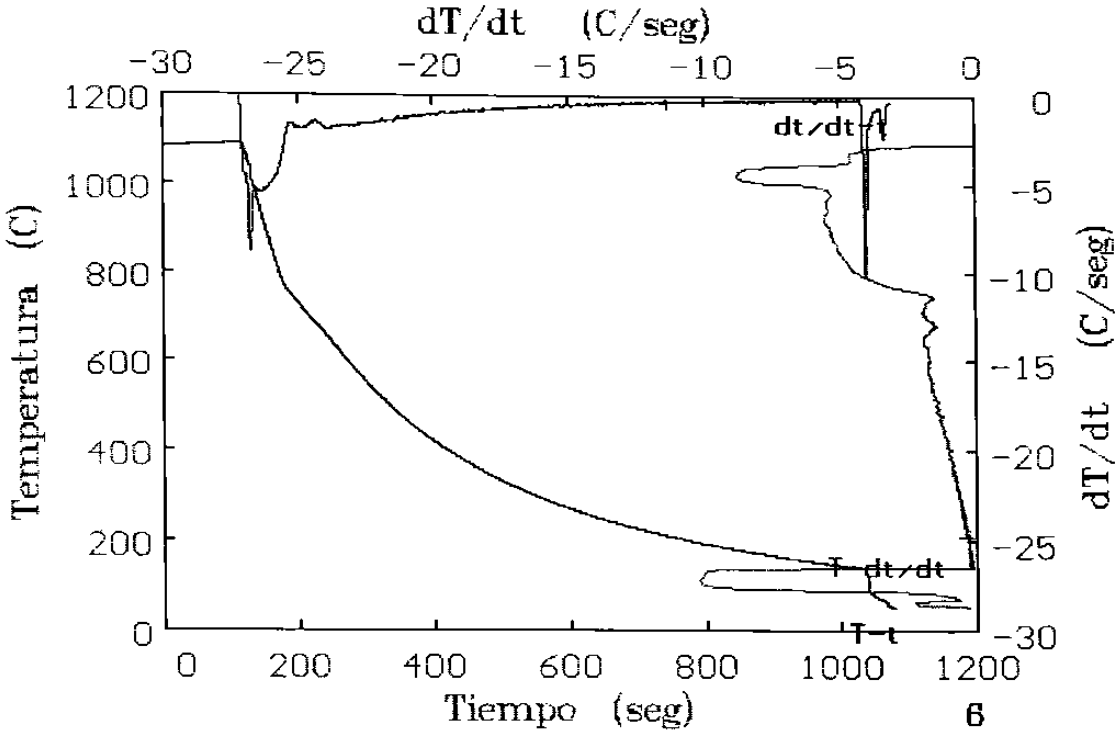
3


dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt
T
dt/dt
T t
0 200 400 600 800 1000 1200
Tiempo (seg)
0
-5
-10
-15
-20
-25
-30
dT/dt (C/seg)

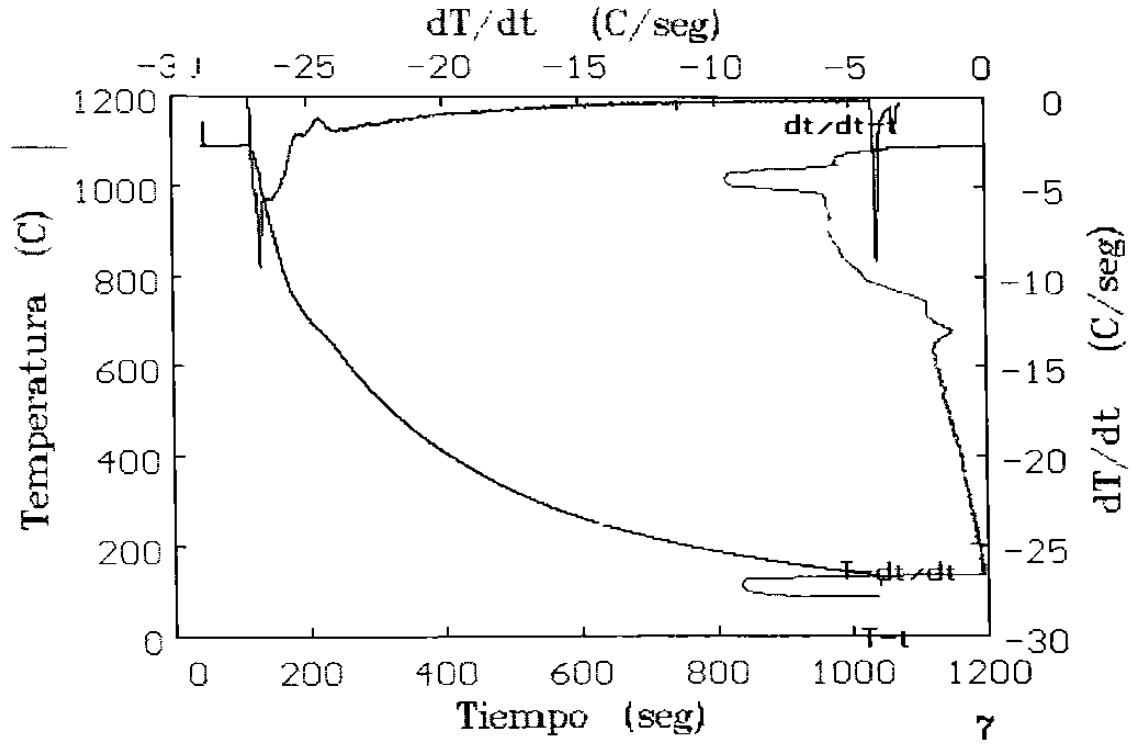
4


dT/dt (C/seg)
-30 -25 20 -15 -10 -5 0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt
T
dt/dt
T t
0 200 400 600 800 1000 1200
Tiempo (seg)
0
-5
-10
-15
-20
-25
-30
dT/dt (C/seg)

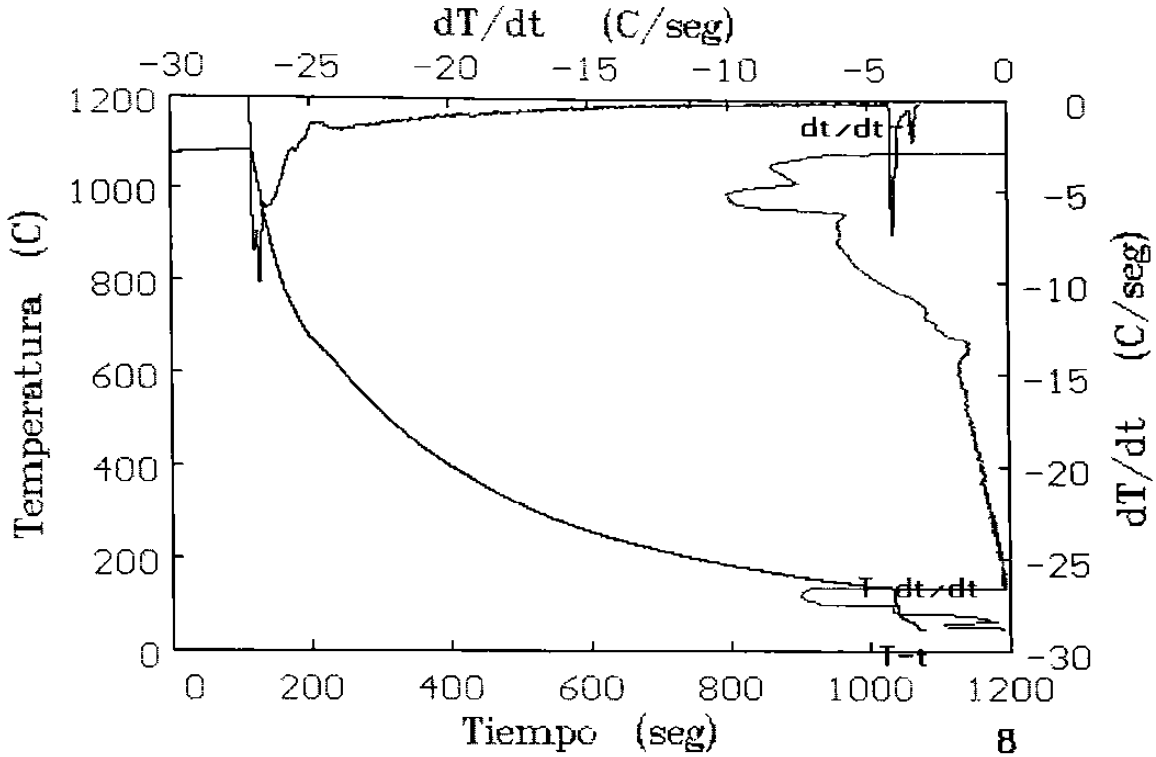
5


dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt
T-dt/dt
T-t
0 200 400 600 800 1000 1200
Tiempo (seg)
0
-5
-10
-15
-20
-25
-30
dT/dt (C/seg)

6

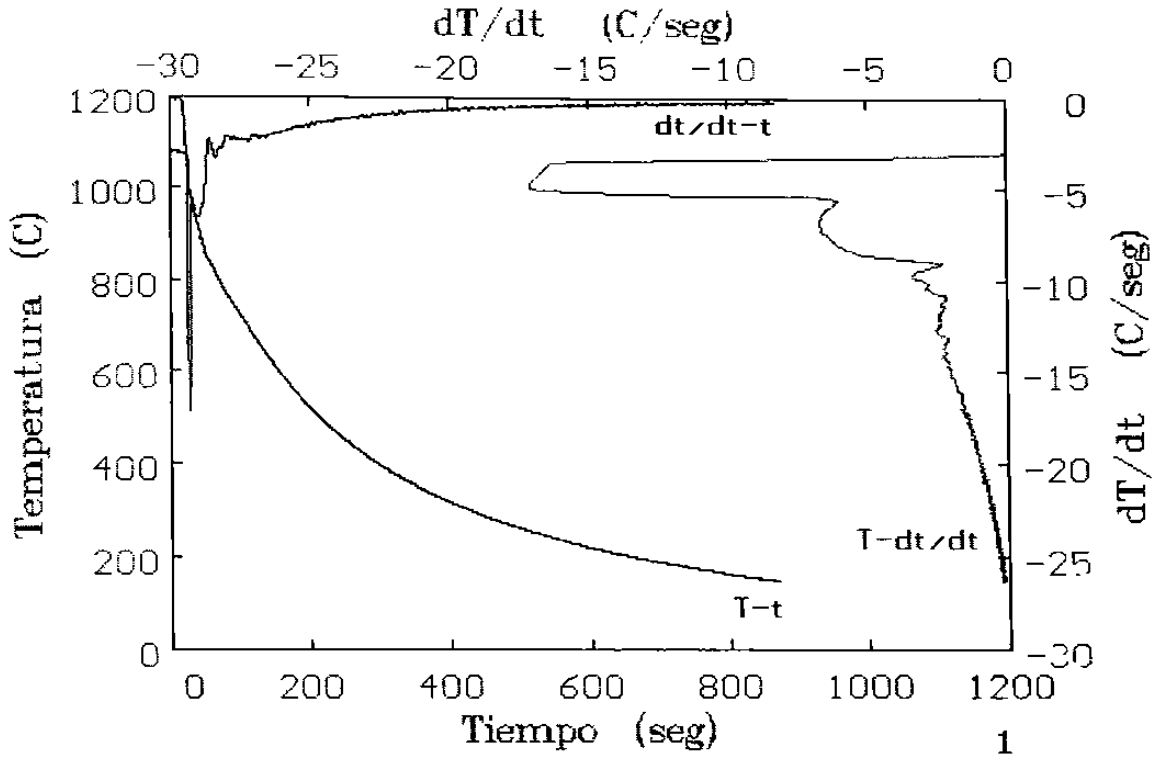

dT/dt (C/seg)
-25 -20 -15 -10 -5 0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt
T-dt/dt
T-t
0 200 400 600 800 1000 1200
Tiempo (seg)
0
-5
-10
-15
-20
-25
-30
dT/dt (C/seg)

7


dT/dt (C/seg)
-30
-25
-20
-15
-10
-5
0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt
T-dt/dt
T-t
0
-5
-10
-15
-20
-25
-30
dT/dt (C/seg)
0
200
400
600
800
1000
1200
Tiempo (seg)

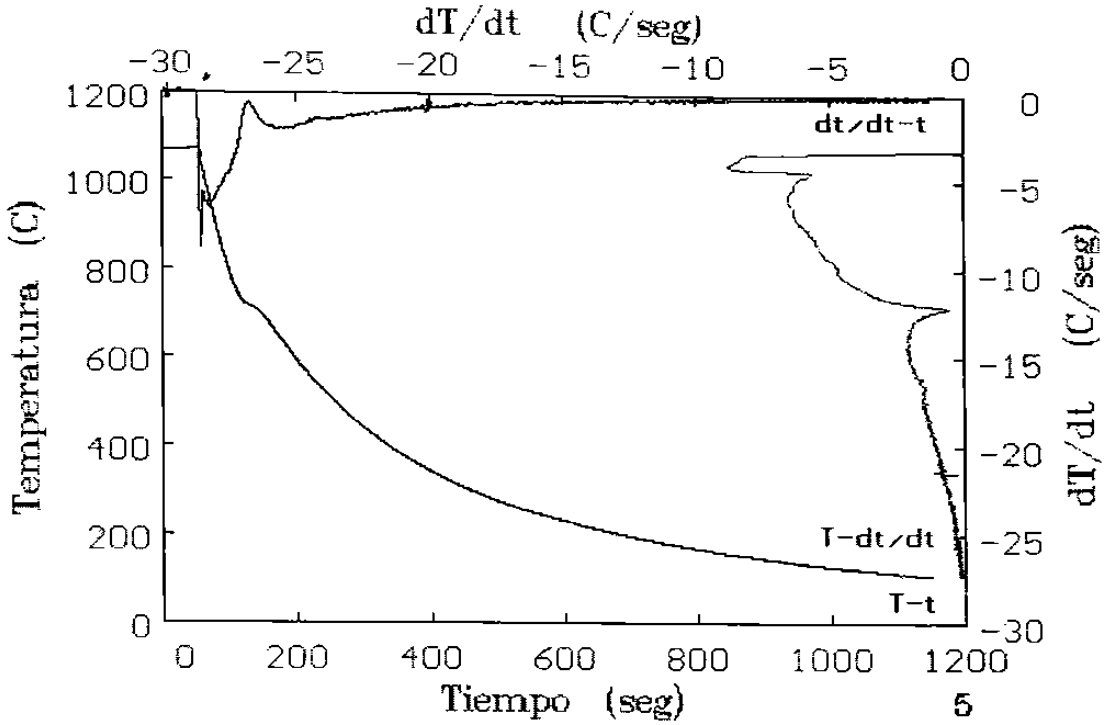
8

Acero "C"

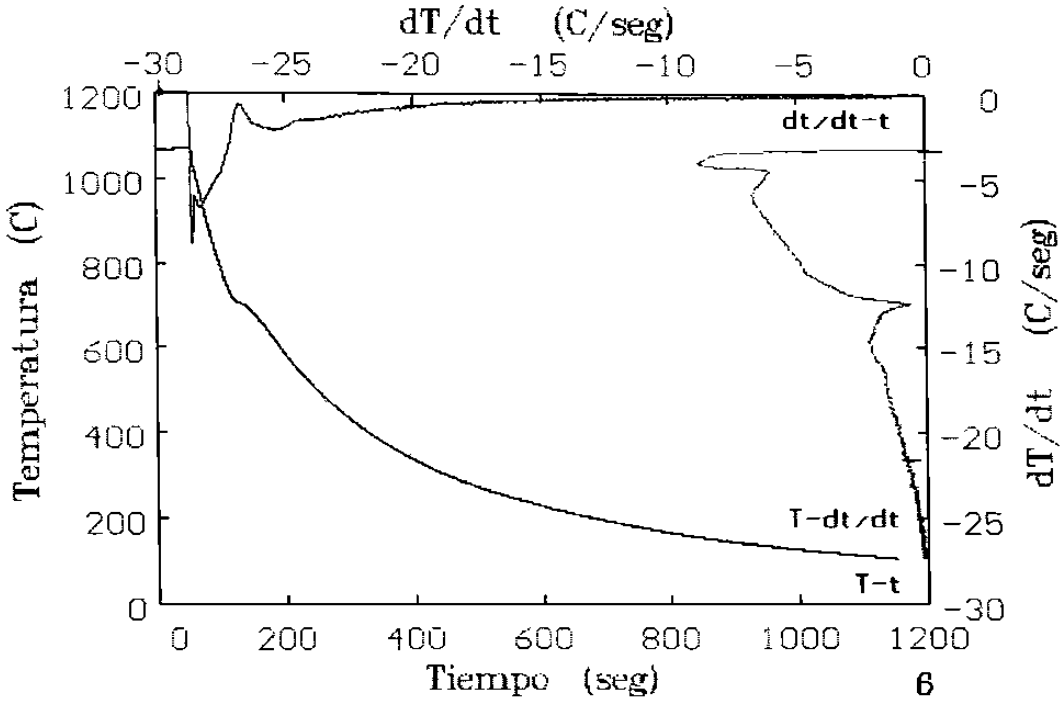

dT/dt (C/seg)
-30
-25
-20
-15
-10
-5
0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt-t
T-dt/dt
T-t
0
-5
-10
-15
-20
-25
-30
dT/dt (C/seg)
0
200
400
600
800
1000
1200
Tiempo (seg)

1

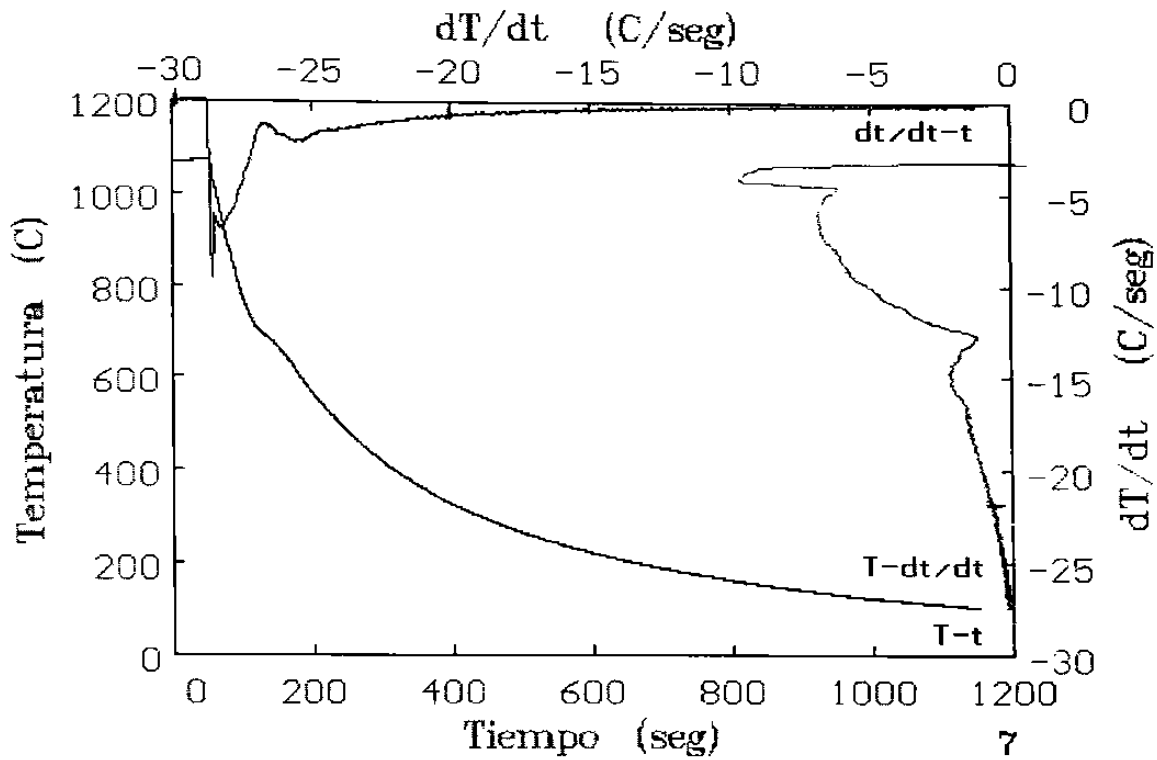
Acero "D"


dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200 1000 800 600 400 200 0
Temperatura (C)
0 -5 -10 -15 -20 -25 -30
dT/dt (C/seg)
dt/dt-t
T-dt/dt
T-t
0 200 400 600 800 1000 1200
Tiempo (seg)

5


dT/dt (C/seg)
-30 -25 -20 -15 -10 -5 0
1200 1000 800 600 400 200 0
Temperatura (C)
0 -5 -10 -15 -20 -25 -30
dT/dt (C/seg)
dt/dt-t
T-dt/dt
T-t
0 200 400 600 800 1000 1200
Tiempo (seg)

6


dT/dt (C/seg)
-30
-25
-20
-15
-10
-5
0
1200
1000
800
600
400
200
0
Temperatura (C)
dt/dt-t
T-dt/dt
T-t
0
-5
-10
-15
-20
-25
-30
dT/dt (C/seg)
0
200
400
600
800
1000
1200
Tiempo (seg)
7

Apéndice A4

Micrografías de la sección transversal de los cuatro aceros.

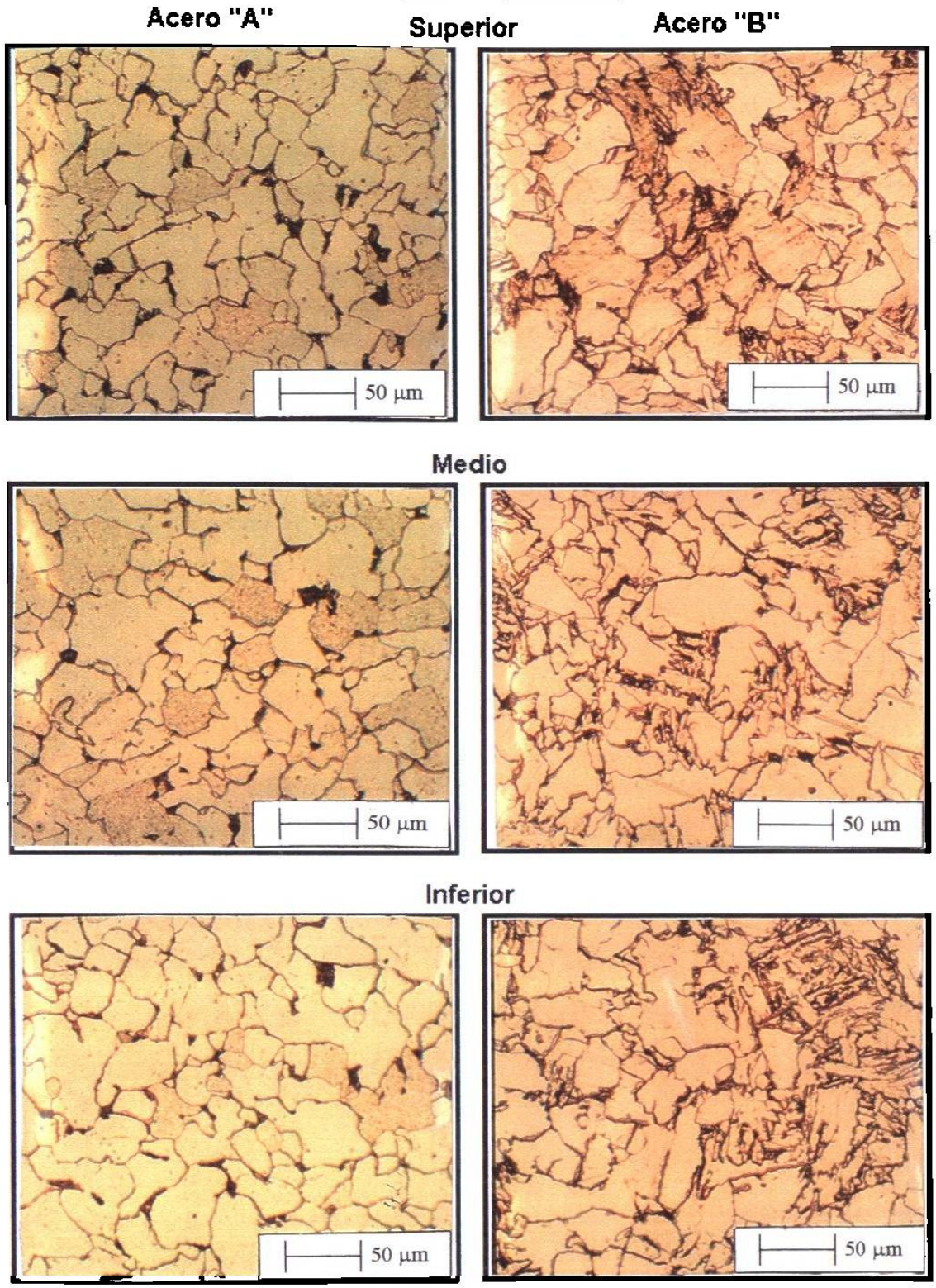


Fig. A.1.- Tamaño de grano ferritico de las muestras laminadas en caliente a 1100°C, ontenidas de la zona sin deformación y enfriadas al aire.

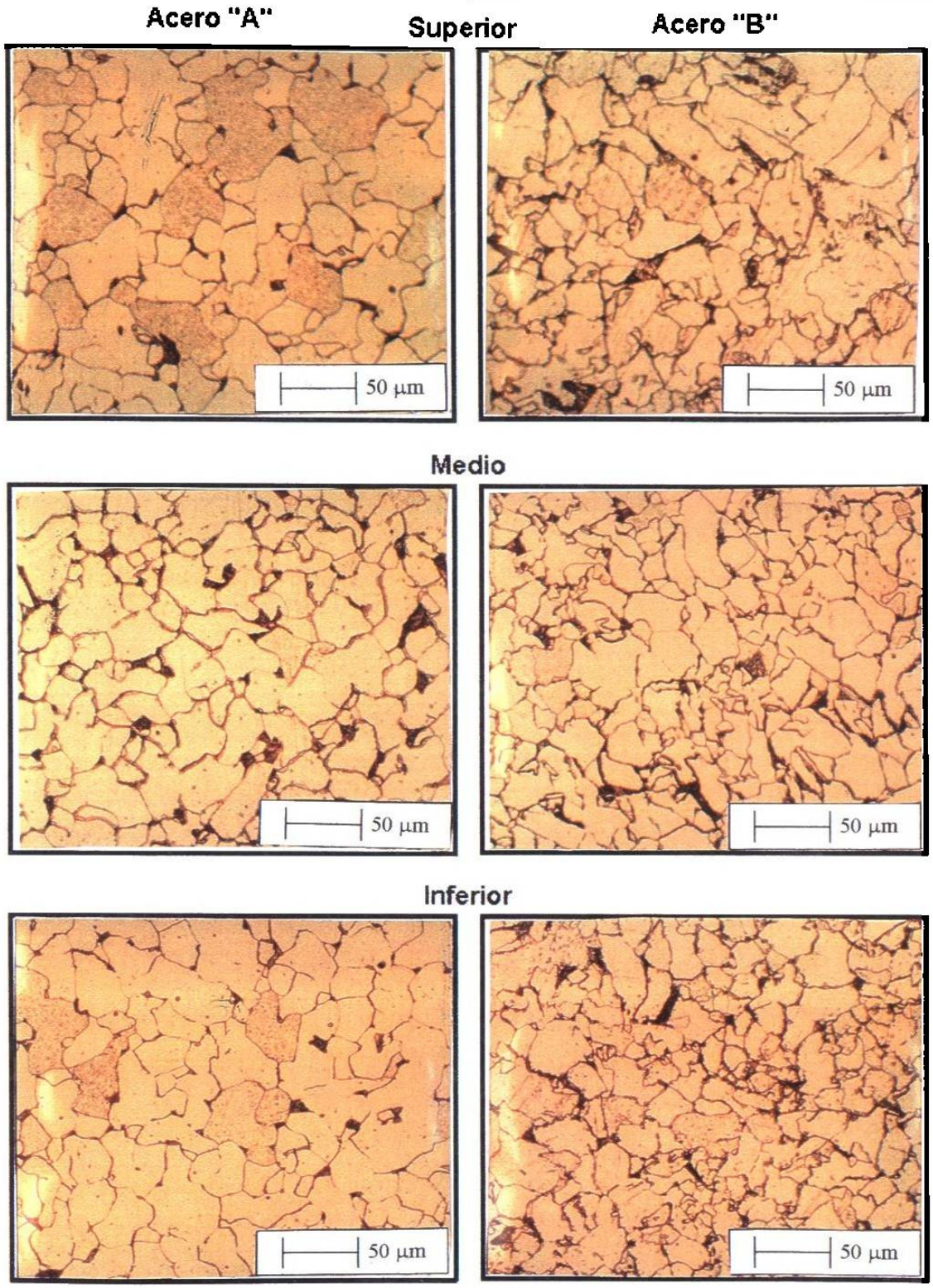


Fig. A.2.- Tamaño de grano ferritico de las muestras laminadas en caliente a 1100°C, con una reducción del 30 % y enfriadas al aire.

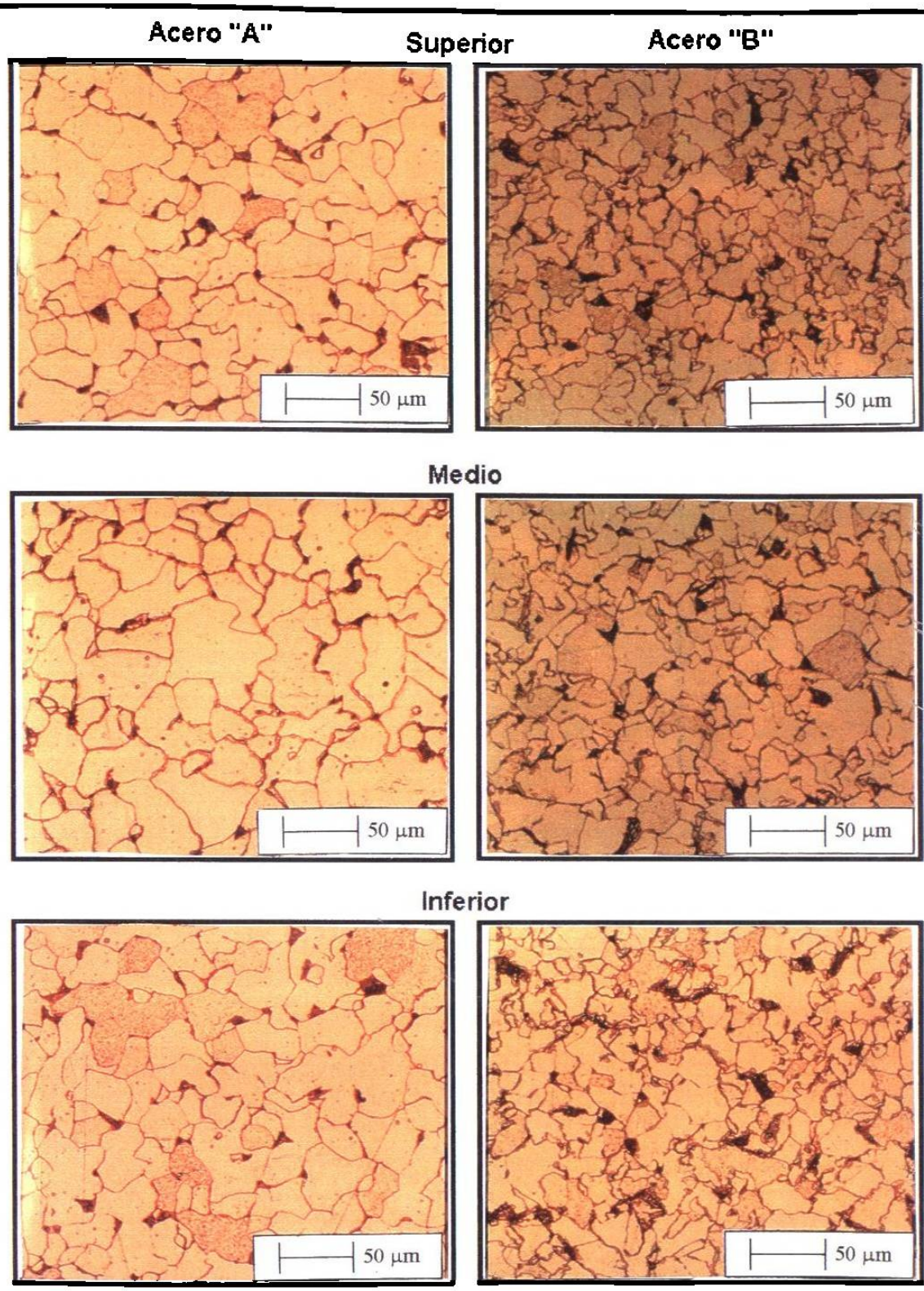


Fig. A.3.- Tamaño de grano ferritico de las muestras laminadas en caliente a 1100°C, con una reducción del 60 % y enfriadas al aire.

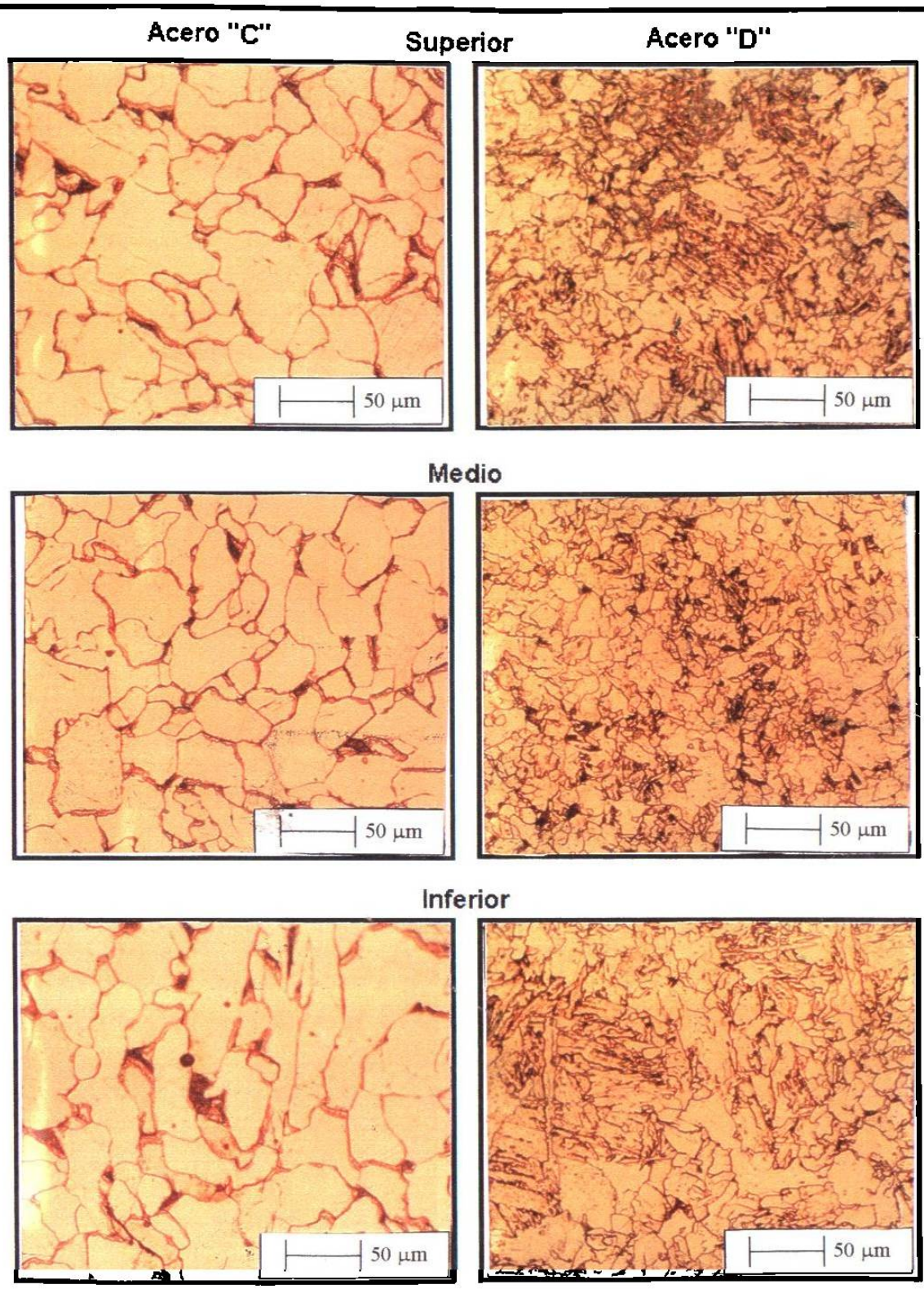


Fig. A.4.- Tamaño de grano ferritico de las muestras laminadas en caliente a 1100°C, ontenidas de la zona sin deformación y enfriadas al aire.

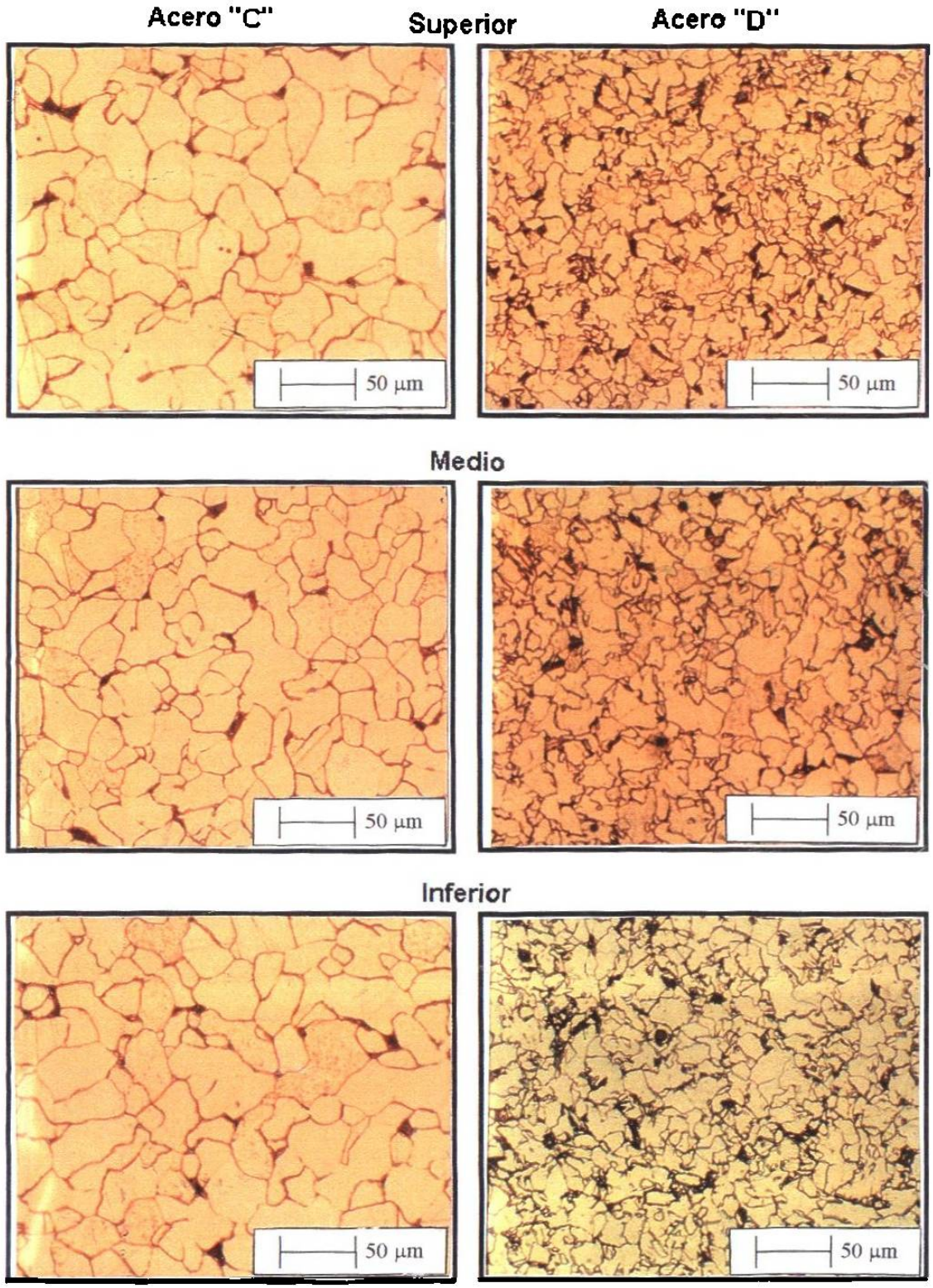


Fig. A.5.- Tamaño de grano ferritico de las muestras laminadas en caliente a 1100°C, con una reducción del 30 % y enfriadas al aire.

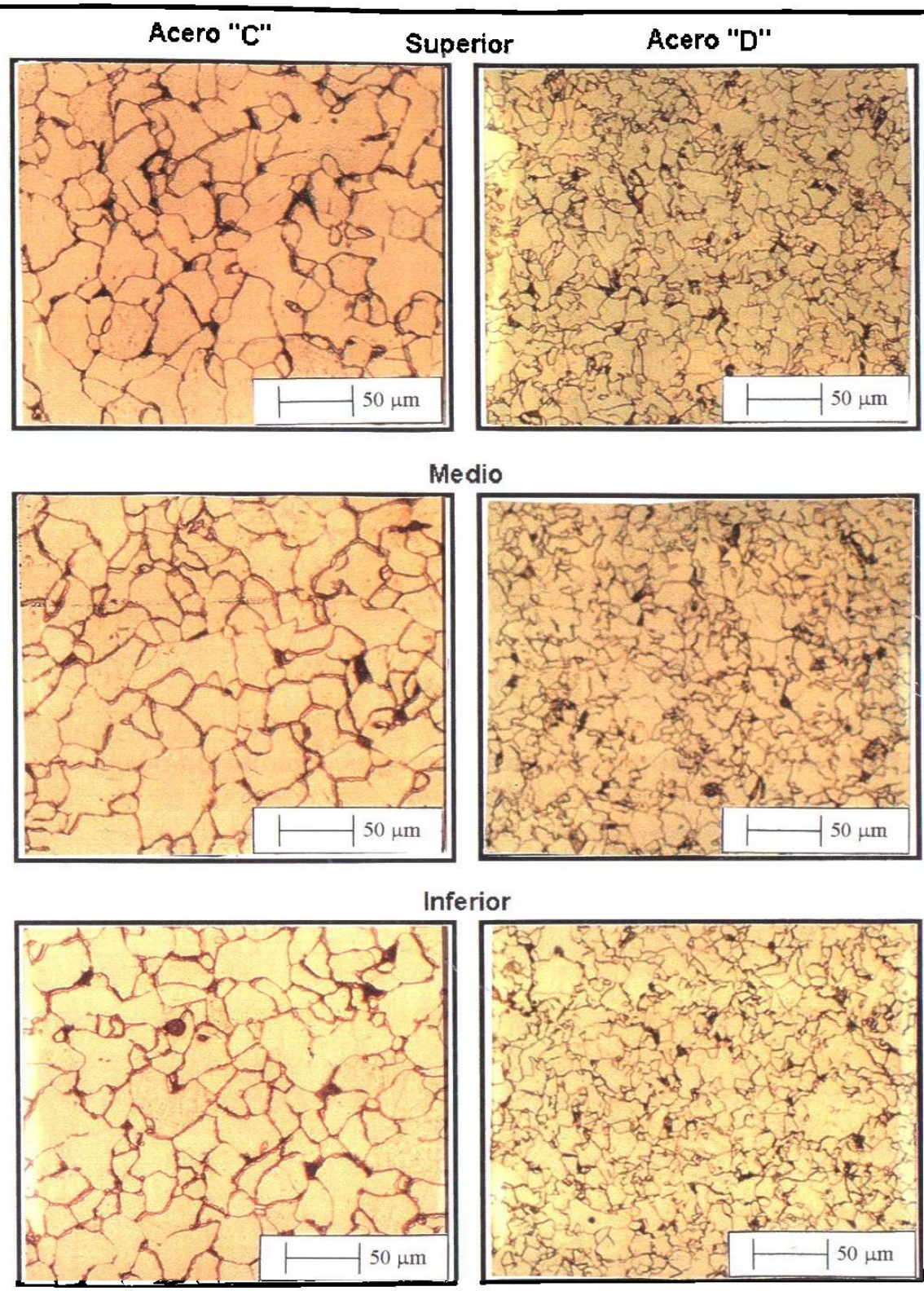
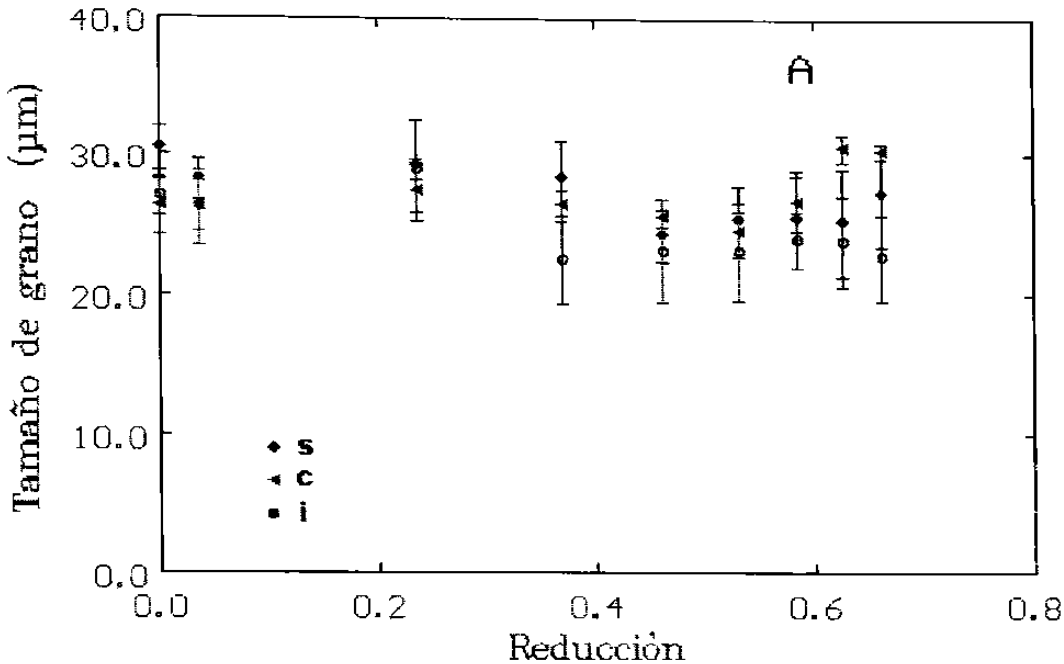


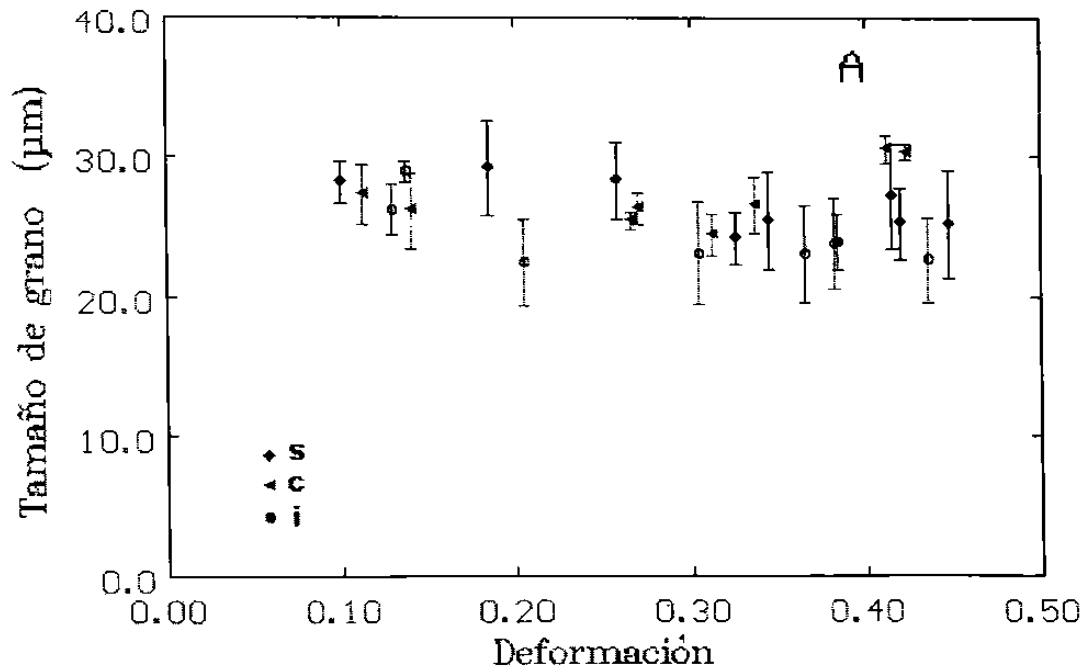
Fig. A.6.- Tamaño de grano ferritico de las muestras laminadas en caliente a 1100°C, con una reducción del 60 % y enfriadas al aire.

Apéndice A5

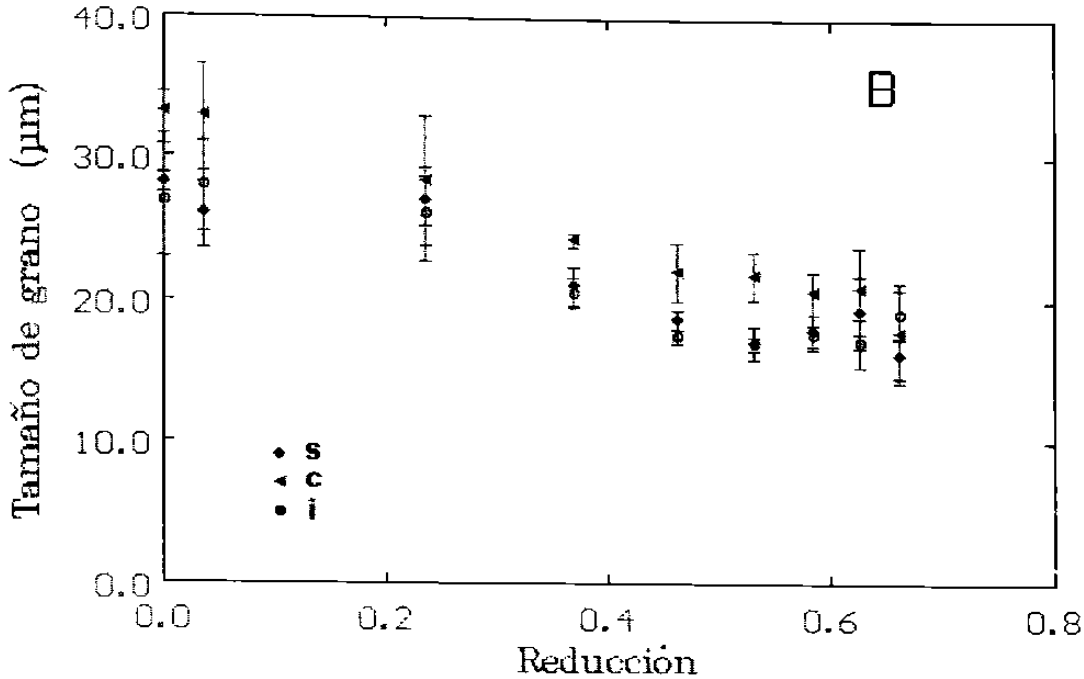
Evolución del tamaño de grano ferrítico registrado en las muestras laminadas.

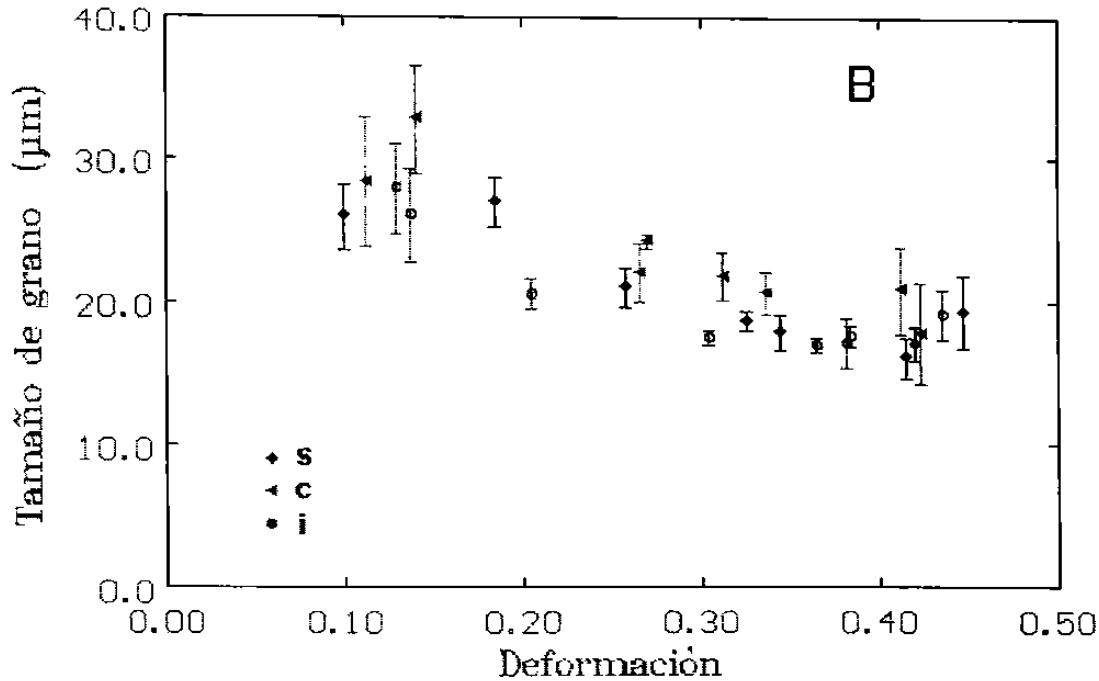
Acero "A"


40.0
30.0
20.0
10.0
0.0
Tamaño de grano (µm)
A
s
c
i
0.0
0.2
0.4
0.6
0.8
Reducción

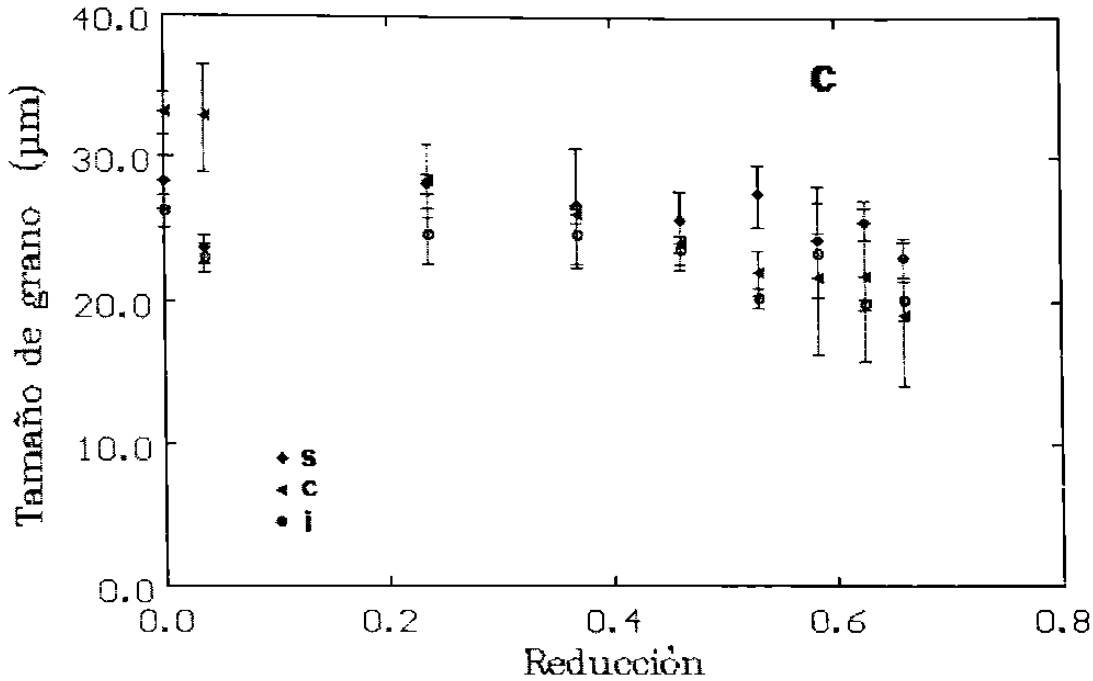

40.0
30.0
20.0
10.0
0.0
Tamaño de grano (µm)
A
s
c
i
0.00
0.10
0.20
0.30
0.40
0.50
Deformación

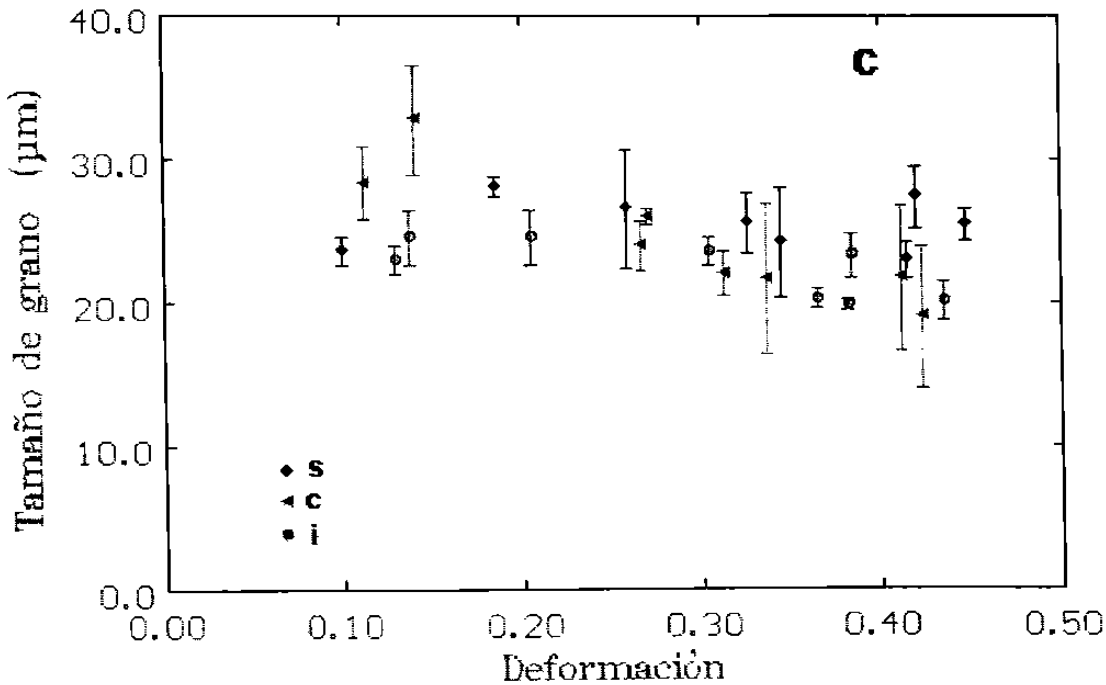
Acero "B"


40.0
30.0
20.0
10.0
0.0
Tamaño de grano (µm)
B
S
C
I
0.0
0.2
0.4
0.6
0.8
Reducción

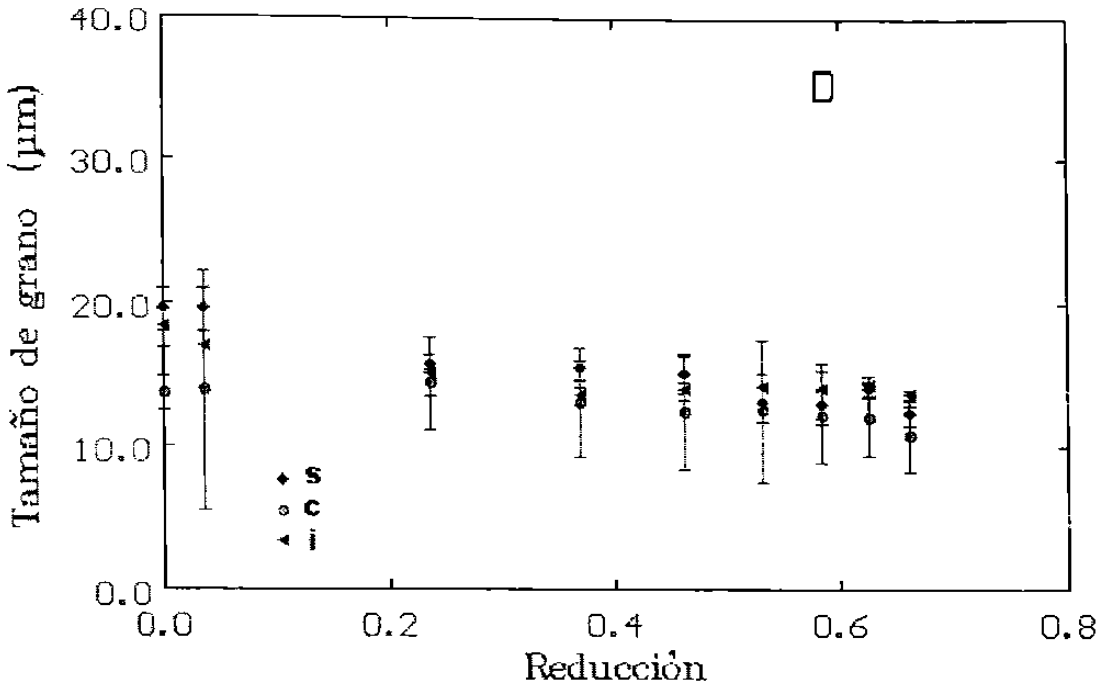

40.0
30.0
20.0
10.0
0.0
Tamaño de grano (µm)
B
S
C
I
0.00
0.10
0.20
0.30
0.40
0.50
Deformación

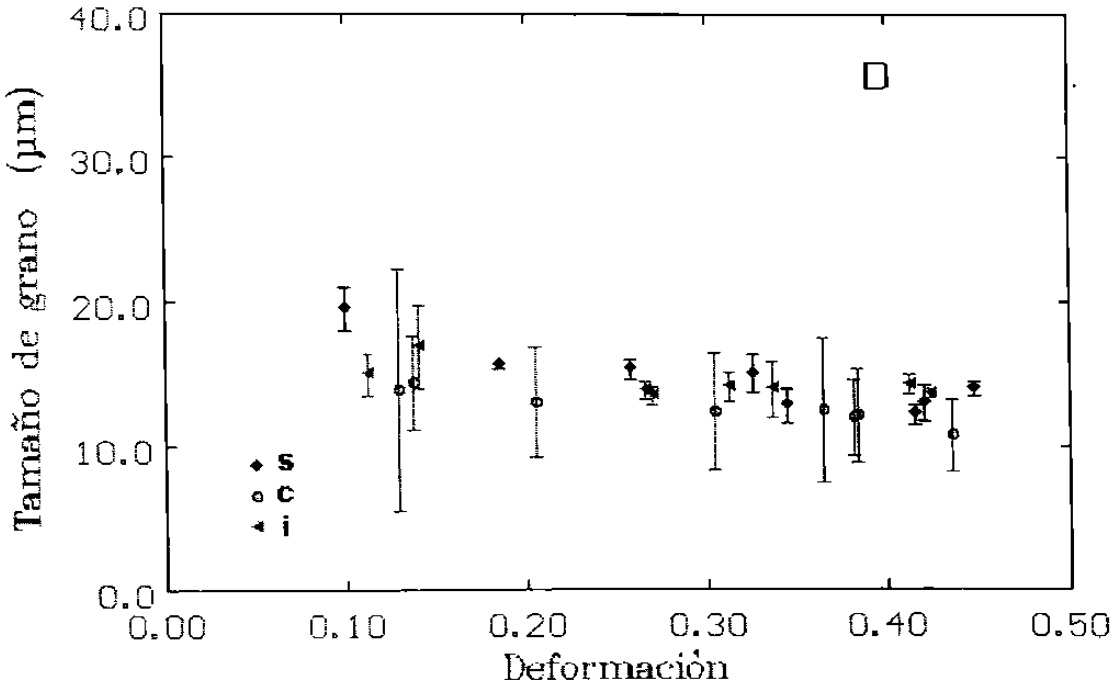
Acero "C"


40.0
30.0
20.0
10.0
0.0
Tamaño de grano (µm)
C
s
c
i
0.0
0.2
0.4
0.6
0.8
Reducción


40.0
30.0
20.0
10.0
0.0
Tamaño de grano (µm)
C
s
c
i
0.00
0.10
0.20
0.30
0.40
0.50
Deformación

Acero "D"


40.0
30.0
20.0
10.0
0.0
Tamaño de grano (µm)
0.0
0.2
0.4
0.6
0.8
Reducción
S
C
i


40.0
30.0
20.0
10.0
0.0
Tamaño de grano (µm)
0.00
0.10
0.20
0.30
0.40
0.50
Deformación
S
C
i

Apéndice "A6"

Temperaturas de transformación calculadas

Acero "A"

Elemento	Composición
C	0.0540
S	0.0080
P	0.0080
Mn	0.186
Si	0.027
Ni	0.002
Mo	0.001
Cu	0.007
Ti	0.001
Nb	0.003
Al	0.031

Transform. de austenita a perlita (A1) y ferrita (A3)

Andrews: Ac1 = 721.8 C Ac3 = 864.0 C
Kasatkin y coautores: Ac1 = 725.7 C Ac3 = 895.9 C

Transformación a martensita.

Payson y Savage: Ms = 461.0 C
Carapella: Ms = 455.7 C
Rowland y Lyle: Ms = 460.1 C
Grange y Stewart: Ms = 496.8 C
Nehrenberg: Ms = 461.9 C
Steven y Haynes: Ms = 529.2 C
Temperatura a (según Steven y Haynes):
10% = 519.2 C
50% = 482.2 C
90% = 426.2 C
99% = 314.2 C
Andrews (lineal): Ms = 510.5 C
Andrews (producto): Ms = 487.4 C

Transformación a bainita (Steven y Haynes).

Inicio (Bs) = 798.5 C
Temperatura a la que se transforma 50% de bainita (B50) = 738.5 C
Temperatura de fin de bainita (Bf) = 738.5 C

Tiempo máximo permisible para obtener (Kunitake y Ohtani):
martensita: 0.0 seg
bainita (sin ferrita ni perlita): 0.03 seg
ferrita y bainita o martensita (sin perlita): 0.25 seg

Acero "B"

Elemento	Composición
C	0.0490
S	0.0100
P	0.0120
Mn	0.765
Si	0.025
Ni	0.002
Mo	0.009
Cu	0.010
Ti	0.002
Nb	0.021
Al	0.029

Transform. de austenita a perlita (A1) y ferrita (A3)

Andrews: Ac1 = 715.4 C Ac3 = 866.4 C
Kasatkin y coautores: Ac1 = 722.1 C Ac3 = 886.5 C

Transformación a martensita.

Payson y Savage: Ms = 443.2 C
Carapella: Ms = 430.7 C
Rowland y Lyle: Ms = 442.4 C
Grange y Stewart: Ms = 475.8 C
Nehrenberg: Ms = 444.1 C
Steven y Haynes: Ms = 512.3 C
Temperatura a (según Steven y Haynes):
10% = 502.3 C
50% = 465.3 C
90% = 409.3 C
99% = 297.3 C
Andrews (lineal): Ms = 494.9 C
Andrews (producto): Ms = 487.5 C

Transformación a bainita (Steven y Haynes).

Inicio (Bs) = 747.1 C
Temperatura a la que se transforma 50% de bainita (B50) = 687.1 C
Temperatura de fin de bainita (Bf) = 687.1 C

Tiempo máximo permisible para obtener (Kunitake y Ohtani):
martensita: 0.1 seg
bainita (sin ferrita ni perlita): 0.12 seg
ferrita y bainita o martensita (sin perlita): 1.74 seg

Acero "C"

Elemento	Composición
C	0.0620
S	0.0020
P	0.0110
Mn	0.569
Si	0.401
Cr	0.022
Ni	0.029
Mo	0.017
Cu	0.092
Ti	0.007
Nb	0.005
Al	0.172
B	0.0022

Transform. de austenita a perlita (A1) y ferrita (A3)

Andrews: Ac1 = 728.3 C Ac3 = 877.5 C
Kasatkin y coautores: Ac1 = 736.1 C Ac3 = 900.7 C
Transformación a martensita.

Payson y Savage: Ms = 440.3 C
Carapella: Ms = 428.5 C
Rowland y Lyle: Ms = 439.3 C
Grange y Stewart: Ms = 477.1 C
Nehrenberg: Ms = 441.5 C
Steven y Haynes: Ms = 511.6 C
Temperatura a (según Steven y Haynes):
10% = 501.6 C
50% = 464.6 C
90% = 408.6 C
99% = 296.6 C
Andrews (lineal): Ms = 494.6 C
Andrews (producto): Ms = 481.8 C

Transformación a bainita (Steven y Haynes).

Inicio (Bs) = 758.0 C
Temperatura a la que se transforma 50% de bainita (B50) = 698.0 C
Temperatura de fin de bainita (Bf) = 698.0 C

Tiempo máximo permisible para obtener (Kunitake y Ohtani):
martensita: 0.1 seg
bainita (sin ferrita ni perlita): 0.09 seg
ferrita y bainita o martensita (sin perlita): 0.50 seg

Acero "D"

Elemento	Composición
C	0.0610
S	0.0040
P	0.0120
Mn	1.270
Si	0.063
Cr	0.005
Ni	0.008
Mo	0.018
Cu	0.035
Ti	0.045
Nb	0.057
Al	0.030

Transform. de austenita a perlita (A1) y ferrita (A3)

Andrews: Ac1 = 711.1 C Ac3 = 863.1 C
Kasatkin y coautores: Ac1 = 717.5 C Ac3 = 881.1 C

Transformación a martensita.

Payson y Savage: Ms = 421.8 C
Carapella: Ms = 403.2 C
Rowland y Lyle: Ms = 420.8 C
Grange y Stewart: Ms = 451.3 C
Nehrenberg: Ms = 422.9 C
Steven y Haynes: Ms = 489.6 C
Temperatura a (según Steven y Haynes):
10% = 479.6 C
50% = 442.6 C
90% = 386.6 C
99% = 274.6 C
Andrews (lineal): Ms = 474.3 C
Andrews (producto): Ms = 479.4 C

Transformación a bainita (Steven y Haynes).

Inicio (Bs) = 697.1 C
Temperatura a la que se transforma 50% de bainita (B50) = 637.1 C
Temperatura de fin de bainita (Bf) = 637.1 C

Tiempo máximo permisible para obtener (Kunitake y Ohtani):
martensita: 0.2 seg
bainita (sin ferrita ni perlita): 0.48 seg

ferrita y bainita o martensita (sin perlita): 9.26 seg

Referencias:

K.W. Andrews: J. Iron Steel Inst. 203(1965) 721
L.A. Carapella: Met. Progr. 46(1944)108
R.A. Grange y C.H. Savage: Trans. AIME 167(1946) 467
O.G. Kasatkin, B.B. Vinokur y V.L. Pilyushenko: Met. Sci. Heat Treat. 26(1984) 27
T. Kunitake y H. Ohtani: Sumitomo Search, Nov. 1979, 18
E.H. Nehrenberg: Trans. AIME 167(1946) 494
P. Payson y C.H. Savage: Trans. ASM 33(1944) 261
E.S. Rowland y S.R. Lyle: Trnas. ASM 37(1946) 27
W. Steven y A.G. Haynes: J. Iron Steel Inst. 183(1956) 349