STEEL 212. 0,3 % C Cr Ni Mo LOW ALLOY STEEL

Designations

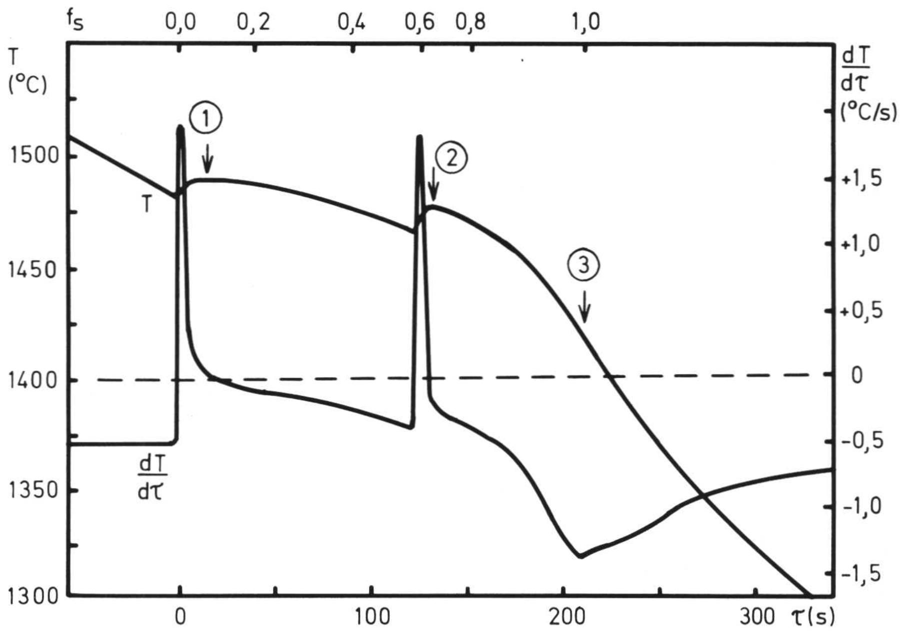
SIS	AISI	Werkstoff Nr
2534	–	–

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Al_{tot}	N
0,29	0,22	0,52	0,009	0,010	1,02	3,2	0,25	0,05	0,03	0,010	0,005

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate, R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, austenitic primary phase, °C	1486	–	–
Liquidus temperature, ferritic primary phase, °C (1)	–	1487	1486
Temperature of austenite formation, °C (2)	–	1478	1477
Solidus temperature, °C (3)	1415	1425	1435
Solidification range, °C	70	60	50
Solidification time, s	80	220	650

Precipitates

–

Microsegregation

Element	Cr	Ni	Mo
I	1,7	1,4	2,2

R = 0,5 °C/s
Tq = 1360 °C

Partly solidified

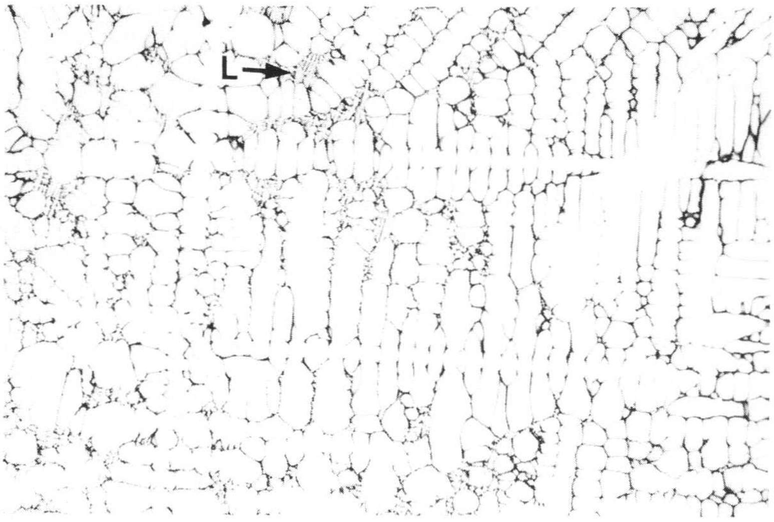


Figure 1
R = 0,5°C/s
Tq = 1480°C
d = 70 μm
δ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

Figure 2
R = 2,0°C/s
Tq = 1360°C
d = 75 μm
γ-dendrites.
(Note: primary γ at this cooling rate.)

400 μm × 25

Figure 3
R = 0,5°C/s
Tq = 1360°C
d = 110 μm
Figures 3–4: Former δ-dendrites, transformed to γ by the peritectic reaction.

400 μm × 25

Figure 4
R = 0,1°C/s
Tq = 1360°C
d = 180 μm

400 μm × 25

STEEL 213. 0,35 % C Cr Mo LOW ALLOY STEEL

Designations

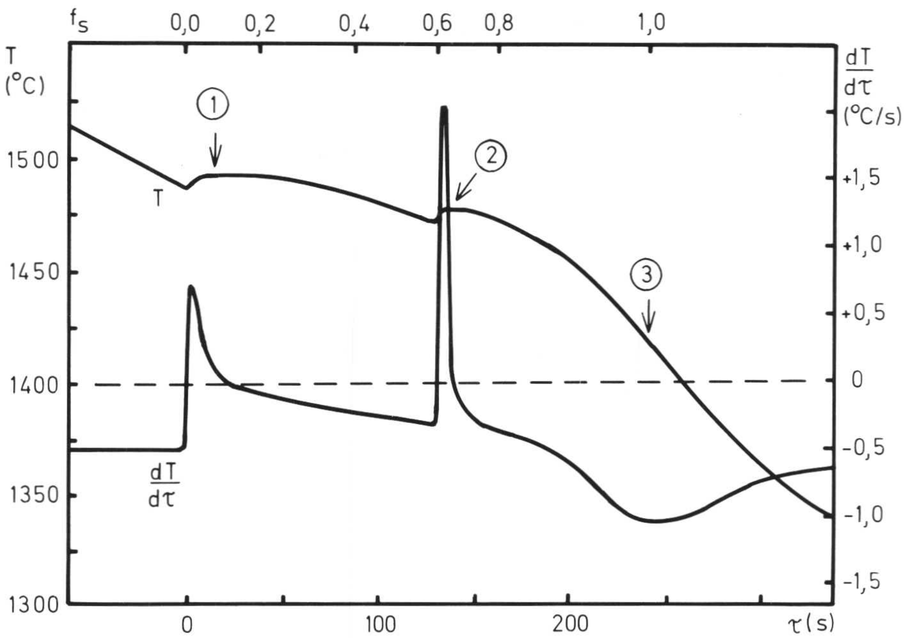
SIS	AISI	Werkstoff Nr
2234	4135	1.7220

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Al_{tot}	N
0,35	0,24	0,67	0,010	0,020	0,92	0,05	0,19	0,07	0,02	0,004	0,008

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate, R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1494	1493	1495
Temperature of austenite formation, °C (2)	1479	1474	1480
Solidus temperature, °C (3)	1405	1415	1425
Solidification range, °C	90	80	70
Solidification time, s	85	230	670

Precipitates

–

Microsegregation

Element	Cr	Mo
I	1,5	2,4

R = 0,5 °C/s
Tq = 1340 °C

Partly solidified

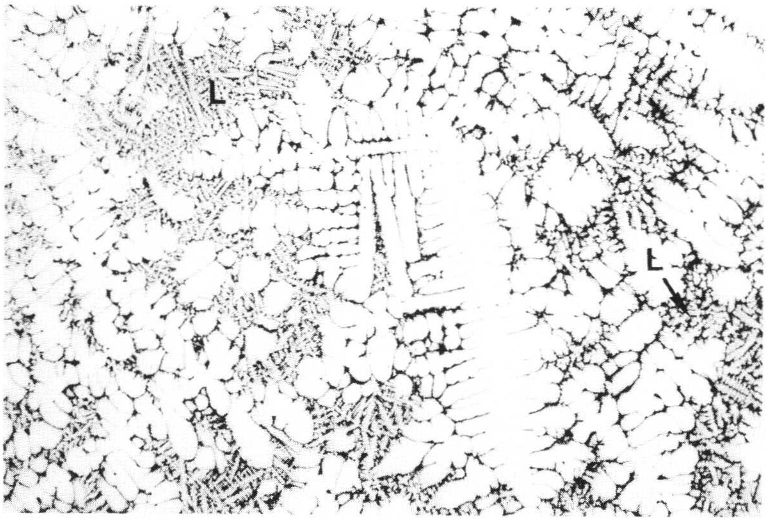


Figure 1

R = 0,5°C/s
Tq = 1485°C
d = 65 μm
δ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

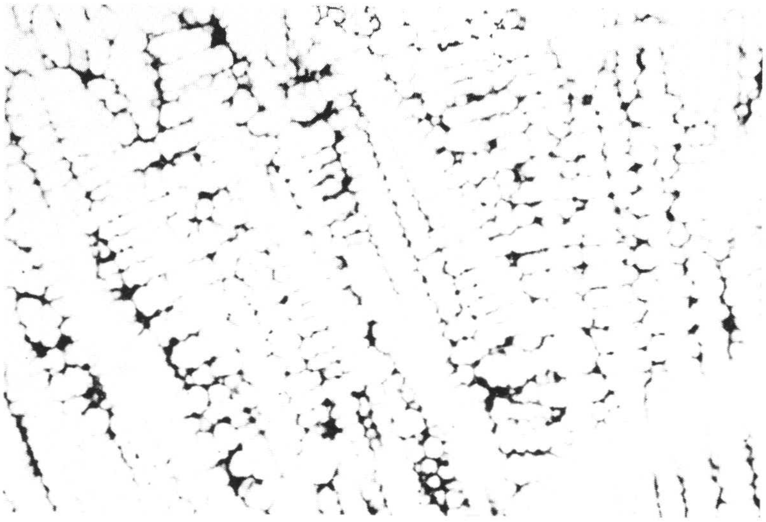


Figure 2

R = 2,0°C/s
Tq = 1340°C
d = 80 μm
Figures 2–4: Former δ-dendrites, transformed to γ by the peritectic reaction.

400 μm × 25

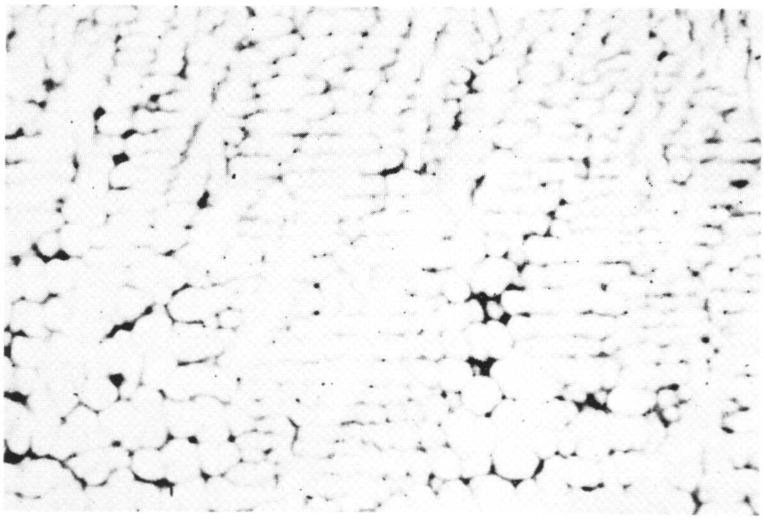


Figure 3

R = 0,5°C/s
Tq = 1340°C
d = 100 μm

400 μm × 25

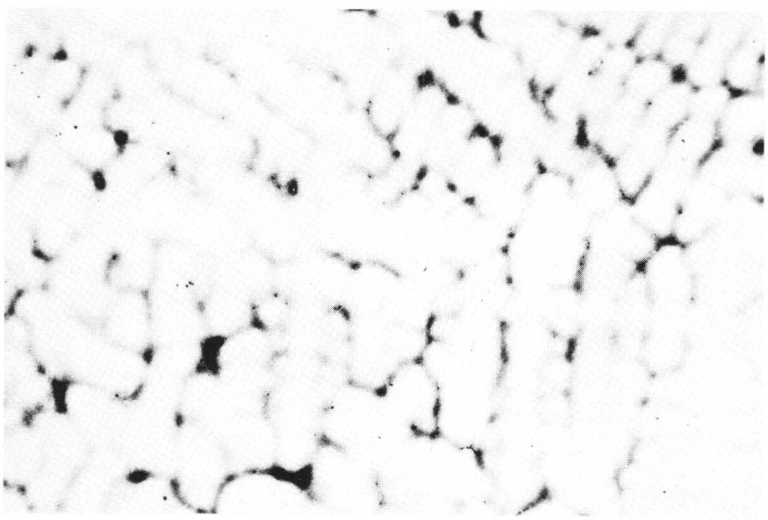


Figure 4

R = 0,1°C/s
Tq = 1340°C
d = 190 μm

400 μm × 25

STEEL 214. 0,5 % C Cr LOW ALLOY STEEL

Designations

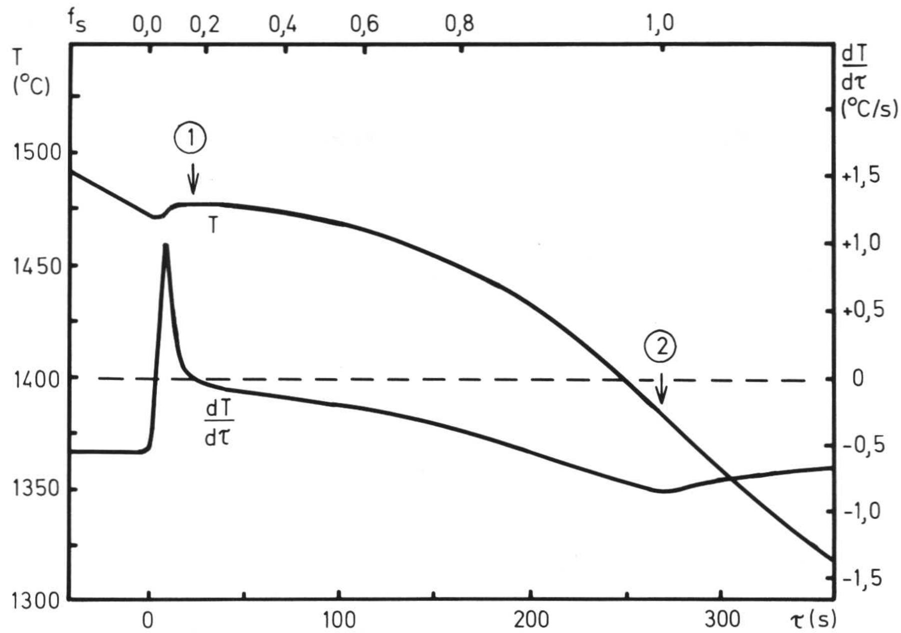
SIS	AISI	Werkstoff Nr
2230	6150	1.8159

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Al_{tot}	N
0,52	0,22	0,85	0,010	0,006	1,07	0,07	0,07	0,04	0,14	≤0,004	0,008

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, austenitic primary phase, °C (1)	1482	1482	1483
Solidus temperature, °C (2)	1380	1385	1400
Solidification range, °C	100	95	80
Solidification time, s	85	250	740

Precipitates

Small amount of interdendritic carbides.

Microsegregation

Element	Cr	V
I	2,1	1,9

R = 0,5 °C/s
Tq = 1310 °C

Partly solidified

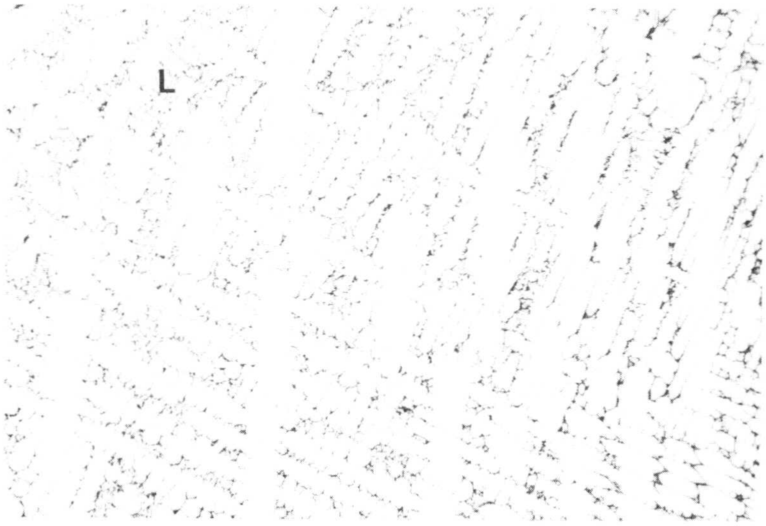


Figure 1
R = 0,5°C/s
Tq = 1470°C
d = 55 μm
γ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

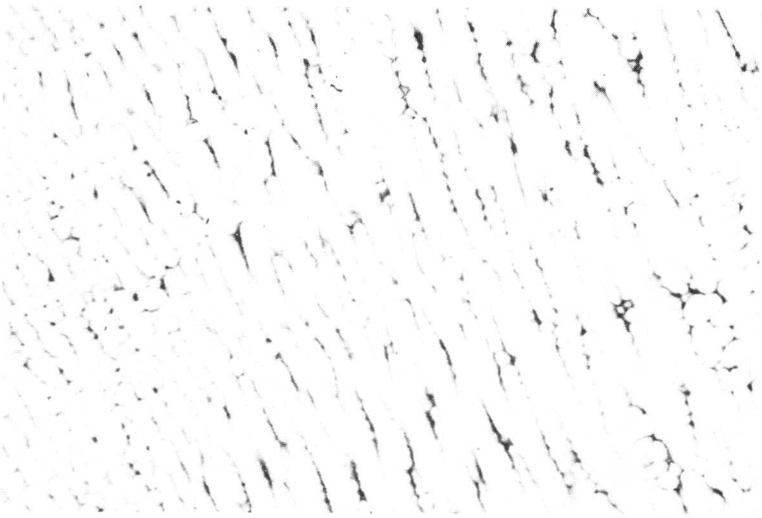


Figure 2
R = 2,0°C/s
Tq = 1310°C
d = 75 μm
Figures 2–4: γ-dendrites.

400 μm × 25

Figure 3
R = 0,5°C/s
Tq = 1310°C
d = 90 μm

400 μm × 25

Figure 4
R = 0,1°C/s
Tq = 1310°C
d = 140 μm

400 μm × 25

STEEL 215. 0,55 % C Cr Ni Mo LOW ALLOY STEEL

Designations

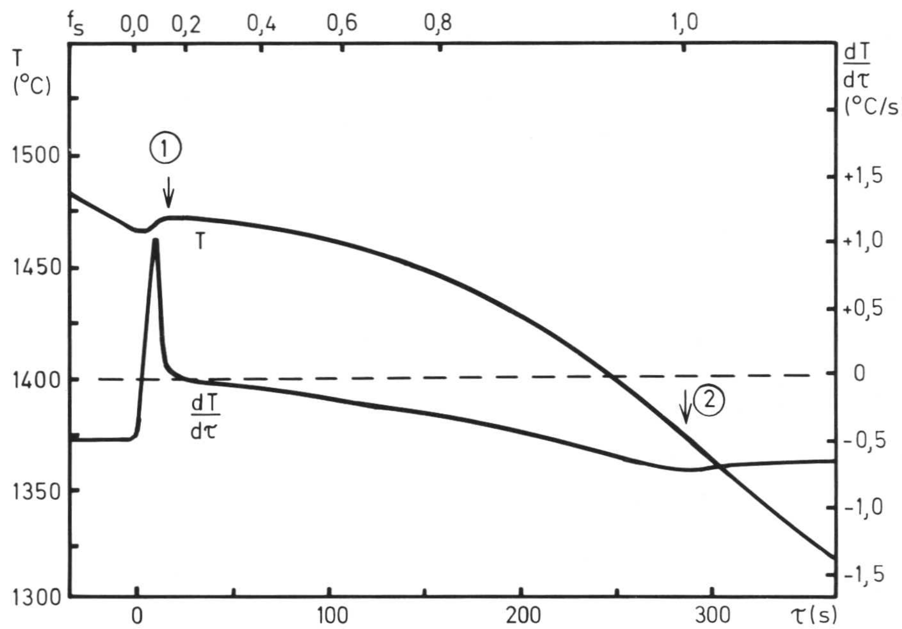
SIS	AISI	Werkstoff Nr
2550	–	1.2721

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Al_{tot}	N
0,55	0,27	0,50	0,019	0,012	0,99	3,0	0,31	0,06	0,08	0,011	0,008

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, austenitic primary phase, °C ①	1471	1471	1472
Temperature of formation of eutectic, °C	1365–1335	–1370	–1375
Solidus temperature, °C ②	1335	1370	1375
Solidification range, °C	140	100	75
Solidification time, s	100	260	720

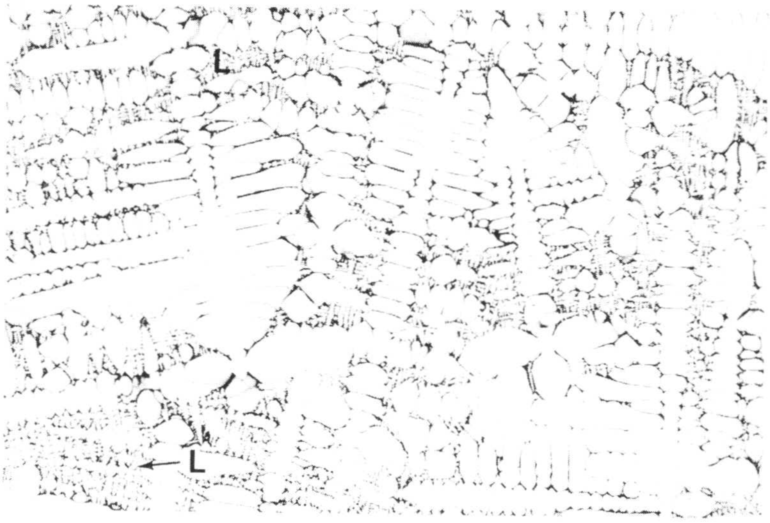
Precipitates

Interdendritic carbide-austenite eutectic, Fe_3P and MnS, (see figure 5).

Microsegregation

Element	Cr	Ni	Mo	V
I	2,1	1,2	2,5	2,0

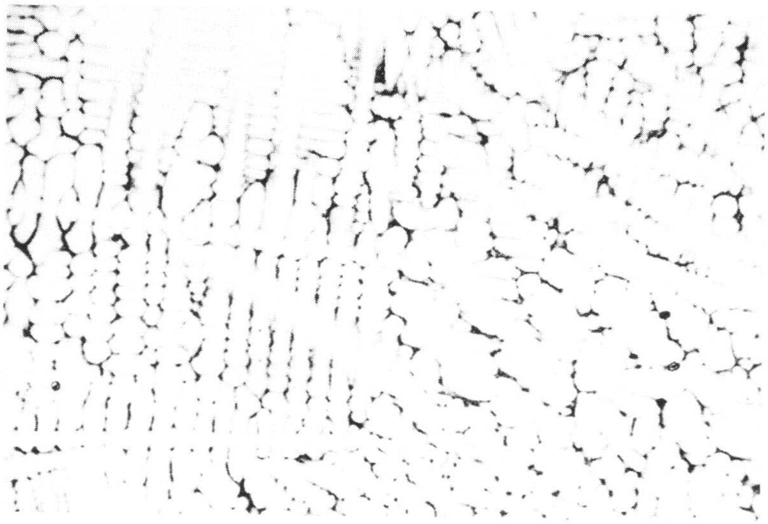
R = 0,5 °C/s
Tq = 1290 °C



Partly solidified

Figure 1
R = 0,5°C/s
Tq = 1465°C
d = 65 μm
γ-dendrites and quenched liquid (L).

400 μm × 25



Completely solidified

Figure 2
R = 2,0°C/s
Tq = 1290°C
d = 70 μm
Figures 2–4: γ-dendrites.

400 μm × 25

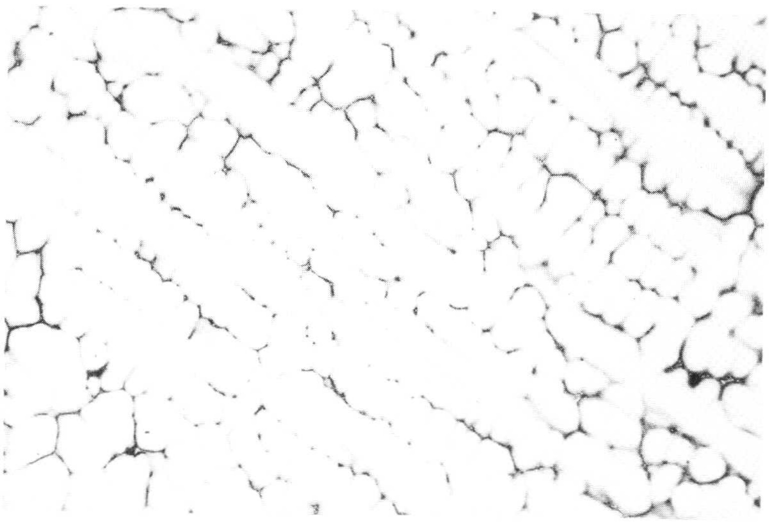


Figure 3
R = 0,5°C/s
Tq = 1290°C
d = 90 μm

400 μm × 25

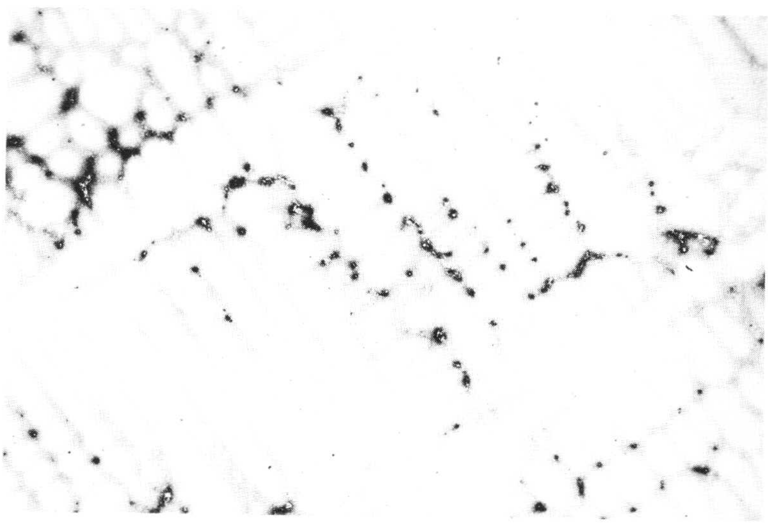


Figure 4
R = 0,1°C/s
Tq = 1290°C
d = 130 μm

400 μm × 25

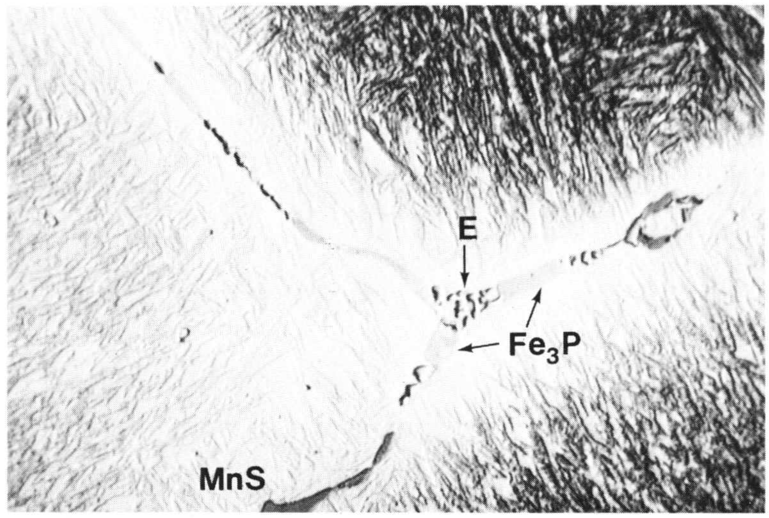


Figure 5
R = 0,5°C/s
Tq = 1290°C
Interdendritic area with carbide-austenite eutectic (E), Fe_3P and MnS.

× 1000 10 μm

STEEL 216. 1,0 % C Cr LOW ALLOY STEEL

Designations

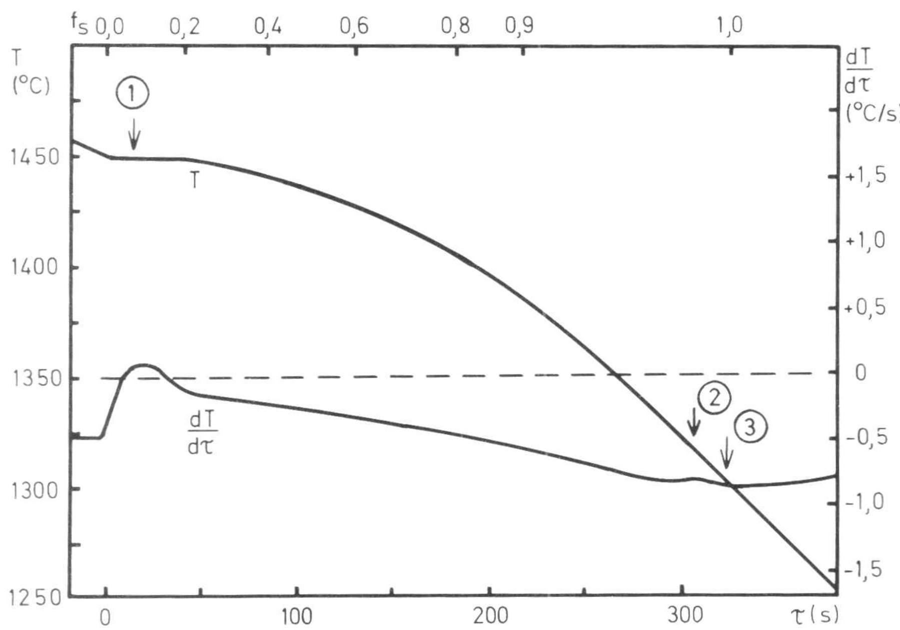
SIS	AISI	Werkstoff Nr
2258	52100	1.3505

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Al_{tot}	N
1,01	0,23	0,33	0,021	0,026	1,55	0,02	0,01	0,04	0,04	0,011	0,003

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, austenitic primary phase, °C (1)	1450	1450	1451
Temperature of formation of eutectic, °C (2)	1320 – 1270	1340 – 1300	– 1300
Solidus temperature, °C (3)	1270	1300	~1300
Solidification range, °C	180	150	150
Solification time, s	170	330	1400

Precipitates

1. Interdendritic Fe_3P-carbide-austenite eutectic (14 % Cr, 5 % P). The eutectic remained after cooling to 850 °C (see figures 5 and 6), but was dissolved after homogenizing for 4 h at 1200 °C.
2. Interdendritic MnS.

Microsegregation

Element	Cr	
I	2,6	R = 0,5 °C/s Tq = 1250 °C

Partly solidified

Figure 1
R = 0,5°C/s
Tq = 1440°C
d = 60 μm
γ-dendrites and quenched liquid (L).

× 25 400 μm

Completely solidified

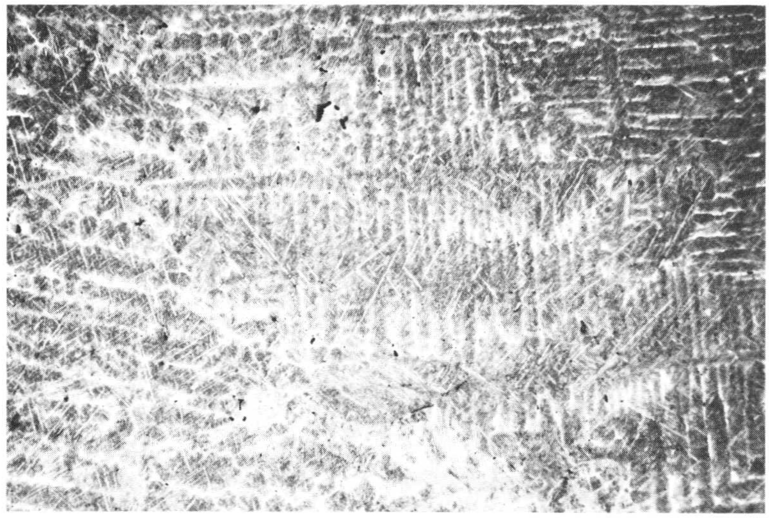


Figure 2
R = 2,0°C/s
Tq = 1250°C
d = 75 μm
Figures 2–4: γ-dendrites.

× 25 400 μm

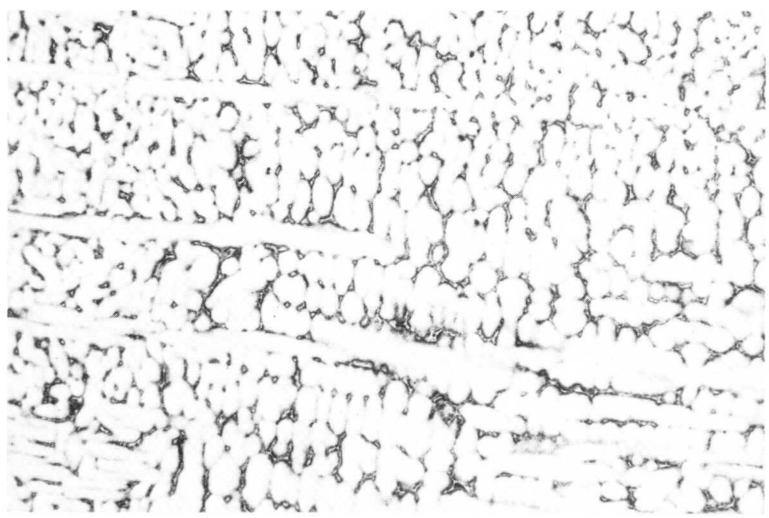


Figure 3
R = 0,5°C/s
Tq = 1250°C
d = 90 μm

× 25 400 μm

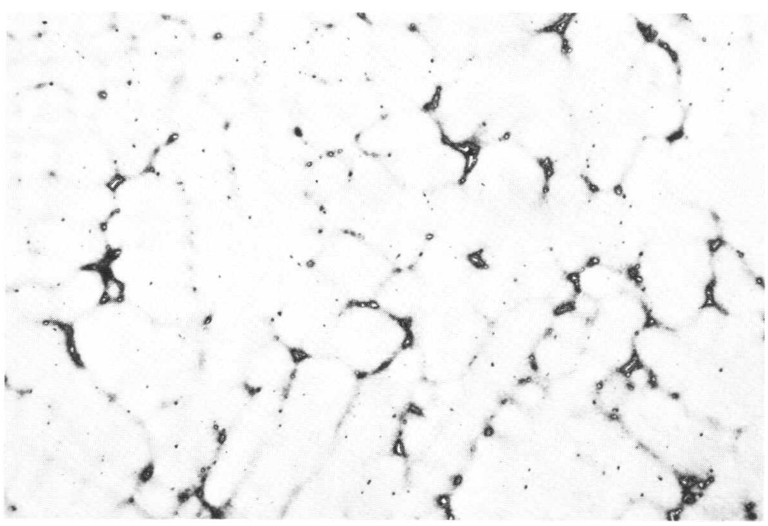


Figure 4
R = 0,1°C/s
Tq = 1250°C
d = 140 μm

× 25 400 μm

Figure 5

R = 2,0°C/s
Tq = 1250°C
Interdendritic Fe_3P-carbide-austenite eutectic (E) (approximately 0,1 vol-%). The eutectic contains 14 % Cr and 5 % P.

10 μm × 1000

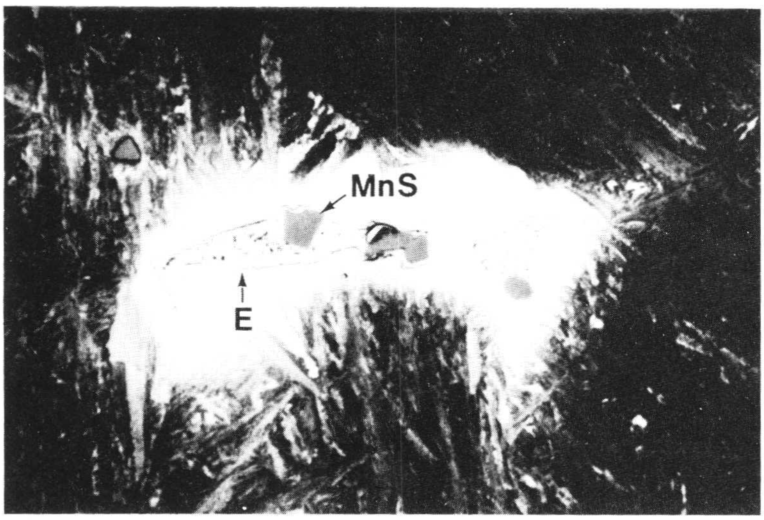


Figure 6

R = 2,0°C/s
Tq = 850°C
After cooling to 850°C, small amounts of the eutectic shown in figure 5 remained. (Annealing for 4 h at 1200°C completely eliminated the eutectic.)

10 μm × 1000

3. Chromium Steels

Steels with chromium as the only, or the dominant alloying element are normally called chromium steels. The two common groups included here are steels with 5 and 13% chromium. In the first family the alloying addition is used to increase hardenability and to give the final product a favourable combination of strength and toughness.

In the 13% Cr-steels, chromium imparts both corrosion resistance and strength. With reference to the structure of the steel products, the group comprises ferritic stainless ($C < 0{,}08\%$), hardenable martensitic stainless ($C \geq 0{,}09\%$), and low carbon hardenable martensitic stainless steels with 4–6% nickel. Because of their constitutional similarity at high temperatures, the 5 and 13% chromium steels are kept together in this work, rather than grouping the 13% Cr- steels with the Cr-Ni stainless materials.

Steels containing 17–25% chromium have not been examined. They are similar to the 13% Cr-group in regard to solidification and structure at high temperatures.

Chromium steels are produced as castings and ingots of moderate size, continuous casting is unusual.

Both the groups of steels investigated are made with a wide range of carbon contents. For a given chromium level the solidification mode is strongly dependent on carbon; this can be seen in the pseudobinary phase diagrams, figures 3.1 and 3.2. Account was taken of this effect of carbon when chosing the production steels for examination; these are given in tables 3.1 and 3.2:

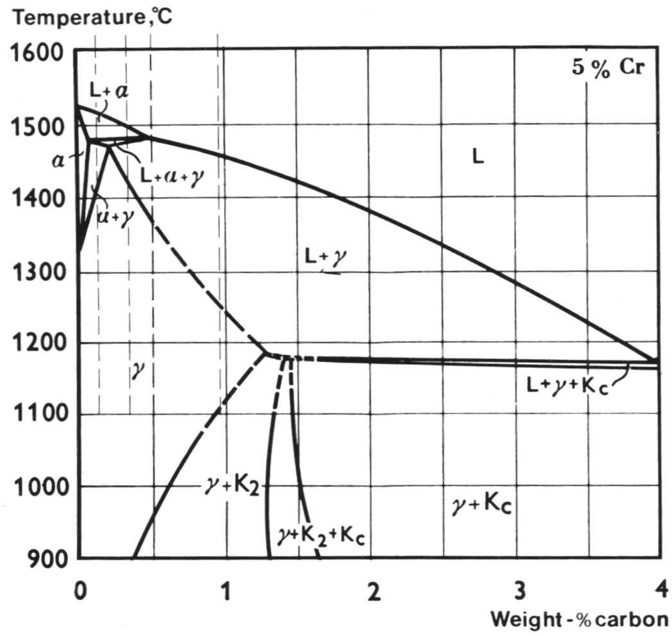


Figure 3.1 Fe-5Cr-C system

No.	C	Si	Mn	Cr	Ni	Mo	V	%
301	0,13	0,4	0,4	5,0	–	0,6	–	
302	0,35	1,0	0,5	5,2	0,2	1,3	1,0	
303	0,50	1,0	0,5	5,1	0,2	1,4	1,2	
304	0,96	0,3	0,7	5,2	0,1	1,2	0,2	

Table 3.1 5% chromium steels

No.	C	Si	Mn	Cr	Ni	%
305	0,04	0,5	0,6	13,4	5,5	
306	0,07	0,5	0,5	12,9	0,2	
307	0,14	0,2	0,7	12,0	1,2	
308	0,32	0,2	0,3	13,9	0,2	
309	0,69	0,4	0,6	13,1	0,2	

Table 3.2 13% chromium steels (see also table 4.1)

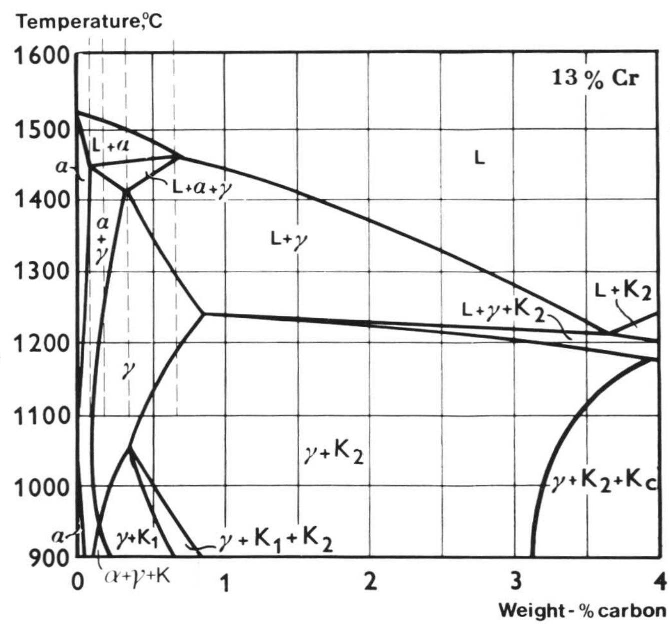


Figure 3.2 Fe-13Cr-C system

(Figures 3.1 and 3.2 after Bungardt et al. *Arch. Eisenhüttenw.* 29 (1958) 3, 193–203, K_c = Fe_3 C, K_1 = $M_{23}C_6$, K_2 = M_7C_3)

As indicated in figures 3.1 and 3.2 these grades cover the following solidification processes:

- primary ferrite formation
- primary ferrite formation followed by a peritectic reaction
- primary austenite formation

It should be noted that the pseudobinary phase diagrams are strictly valid for ternary Fe-Cr-C-alloys only. The superimposed lines for the commercial steel grades are therefore only indicative.

References

The solidification of chromium steels has not been widely studied. General aspects of the process have been reported, [55–59]. Research work on microsegregation is described in references [60–64].

STEEL 301. 0,1 % C 5 % CHROMIUM STEEL

Designations

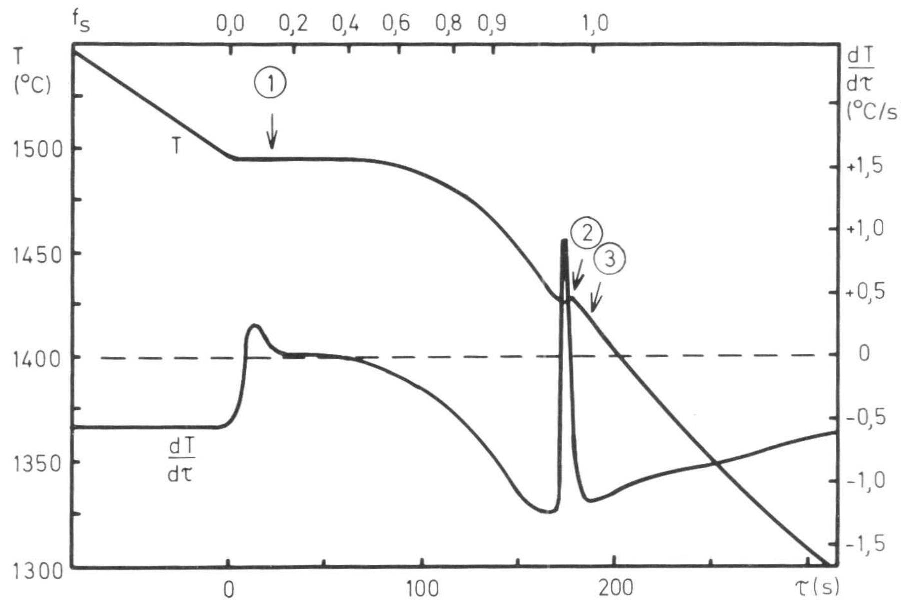
SIS	AISI	Werkstoff Nr
–	501	1.7362

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,13	0,36	0,37	0,003	0,007	5,0	0,01	0,58	0,02	0,01	0,01	0,009	0,006

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1508	1501	1506
Temperature of austenite formation, °C (2)	1443	1426	1444
Solidus temperature, °C (3)	1405	1415	1440
Solidification range, °C	105	85	65
Solidification time, s	85	190	790

Precipitates

–

Microsegregation

Element	Cr	Mo	
I	1,1	1,4	R = 0,5 °C/s Tq = 1375 °C

Partly solidified

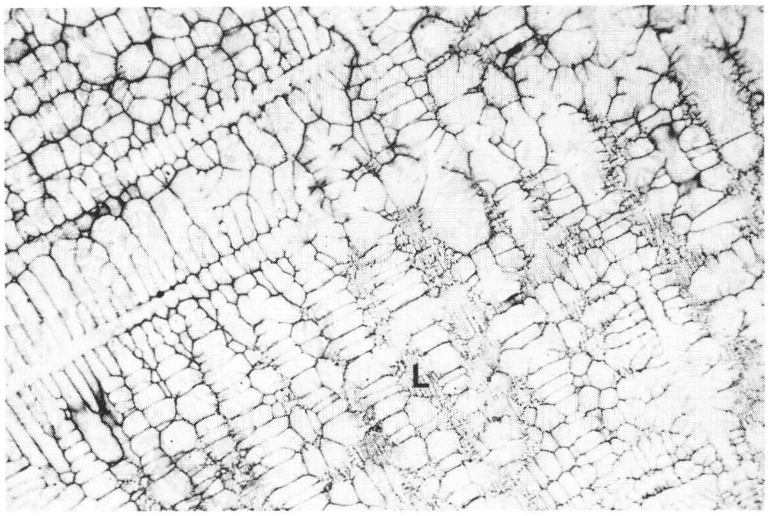


Figure 1
R = 0,5°C/s
Tq = 1495°C
d = 65 μm
δ-dendrites and quenched liquid (L).

× 25 400 μm

Completely solidified

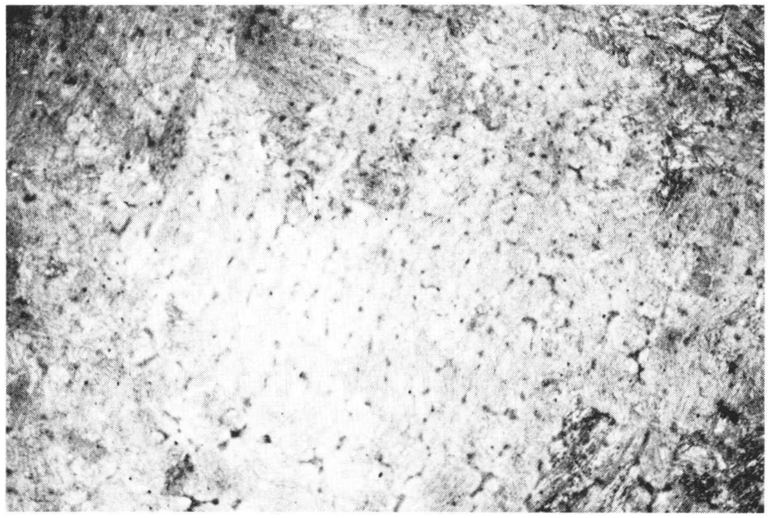


Figure 2
R = 2,0°C/s
Tq = 1375°C
d = 85 μm
Figures 2–4: Former δ-dendrites, transformed to γ by the peritectic reaction.

× 25 400 μm

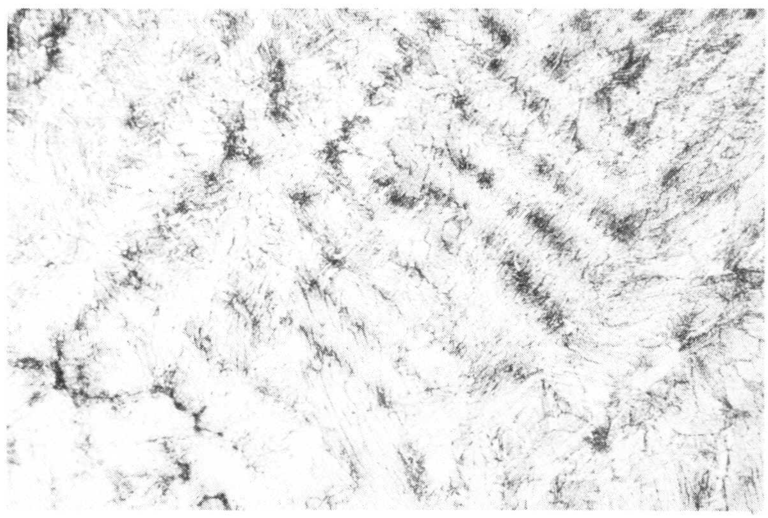


Figure 3
R = 0,5°C/s
Tq = 1375°C
d = 160 μm

× 25 400 μm

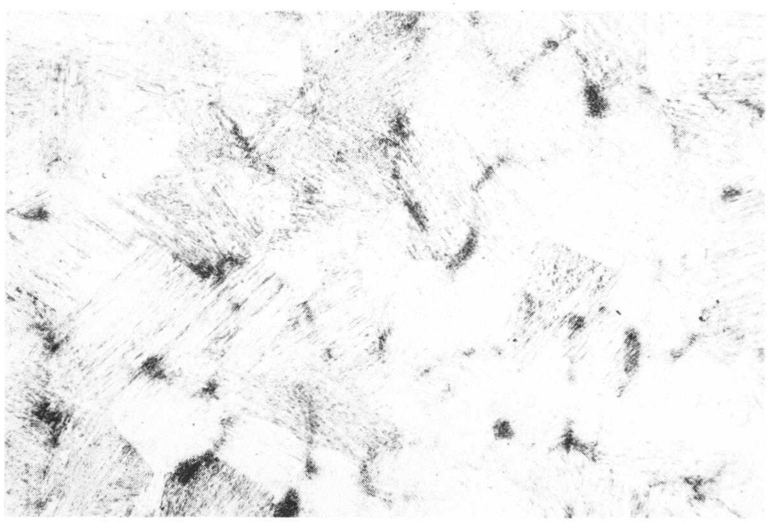


Figure 4
R = 0,1°C/s
Tq = 1375°C
d = 275 μm

× 25 400 μm

STEEL 302. 0,35 % C Mo V 5 % CHROMIUM STEEL

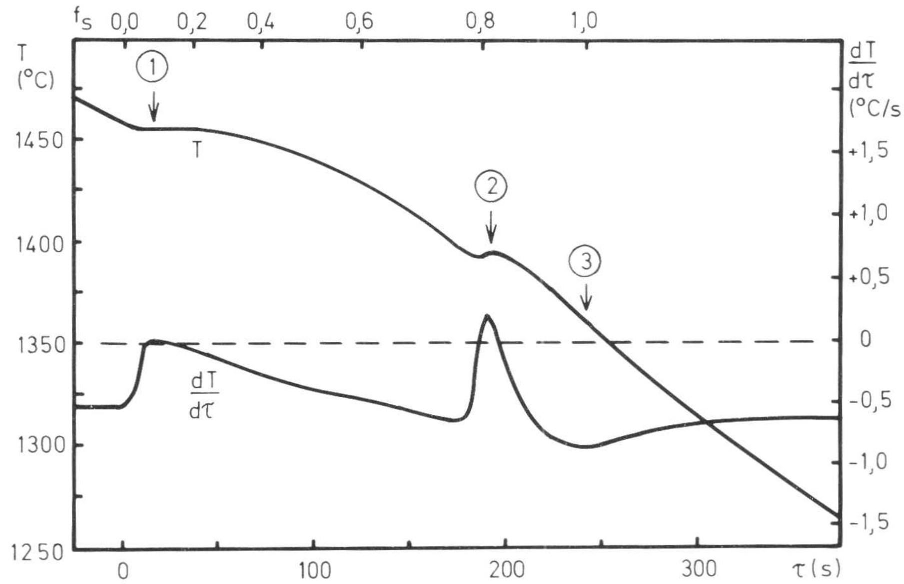
Designations

SIS	AISI	Werkstoff Nr
2242	H 13	1.2344

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,35	1,03	0,46	0,020	0,007	5,2	0,23	1,34	0,11	0,09	1,0	0,013	0,026

Thermal Analysis



R = 0,5°C/s

	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1471	1464	1470
Temperature of austenite formation, °C (2)	1370	1387	1412
Solidus temperature, °C (3)	1335	1360	1380
Solidification range, °C	135	105	90
Solidification time, s	100	250	990

Precipitates

Small amount of eutectic carbide.

Microsegregation

Element	Cr	Ni	Mo	V
I	1,2	1,0	1,5	1,7

R = 0,5 °C/s
Tq = 1300 °C

Partly solidified

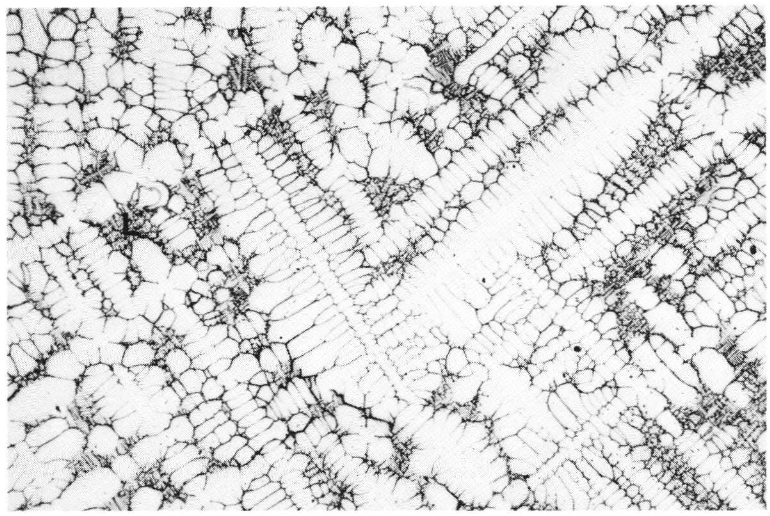


Figure 1
R = 0,5°C/s
Tq = 1450°C
d = 55 μm
δ-dendrites and quenched liquid (L).

× 25 400 μm

Completely solidified

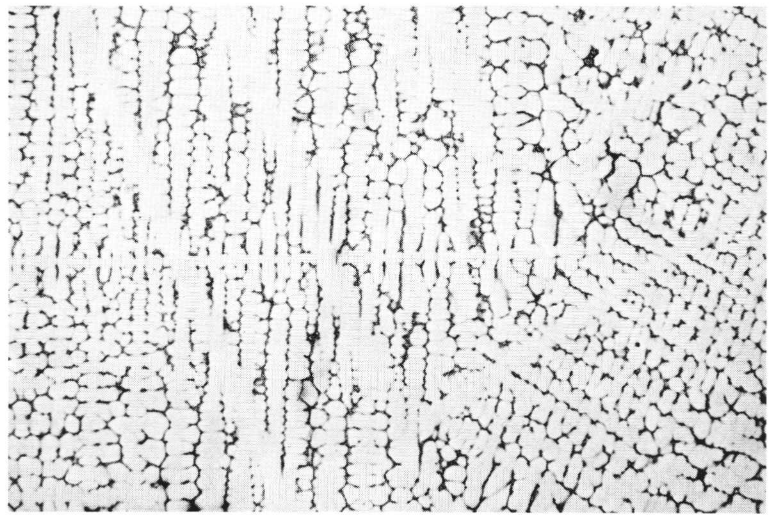


Figure 2
R = 2,0°C/s
Tq = 1300°C
d = 70 μm
Figures 2–4: Former δ-dendrites, transformed to γ by the peritectic reaction.

× 25 400 μm

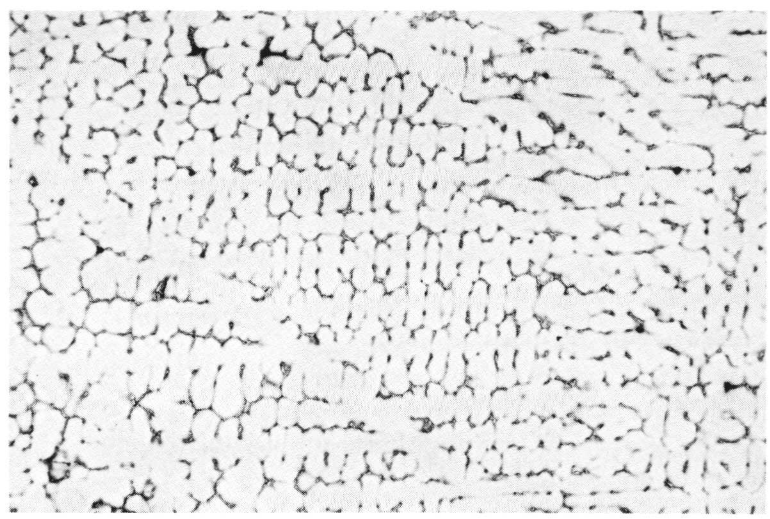


Figure 3
R = 0,5°C/s
Tq = 1300°C
d = 80 μm

× 25 400 μm

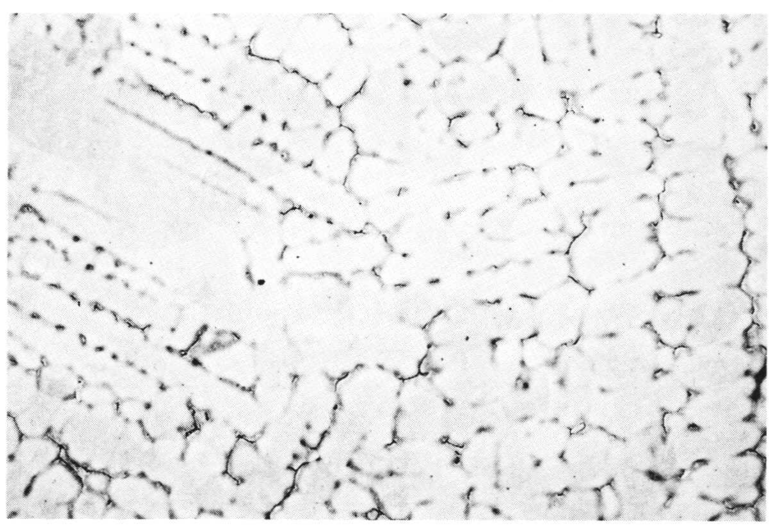


Figure 4
R = 0,1°C/s
Tq = 1300°C
d = 120 μm

× 25 400 μm

STEEL 303. 0,5 % C Mo V 5 % CHROMIUM STEEL

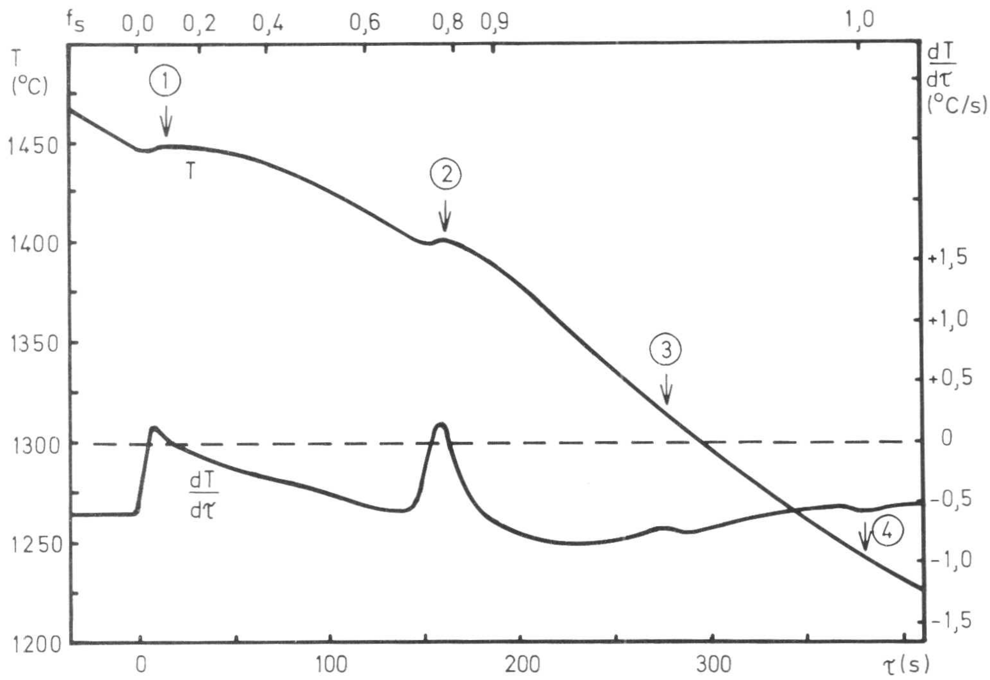
Designations

SIS	AISI	Werkstoff Nr
–	–	–

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,50	1,00	0,48	0,025	0,010	5,1	0,18	1,36	0,10	0,02	1,20	0,013	0,036

Thermal Analysis



R = 0,5°C/s

	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1460	1460	1460
Temperature of austenite formation, °C (2)	1410	1410	1412
Temperature of formation of MC-austenite eutectic,°C (3)	1320 – 1240	1345 – 1300	– 1320
Solidus temperature, °C (4)	1140	1240	1260
Solidification range, °C	320	220	200
Solidification time, s	170	380	1900

Precipitates

1. Interdendritic MC-austenite eutectic, MC was of the VC type, (see figures 6 – 8).
2. Small amount of interdendritic $M_{23}C_6$-austenite eutectic,(M was Cr, Fe and Mo), precipitated after the MC carbide.

Microsegregation

Element	Cr	Mo	V
I	1,3	1,5	1,3

R = 0,5 °C/s
Tq = 1200 °C

Partly solidified

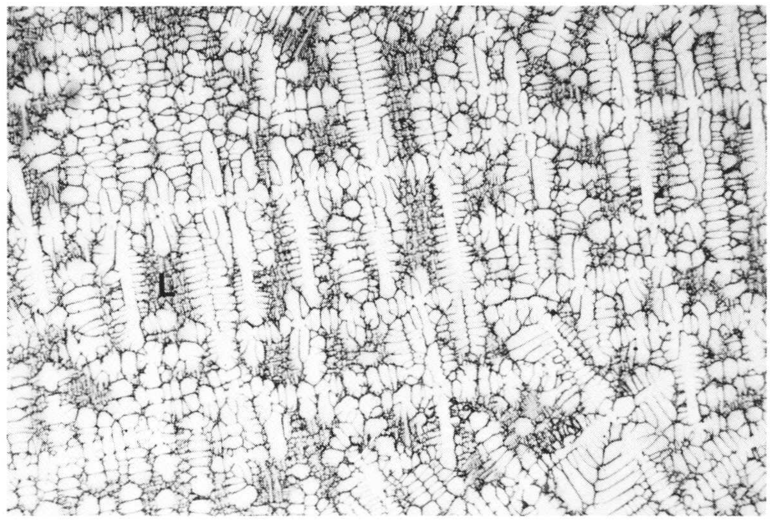


Figure 1
R = 0,5°C/s
Tq = 1445°C
d = 55 μm
δ-dendrites and quenched liquid (L).

× 25 400 μm

Completely solidified

Figure 2
R = 2,0°C/s
Tq = 1140°C
d = 60 μm
Figures 2–4: Former δ-dendrites, (transformed to γ by the peritectic reaction), and interdendritic carbide eutectic.

× 25 400 μm

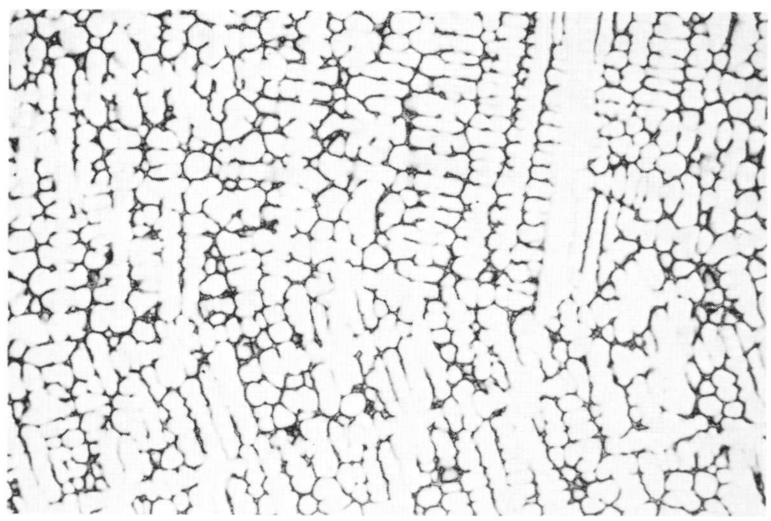


Figure 3
R = 0,5°C/s
Tq = 1200°C
d = 80 μm

× 25 400 μm

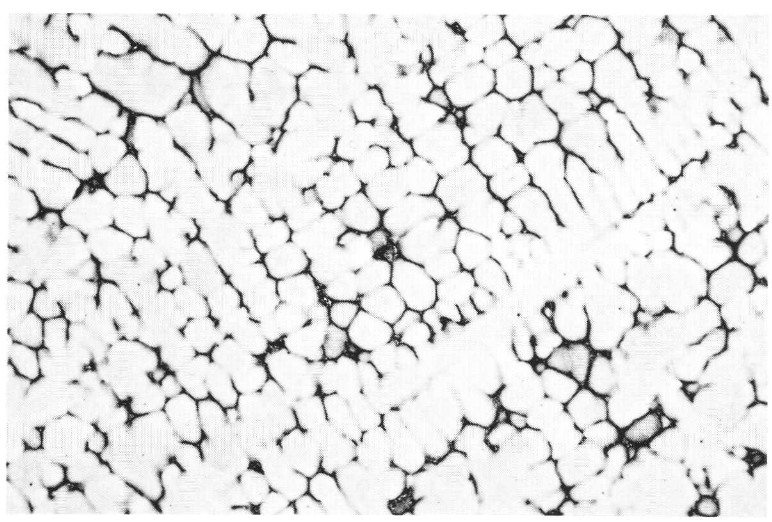


Figure 4
R = 0,1°C/s
Tq = 1200°C
d = 110 μm

× 25 400 μm

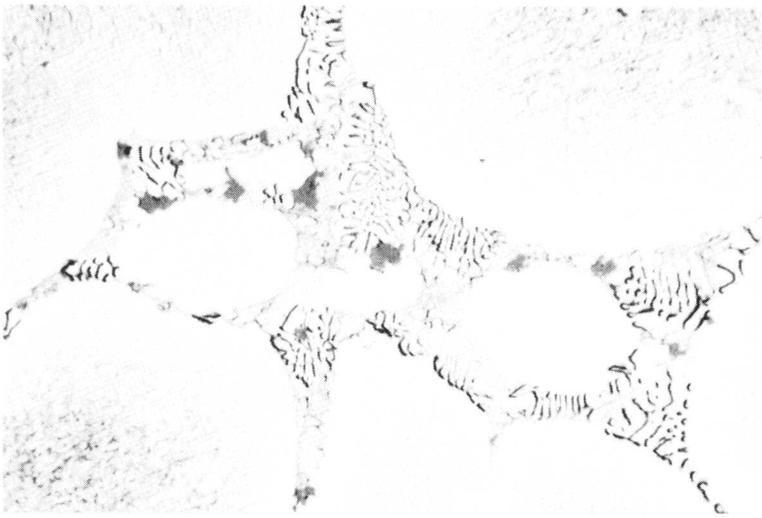


Figure 5
R = 2,0°C/s
Tq = 1290°C
Quenched liquid.

10 μm × 1000

Figure 6
R = 2,0°C/s
Tq = 1200°C
Eutectic formation of MC.
(L→MC+γ)

10 μm × 1000

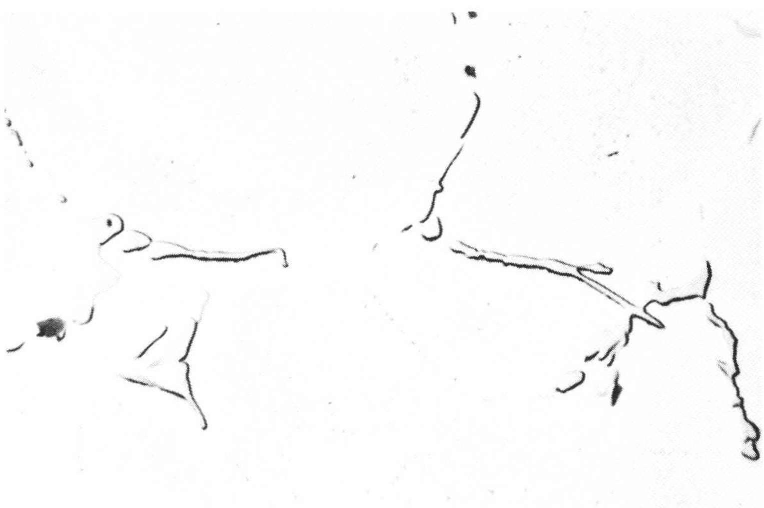


Figure 7
R = 2,0°C/s
Tq = 1000°C
Morphology of MC.

10 μm × 1000

Figure 8
R = 2,0°C/s
Tq = 1000°C
Interdendritic distribution of MC.

100 μm × 150

STEEL 304. 1,0 % C Mo 5 % CHROMIUM STEEL

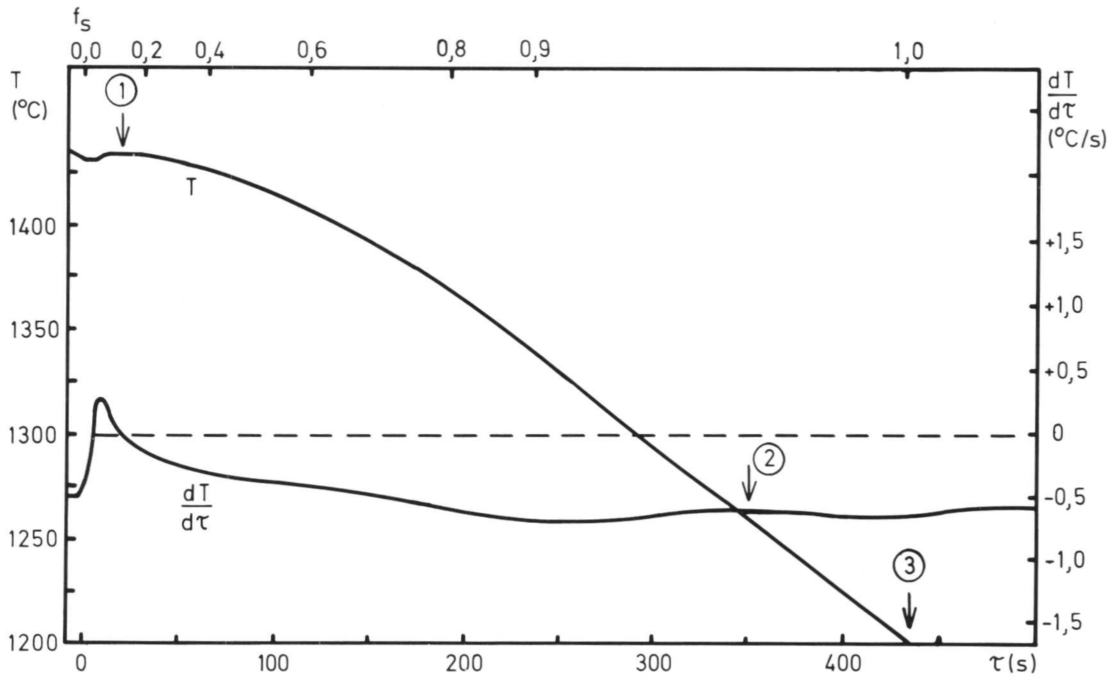
Designations

SIS	AISI	Werkstoff Nr
2260	A 2	1.2363

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,96	0,29	0,67	0,020	0,015	5,2	0,13	1,19	0,09	0,05	0,21	0,014	0,024

Thermal Analysis



R = 0,5°C/s

	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, austenitic primary phase, °C (1)	1435	1434	1438
Temperature of formation of eutectic, °C (2)	1150–1130	–1200	–1215
Solidus temperature, °C (3)	1130	1200	1215
Solidification range, °C	305	235	225
Solidification time, s	185	440	2700

Precipitates

Interdendritic M_7C_3 – austenite eutectic, (see figures 5–7).

Microsegregation

Element	Cr	Mo	V
I	1,4	1,9	1,7

R = 0,5 °C/s
Tq = 1200 °C

Partly solidified

Figure 1
R = 0,5°C/s
Tq = 1420°C
d = 55 μm
γ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

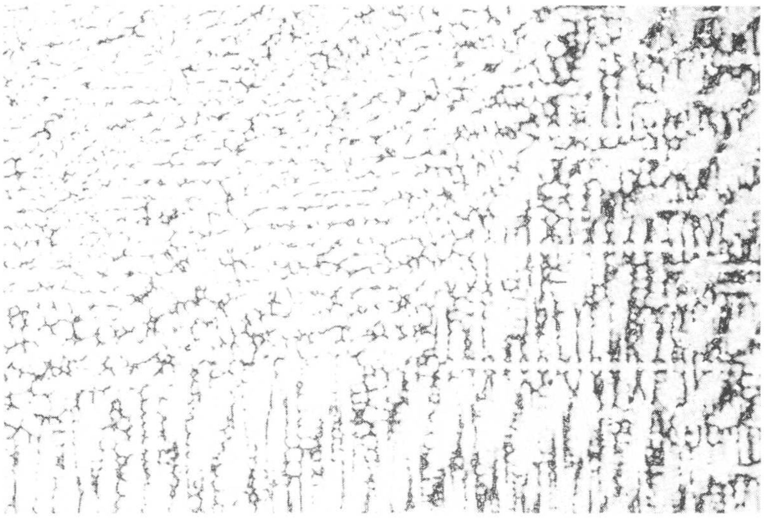


Figure 2
R = 2,0°C/s
Tq = 1130°C
d = 65 μm
Figures 2–4: γ-dendrites and interdendritic carbide eutectic.

400 μm × 25

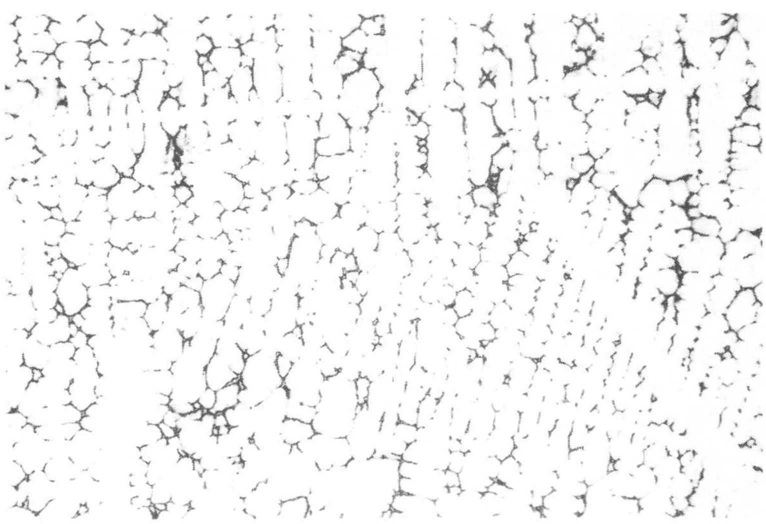


Figure 3
R = 0,5°C/s
Tq = 1200°C
d = 80 μm

400 μm × 25

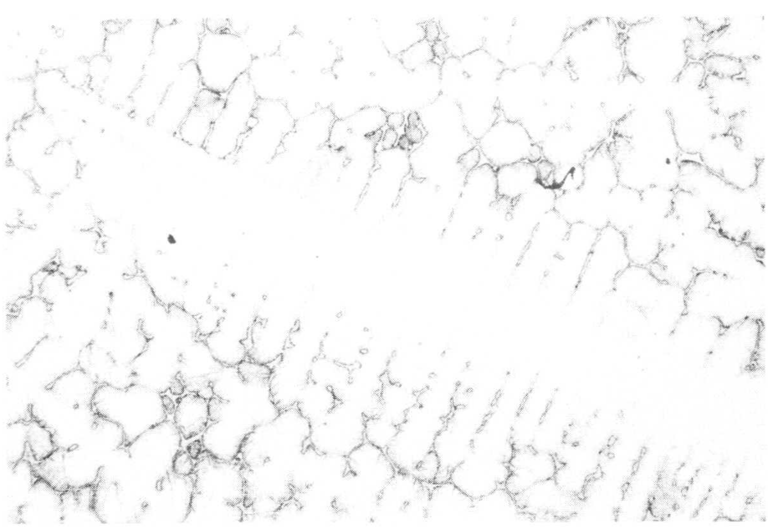


Figure 4
R = 0,1°C/s
Tq = 1200°C
d = 110 μm

400 μm × 25

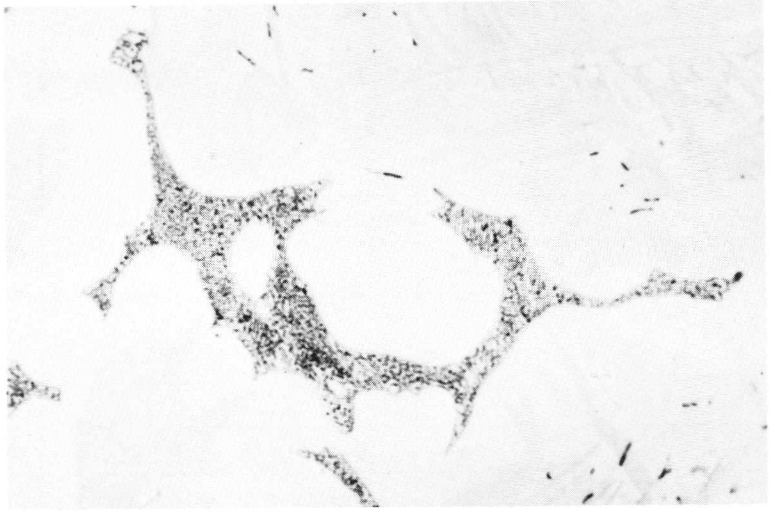


Figure 5
R = 2,0°C/s
Tq = 1200°C
Quenched liquid.

× 1000 10 μm

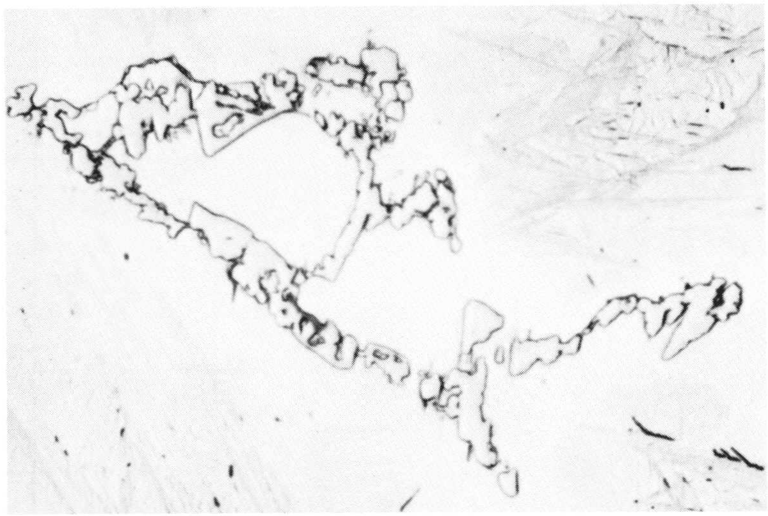


Figure 6
R = 2,0°C/s
Tq = 1000°C
Morphology of M_7C_3.

× 1000 10 μm

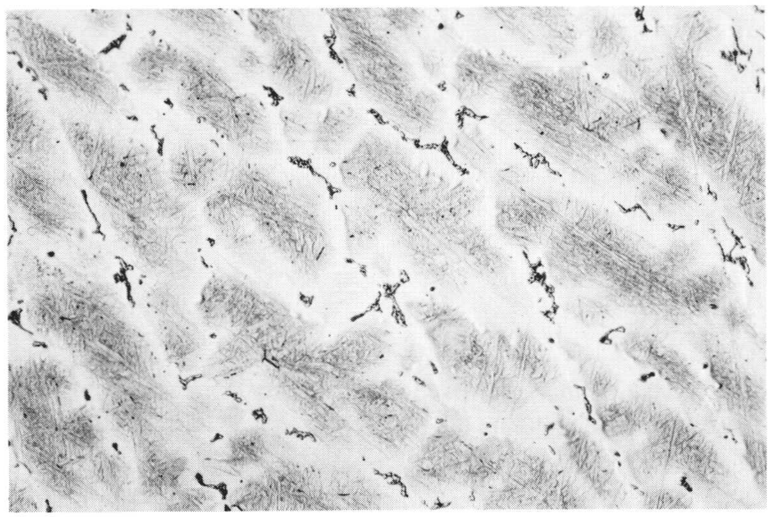


Figure 7
R = 2,0°C/s
Tq = 1000°C
Interdendritic distribution of M_7C_3.

× 150 100 μm

STEEL 305. 0,04 % C 5 % Ni 13 % CHROMIUM STEEL

Designations

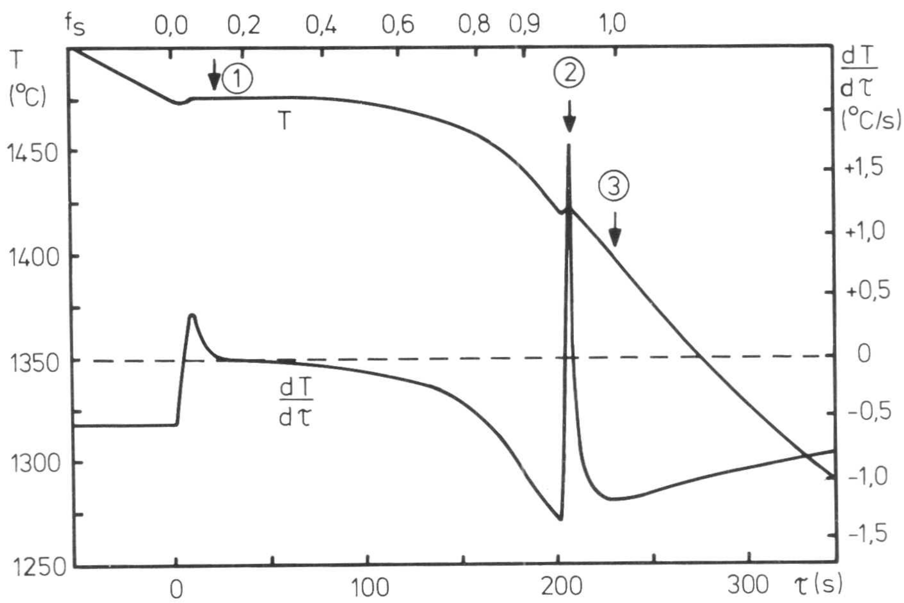
SIS	AISI	Werkstoff Nr
–	–	–

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,04	0,54	0,61	0,010	0,009	13,4	5,5	0,07	0,07	0,01	0,01	0,019	0,032

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1470	1476	1476
Temperature of austenite formation, °C (2)	1410	1419	1425
Solidus temperature, °C (3)	1355	1395	1420
Solidification range, °C	115	80	60
Solidification time, s	100	230	670

Precipitates

–

Microsegregation

Element	Cr	Ni
I	1,1	1,2

R = 0,5 °C/s
Tq = 1350 °C

Partly solidified

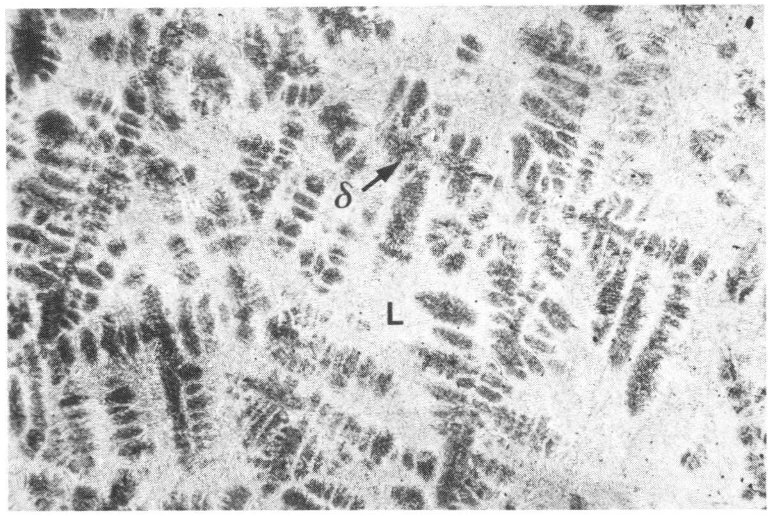


Figure 1
R = 0,5°C/s
Tq = 1473°C
d = 75 μm
δ-dendrites and quenched liquid (L).

× 25 400 μm

Completely solidified

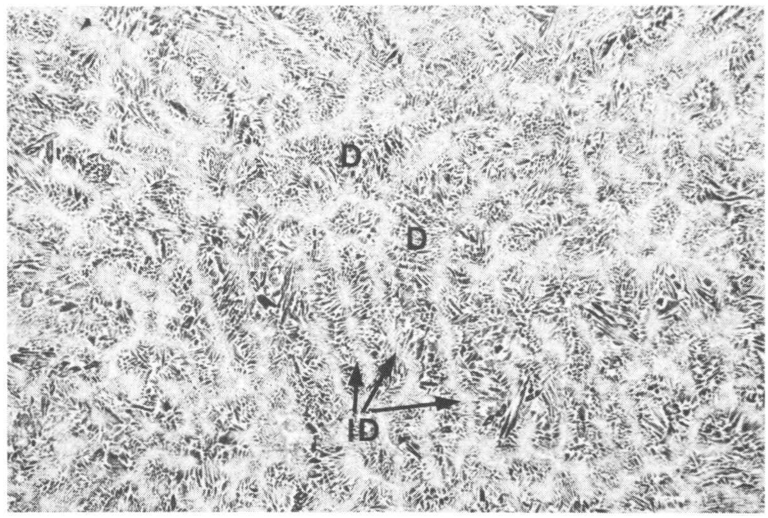


Figure 2
R = 2,0°C/s
Tq = 1350°C
d = 140 μm
Figures 2–4: Former δ-dendrites (D).
White interdendritic areas (ID).
Most of the δ transformed to γ by the peritectic reaction.

× 25 400 μm

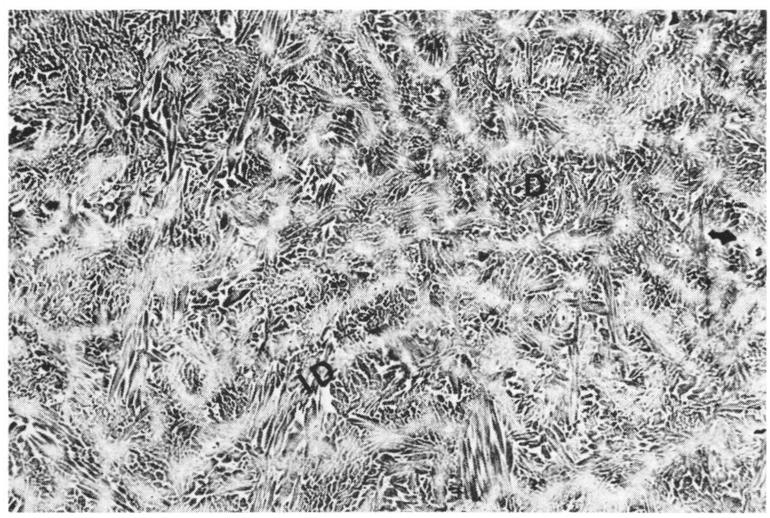


Figure 3
R = 0,5°C/s
Tq = 1350°C
d = 240 μm

× 25 400 μm

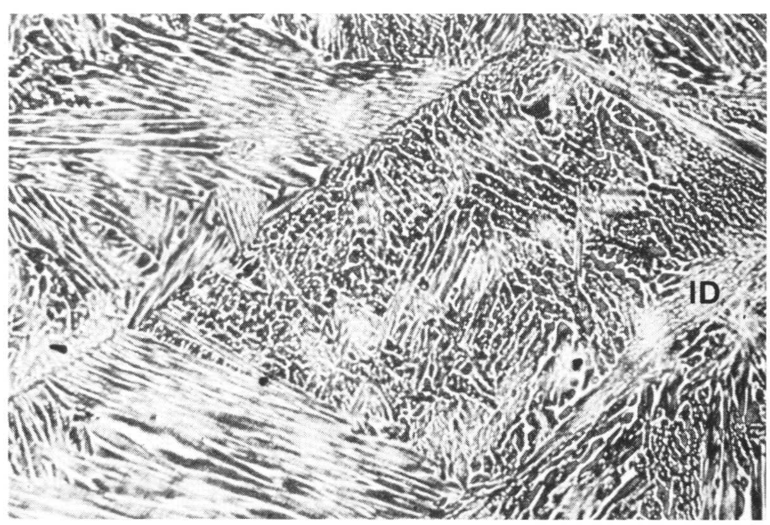


Figure 4
R = 0,1°C/s
Tq = 1350°C
d = 520 μm

× 25 400 μm

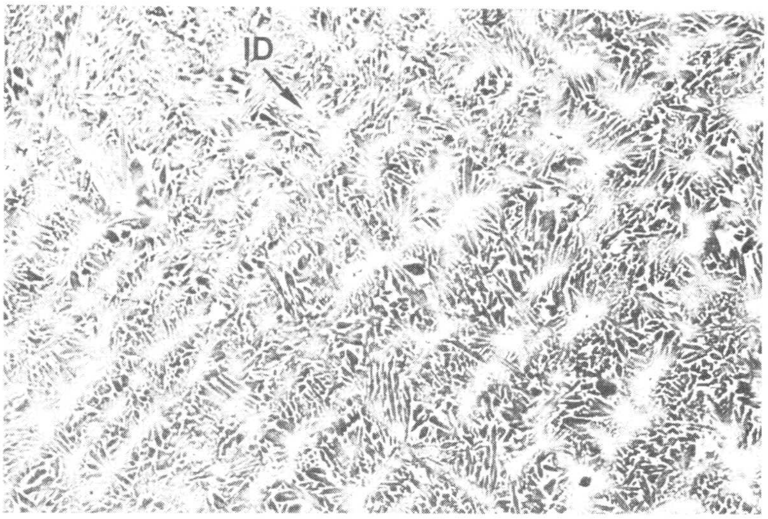


Figure 5
R = 0,5°C/s
Tq = 1200°C
(d_{1200} = 260 μm)
Former δ-dendrites (D).
White interdendritic areas (ID).
Most of the δ transformed to γ by the peritectic reaction.

400 μm × 25

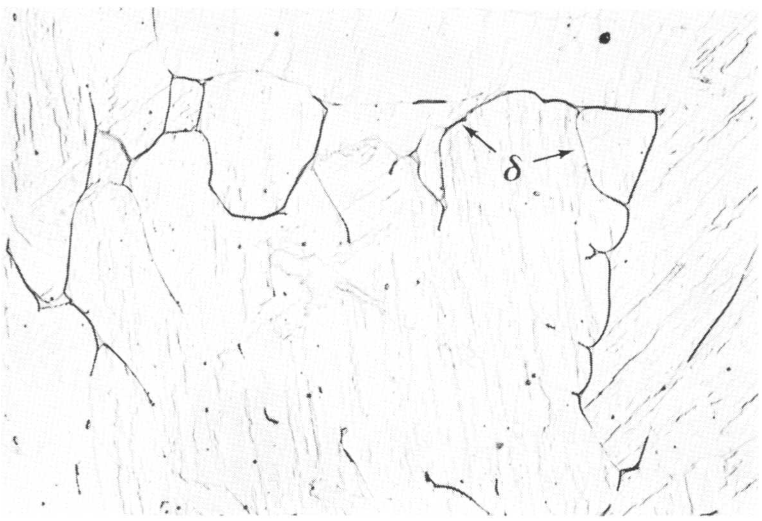


Figure 6
R = 2,0°C/s
Tq = 1350°C
Residual dendritic ferrite (δ) in the γ-matrix.

25 μm × 600

Figure 7
R = 0,1°C/s
Tq = 1350°C
Residual dendritic ferrite (δ) in the γ-matrix.

25 μm × 600

STEEL 306. 0,07 % C 13 % CHROMIUM STEEL

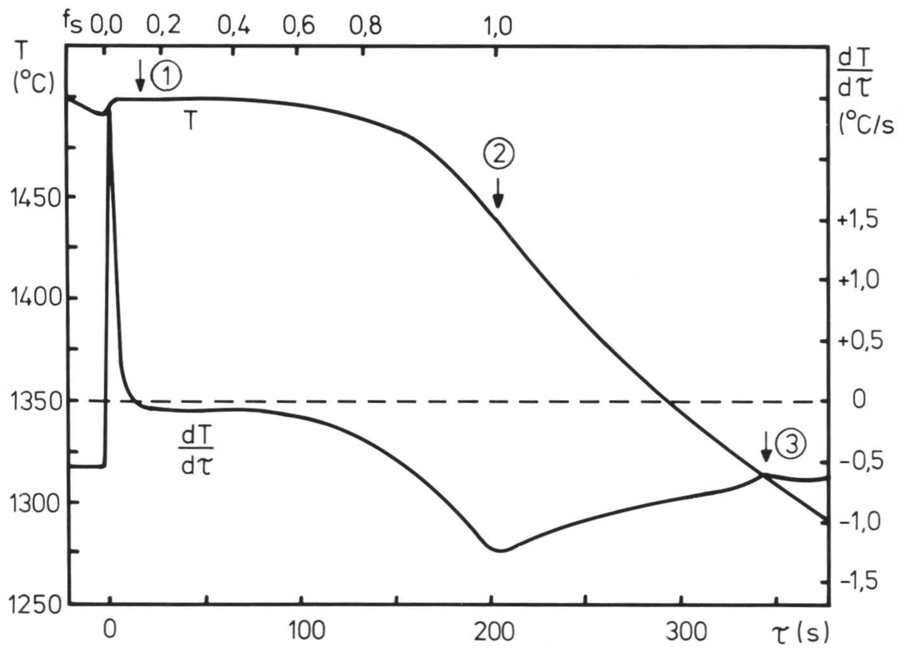
Designations

SIS	AISI	Werkstoff Nr
2301	410 S	1.4000

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,07	0,54	0,48	0,020	0,006	12,9	0,17	0,02	0,10	0,01	≤0,01	0,026	0,039

Thermal Analysis



R = 0,5°C/s

	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C ①	1497	1500	1500
Solidus temperature, °C ②	1435	1440	1455
Temperature of solid phase transformation of ferrite to austenite, °C ③	1325 – 1270	1330 – 1290	
Solidification range, °C	65	60	45
Solidification time, s	80	210	610

Precipitates

–

Microsegregation

Element	Cr	Ni	
I	1,0	1,0	R = 0,5 °C/s Tq = 1400 °C

Partly solidified

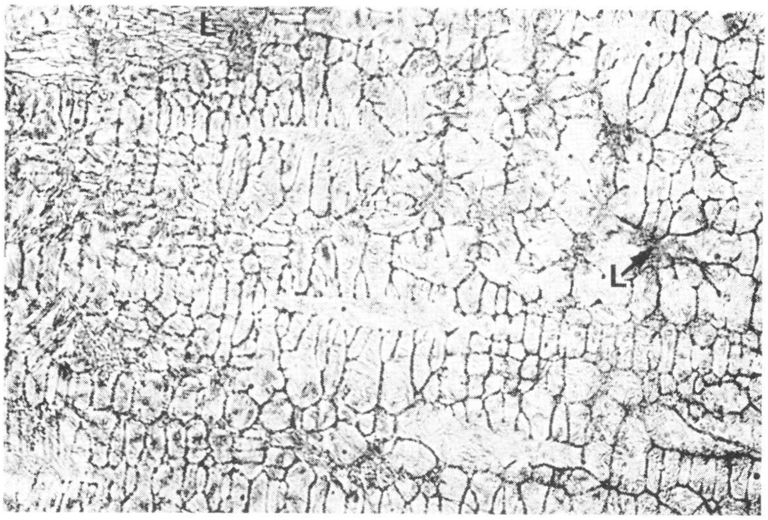


Figure 1
R = 0,5°C/s
Tq = 1498°C
d = 90 μm
δ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

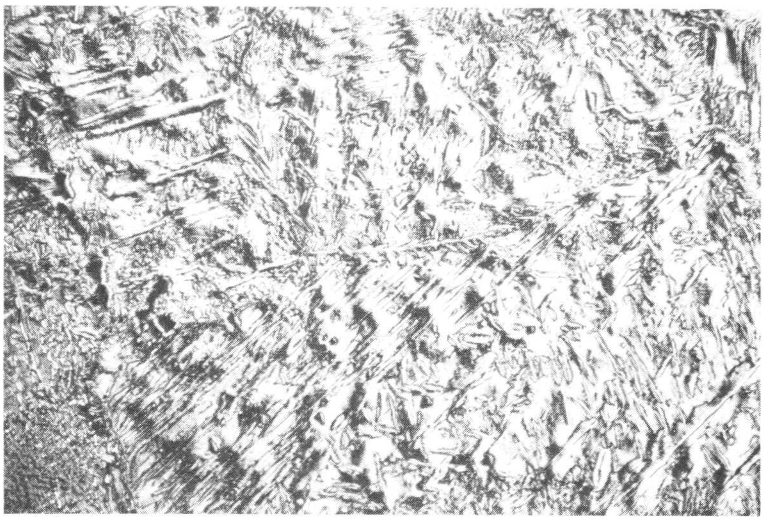


Figure 2
R = 2,0°C/s
Tq = 1400°C
d = 205 μm
Figures 2–3: δ-dendrites.
Light interdendritic areas.
(Interference contrast.)

400 μm × 25

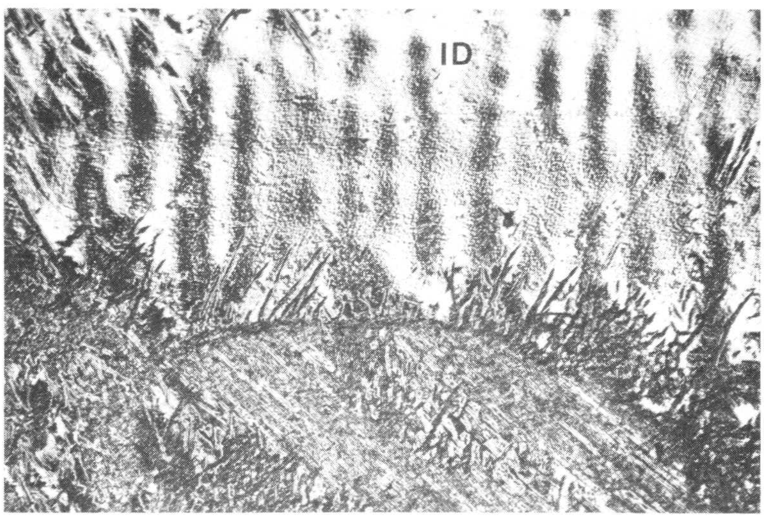


Figure 3
R = 0,5°C/s
Tq = 1400°C
d = 260 μm

400 μm × 25

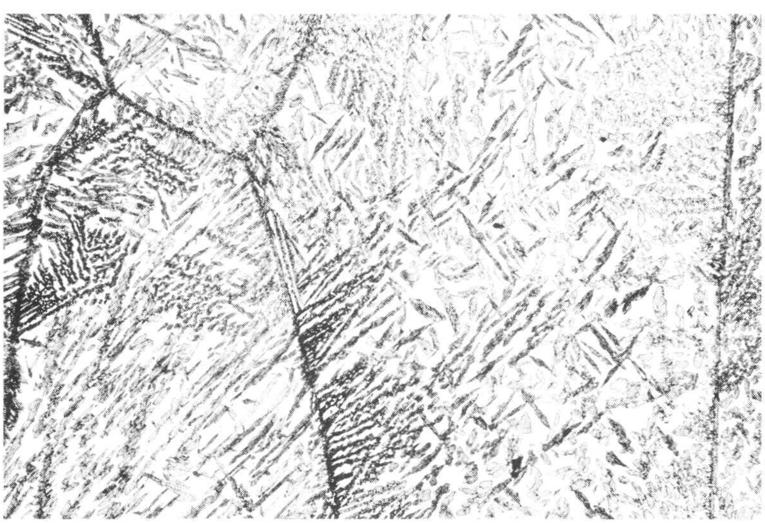


Figure 4
R = 0,1°C/s
Tq = 1400°C
d = –
No dendrites visible due to absence of segregation. Austenite (dark) precipitated during quenching.

400 μm × 25

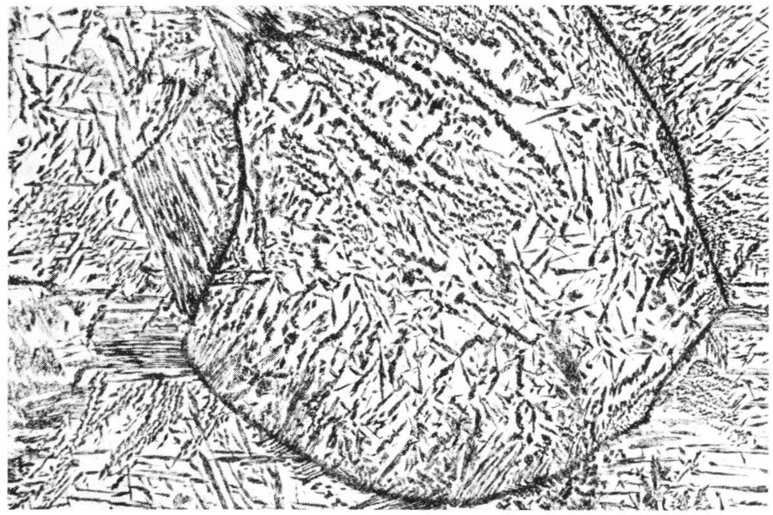


Figure 5
R = 0,5°C/s
Tq = 1400°C
Austenite (dark) precipitated during quenching from 1400°C.

× 25 400 μm

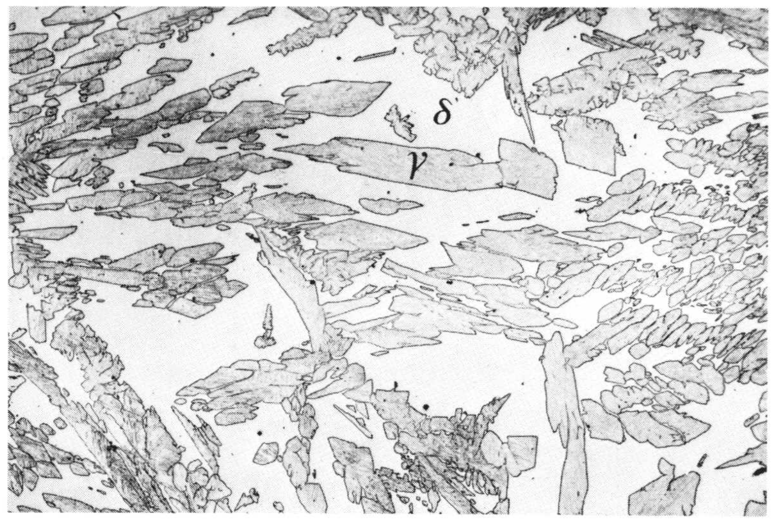


Figure 6
R = 0,5°C/s
Tq = 1200°C
Austenite (γ) precipitated during cooling to 1200°C (solid state transformation).
(d_{1200} = 270 μm)

× 25 400 μm

STEEL 307. 0,1 % C Ni 12 % CHROMIUM STEEL

Designations

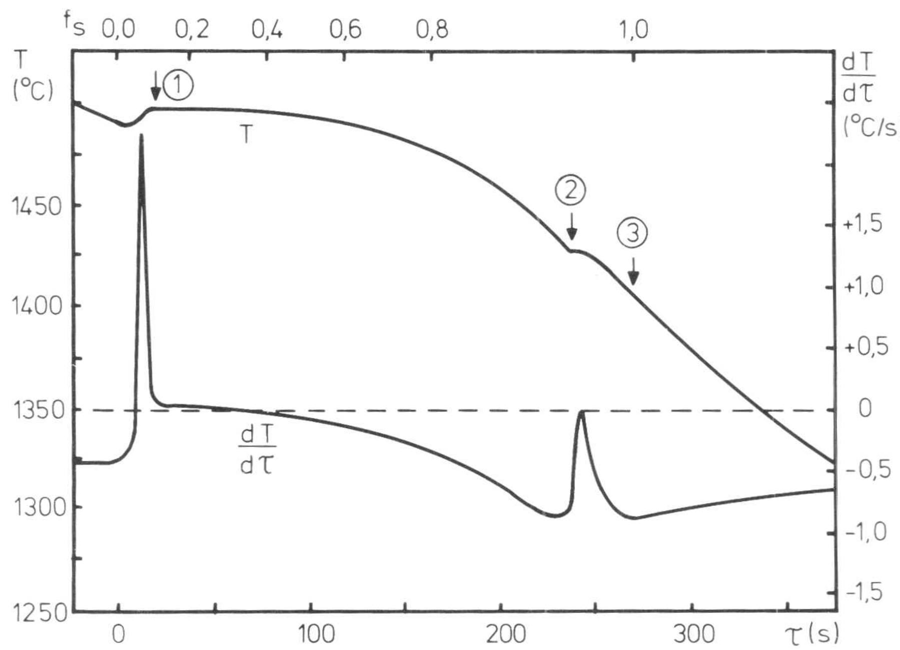
SIS	AISI	Werkstoff Nr
2302	(414)	1.4008

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,14	0,19	0,68	0,009	0,014	12,0	1,20	0,01	0,03	0,01	0,02	0,001	0,040

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1490	1495	1494
Temperature of austenite formation, °C (2)	1416	1425	1401
Solidus temperature, °C (3)	1390	1400	1400
Solidification range, °C	100	95	95
Solidification time, s	95	255	1070

Precipitates

—

Microsegregation

Element	Cr	Ni
I	1,1	1,3

R = 0,5 °C/s
Tq = 1360 °C

Partly solidified

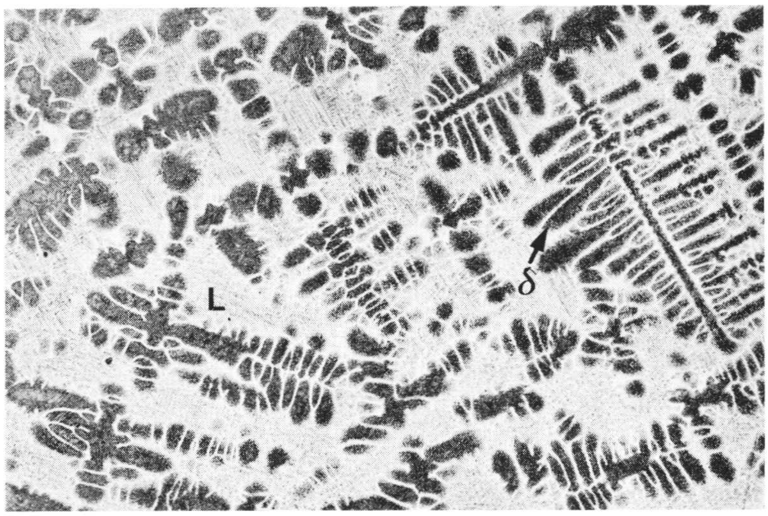


Figure 1
R = 0,5°C/s
Tq = 1493°C
d = 75 μm
δ-dendrites and quenched liquid (L).

× 25 400 μm

Completely solidified

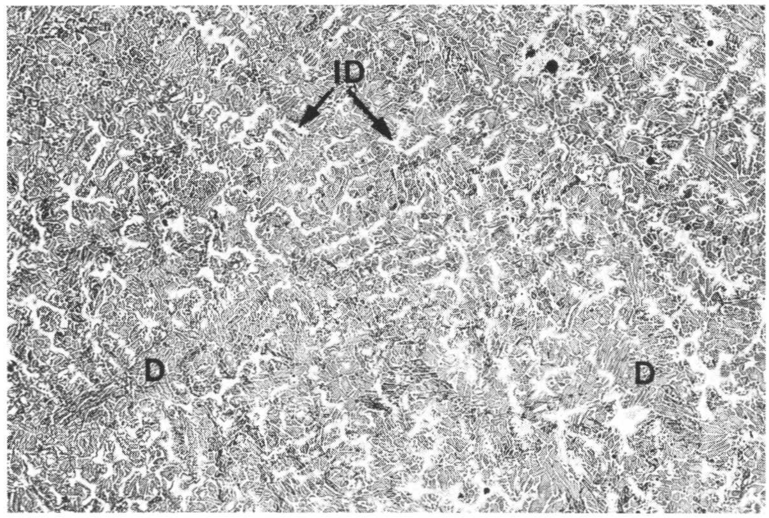


Figure 2
R = 2,0°C/s
Tq = 1360°C
d = 150 μm
Figures 2–4: Former δ-dendrites (D).
White interdendritic areas (ID).
(Most of the δ transformed to γ by the peritectic reaction.)

× 25 400 μm

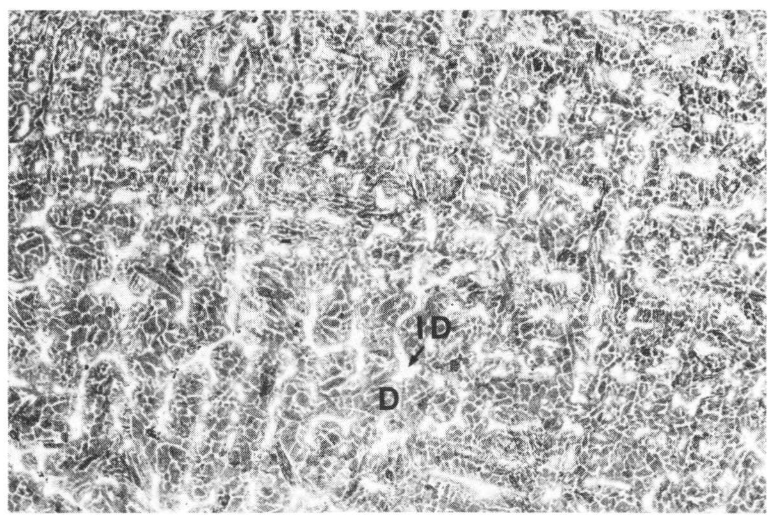


Figure 3
R = 0,5°C/s
Tq = 1360°C
d = 180 μm

× 25 400 μm

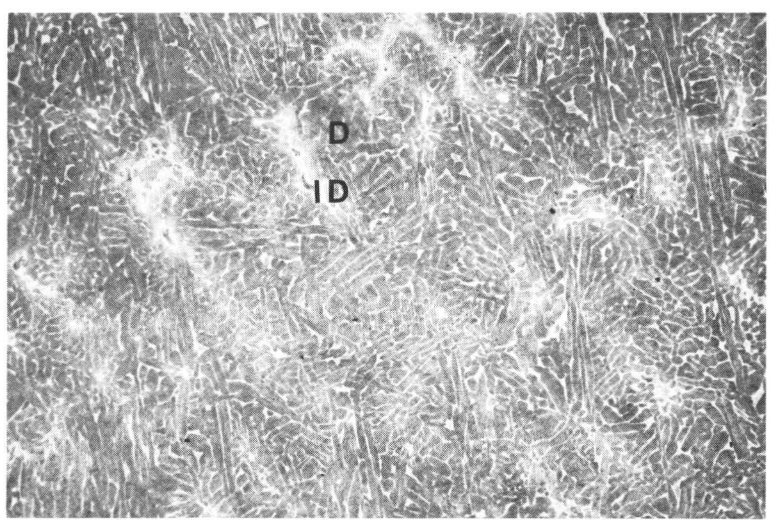


Figure 4
R = 0,1°C/s
Tq = 1360°C
d = 470 μm

× 25 400 μm

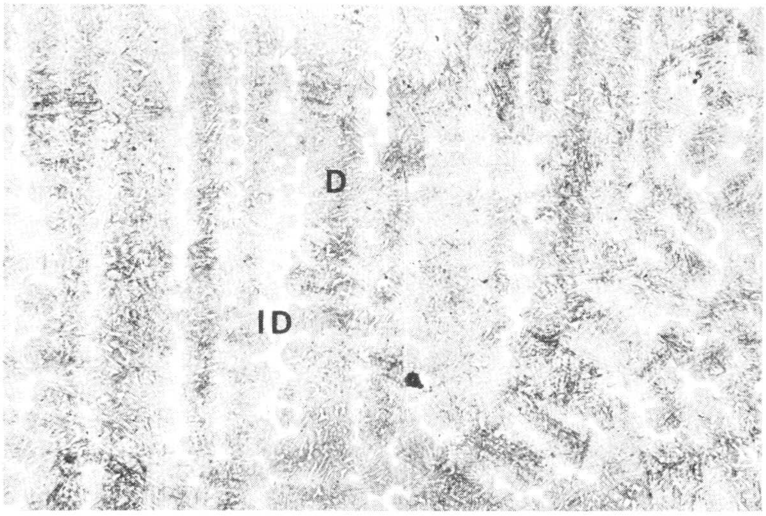


Figure 5
R = 0,5°C/s
Tq = 1200°C
(d_{1200} = 250 μm)
Former δ-dendrites (D).
White interdendritic areas (ID).
(Most of the δ transformed to γ by the peritectic reaction.)

400 μm × 25

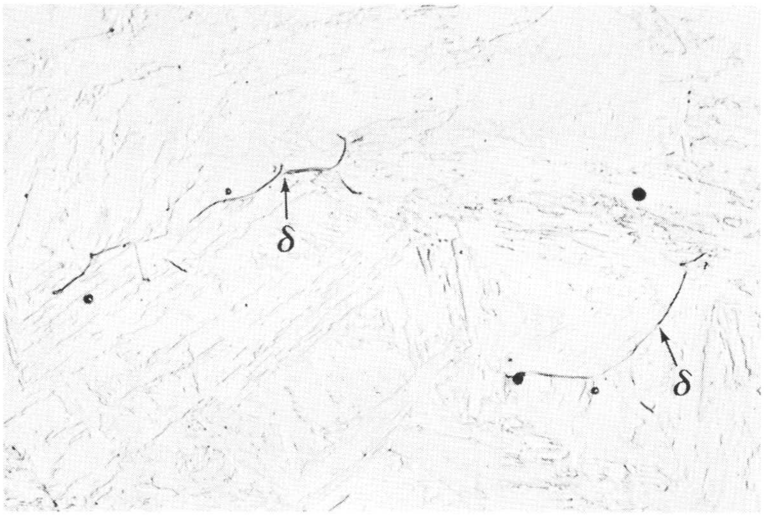


Figure 6
R = 2,0°C/s
Tq = 1360°C
Residual dendritic ferrite (δ) in the γ-matrix.

25 μm × 600

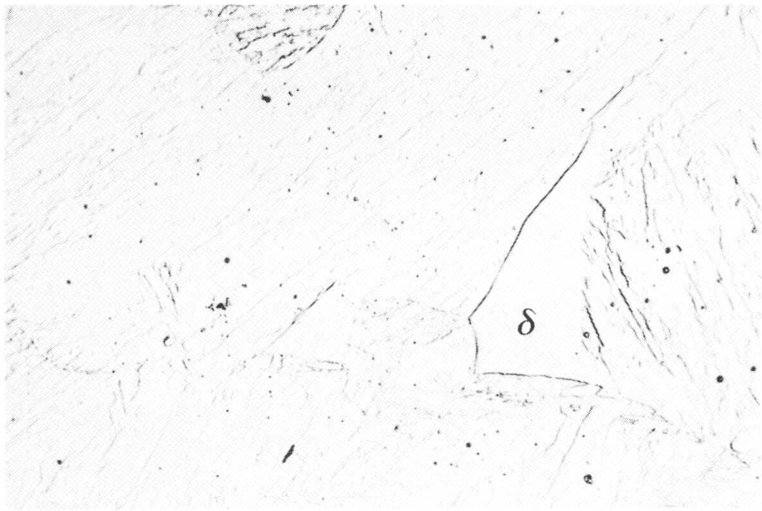


Figure 7
R = 0,1°C/s
Tq = 1360°C
Residual dendritic ferrite (δ) in the γ-matrix.
Figures 6–7: Note the influence of cooling rate on ferrite coarseness.

25 μm × 600

STEEL 308. 0,3 % C 14 % CHROMIUM STEEL

Designations

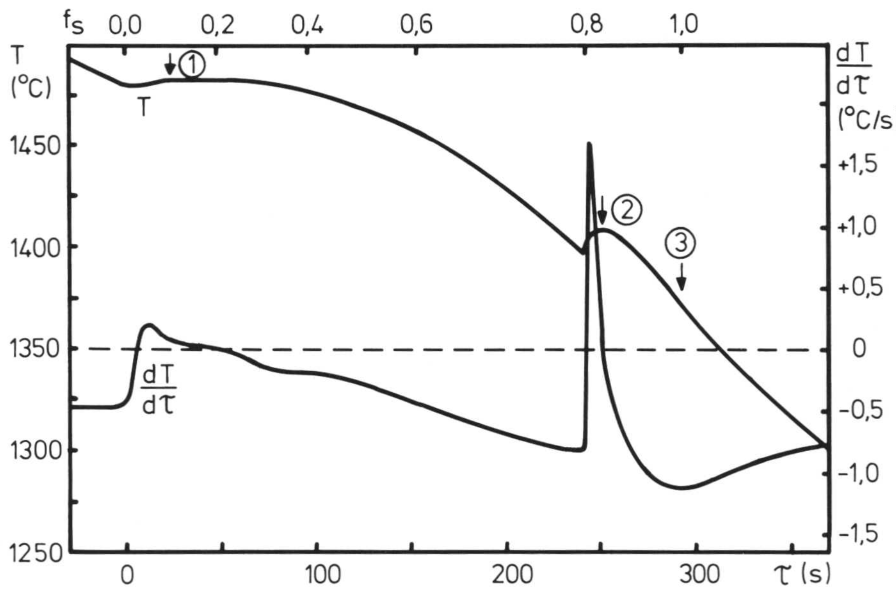
SIS	AISI	Werkstoff Nr
2304	(420)	1.4028

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,32	0,15	0,30	0,009	0,008	13,9	0,16	0,01	0,01	0,22	0,03	0,003	0,013

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1480	1483	1482
Temperature of austenite formation, °C (2)	1400	1407	1401
Solidus temperature, °C (3)	1370	1375	1390
Solidification range, °C	110	105	90
Solidification time, s	100	290	1100

Precipitates

Interdendritic ferrite, (see figures 7–8).

Microsegregation

Element	Cr	Ni	
I	1,2	1,0	R = 0,5 °C/s Tq = 1345 °C

Partly solidified

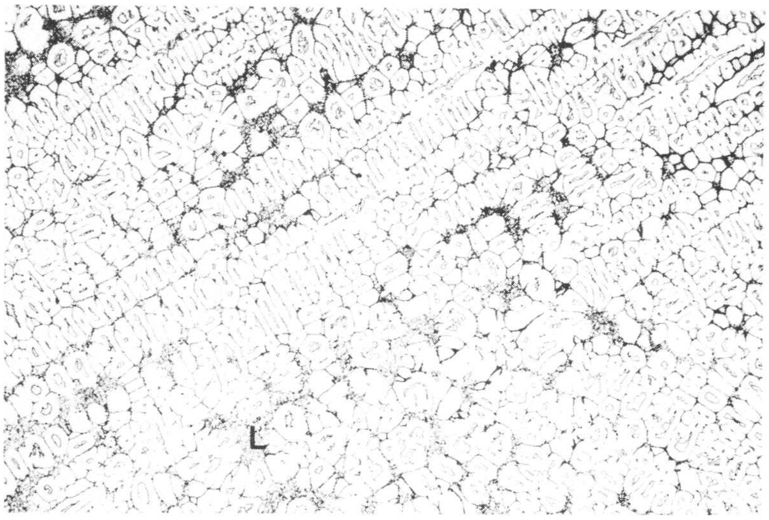


Figure 1
R = 0,5°C/s
Tq = 1410°C
d = 75 μm
δ-dendrites (almost completely transformed to γ) and quenched liquid (L), (compare figure 6).

400 μm × 25

Completely solidified

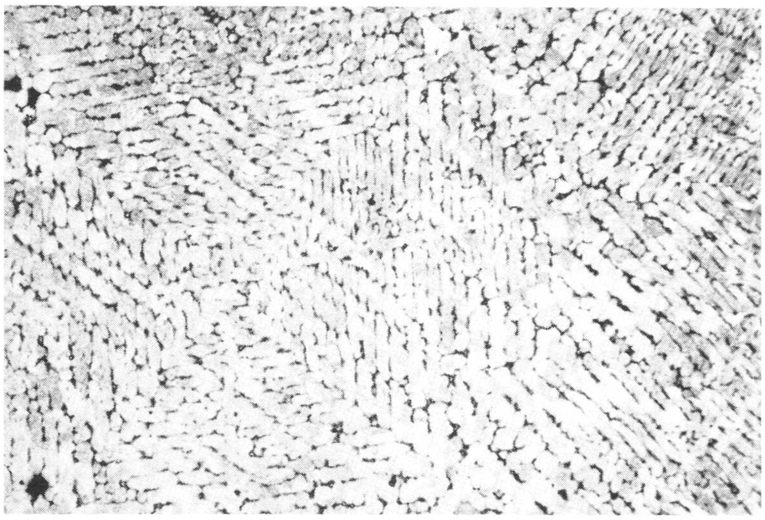


Figure 2
R = 2,0°C/s
Tq = 1345°C
d = 75 μm
Figures 2–4: Former δ-dendrites, (transformed to γ by the peritectic reaction), and interdendritic ferrite (δ).

400 μm × 25

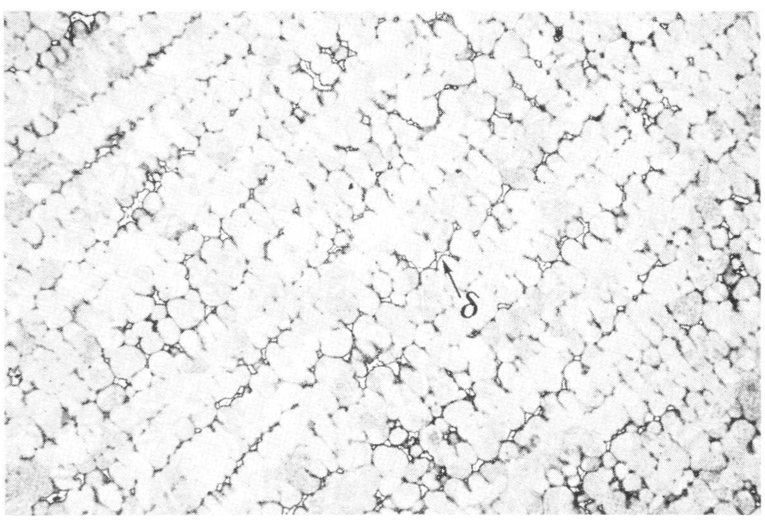


Figure 3
R = 0,5°C/s
Tq = 1345°C
d = 100 μm

400 μm × 25

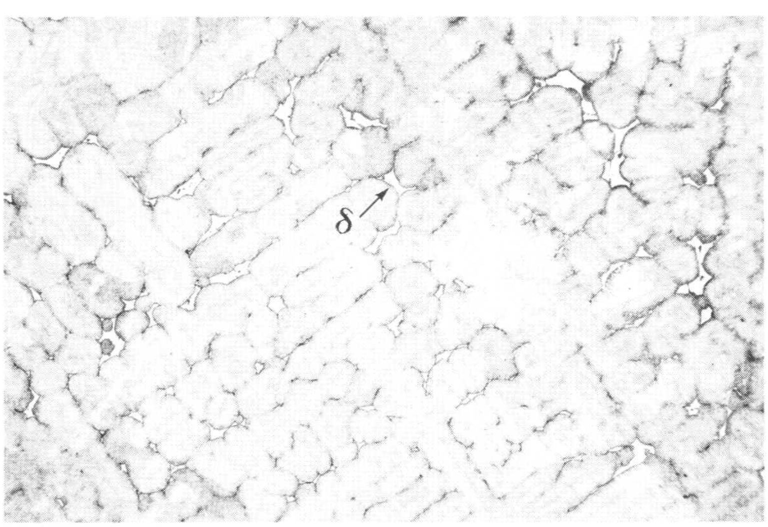


Figure 4
R = 0,1°C/s
Tq = 1345°C
d = 210 μm

400 μm × 25

Figure 5
R = 0,5°C/s
Tq = 1200°C
(d_{1200} = 110 μm)
Former δ-dendrites, (transformed to γ by the peritectic reaction), and interdendritic ferrite (δ).

× 25 400 μm

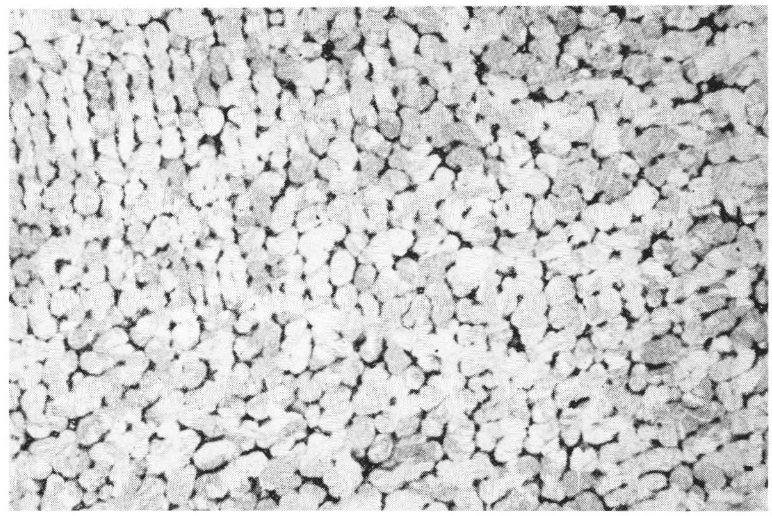


Figure 6
R = 0,5°C/s
Tq = 1410°C
Former δ-dendrite, almost completely transformed to γ by the peritectic reaction, with residual δ in the centre. L = quenched liquid.

× 150 100 μm

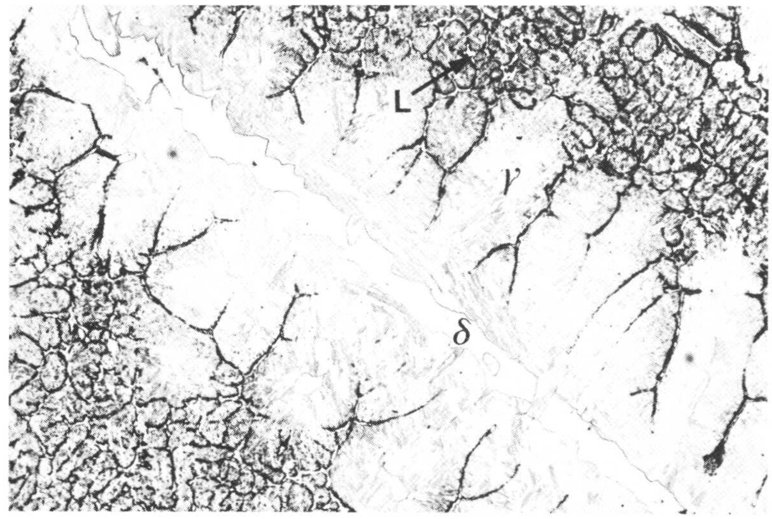


Figure 7
R = 2,0°C/s
Tq = 1345°C
Interdendritic ferrite (δ).

× 150 100 μm

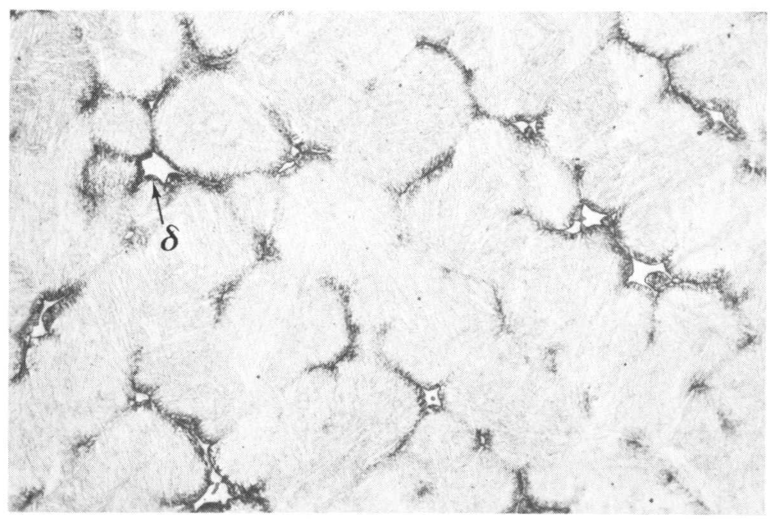
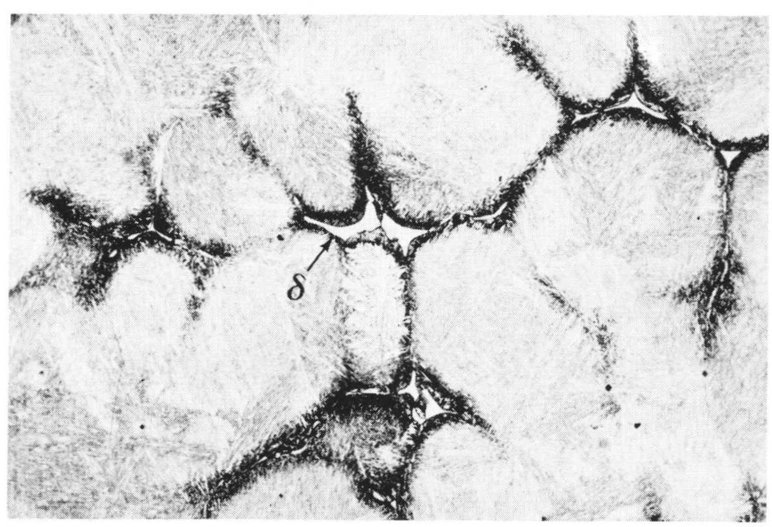


Figure 8
R = 0,5°C/s
Tq = 1200°C
Interdendritic ferrite (δ).

× 150 100 μm



STEEL 309. 0,7 % C 13 % CHROMIUM STEEL

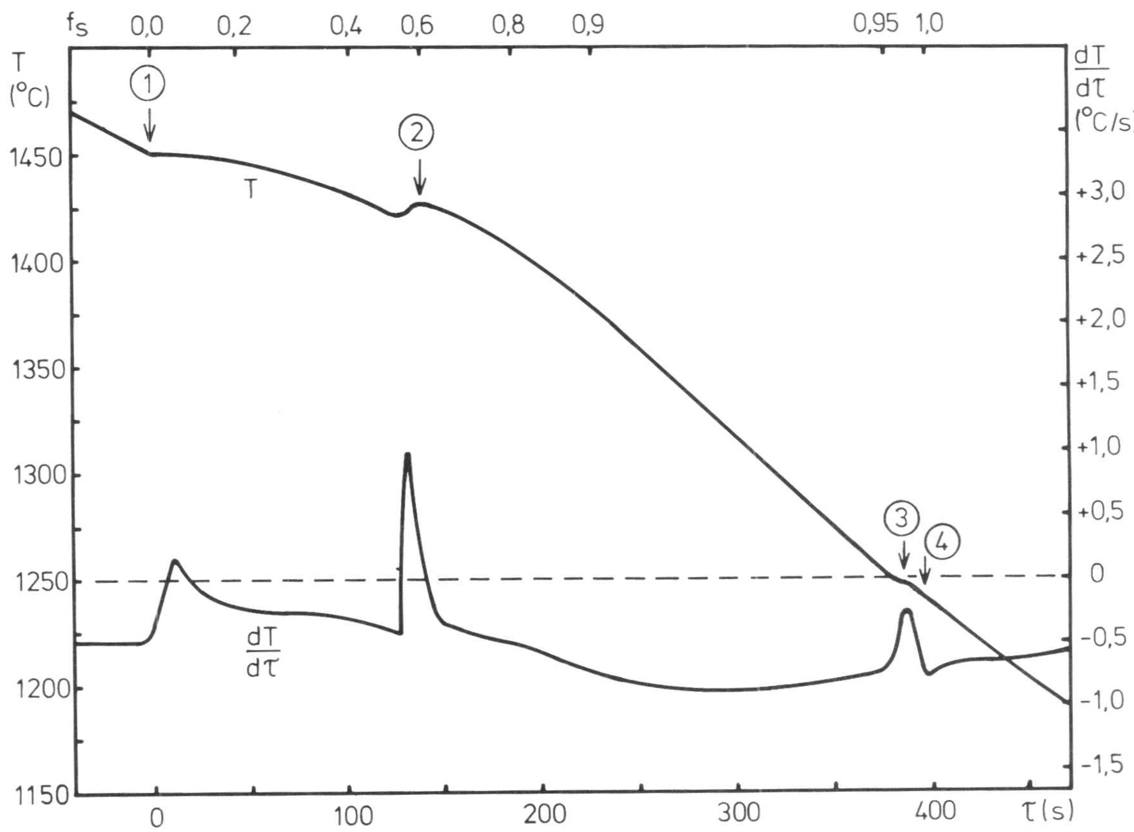
Designations

SIS	AISI	Werkstoff Nr
–	–	–

Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	W	V	Al_{tot}	N
0,69	0,43	0,64	0,014	0,005	13,1	0,20	0,07	0,02	0,22	0,03	0,002	0,025

Thermal Analysis



R = 0,5°C/s

	Average Cooling Rate, R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1442	1448	1444
Temperature of austenite formation, °C (2)	1414	1422	1415
Temperature of formation of eutectic, °C (3)	1240 – 1195	1250 – 1240	1260 – 1245
Solidus temperature, °C (4)	1195	1240	1245
Solidification range, °C	245	210	200
Solidification time, s	160	405	2140

Precipitates

Interdendritic M_7C_3-austenite eutectic. The amount of carbide eutectic increased with increasing cooling rate, (see figures 5 – 8).

Microsegregation

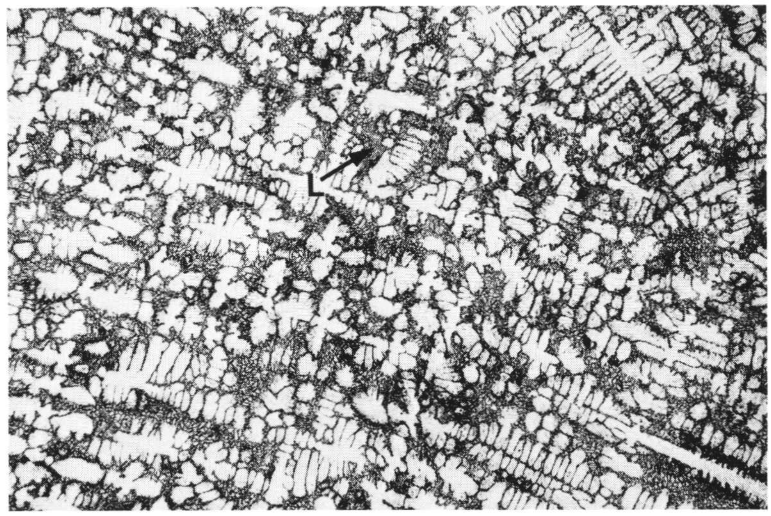
Element	Cr	Ni
I	1,2	1,0

R = 0,5 °C/s
Tq = 1240 °C

Partly solidified

Figure 1
R = 0,5°C/s
Tq = 1418°C
d = 50 μm
Former δ-dendrites, (completely transformed to γ by the peritectic reaction), and quenched liquid (L).

× 25 400 μm



Completely solidified

Figure 2
R = 2,0°C/s
Tq = 1195°C
d = 65 μm
Figures 2–4: Former δ-dendrites, (transformed to γ by the peritectic reaction).
Interdendritic carbide eutectic (compare figures 5–8).

× 25 400 μm

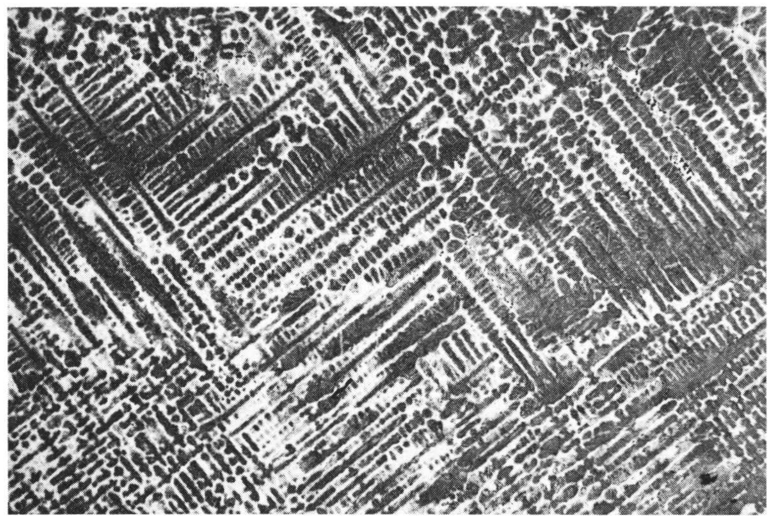


Figure 3
R = 0,5°C/s
Tq = 1240°C
d = 80 μm

× 25 400 μm

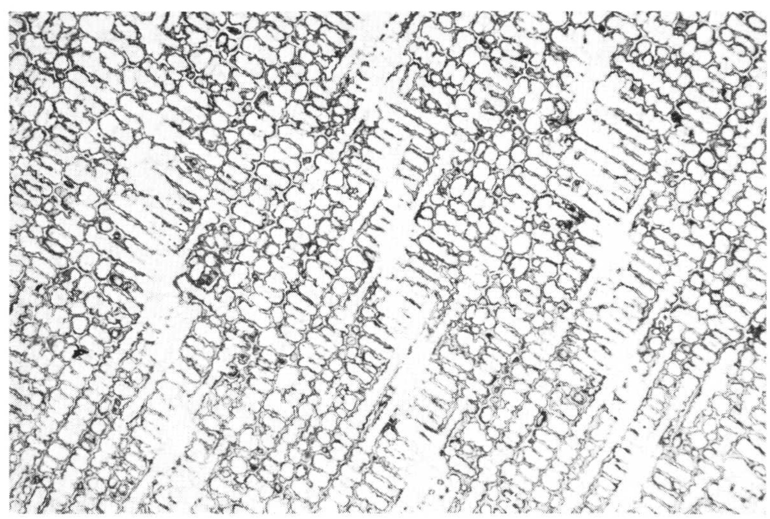
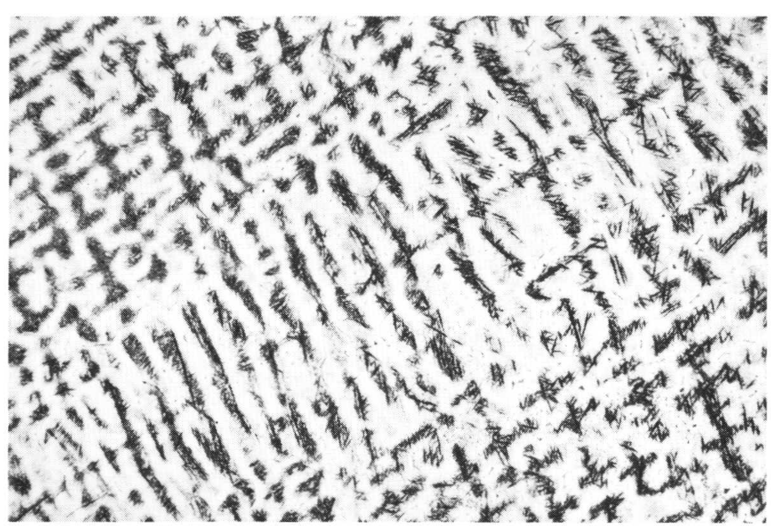


Figure 4
R = 0,1°C/s
Tq = 1240°C
d = 130 μm

× 25 400 μm



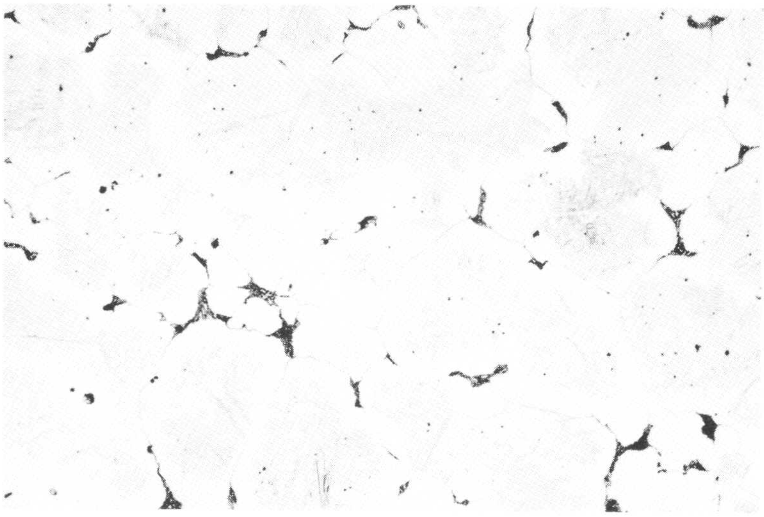


Figure 5
R = 0,5°C/s
Tq = 1240°C
Interdendritic M_7C_3-γ eutectic. 3,5 vol-% carbide.

100 μm × 150

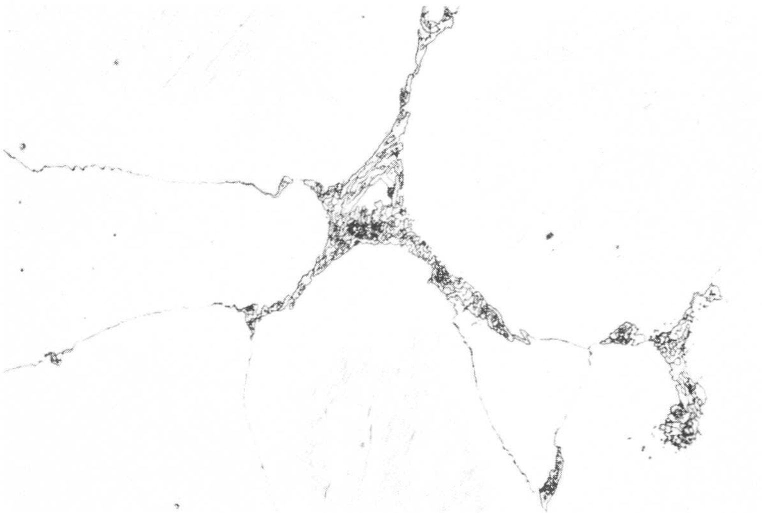


Figure 6
R = 2,0°C/s
Tq = 1195°C
M_7C_3-γ eutectic. 4,5 vol-% carbide.

25 μm × 600

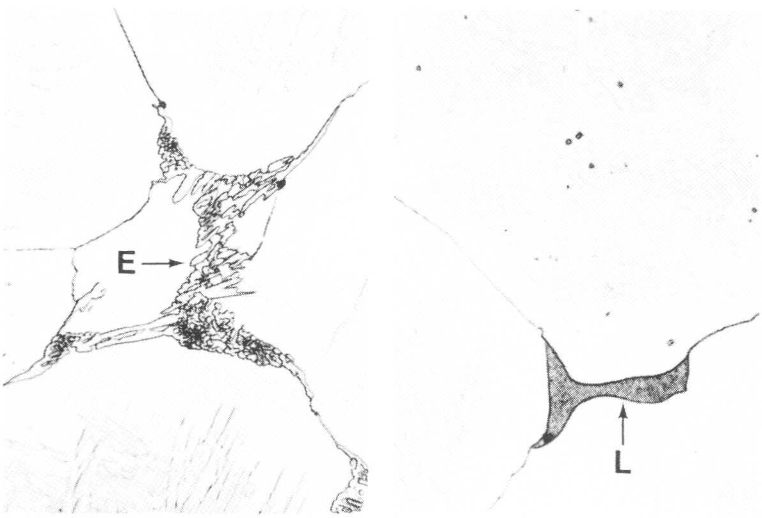


Figure 7
R = 0,5°C/s
Tq = 1245°C
M_7C_3-γ eutectic (E) and small amounts of liquid (L).

25 μm × 600

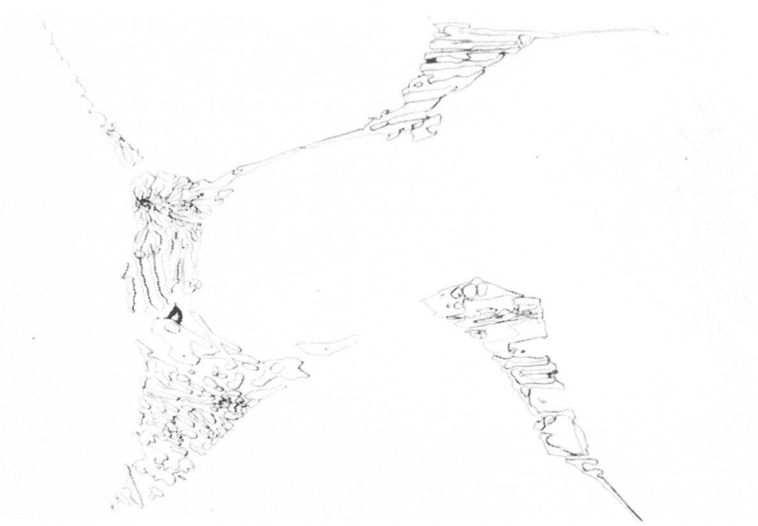


Figure 8
R = 0,1°C/s
Tq = 1240°C
M_7C_3-γ eutectic. 2,4 vol-% carbide.

25 μm × 600

4. Stainless and Heat Resistant Steels

The main alloying element is chromium in amounts between 12 and 30%. Most common stainless steels also contain considerable quantities of other alloying elements of which molybdenum and nickel are the most important. The main object of these additions is to increase the corrosion resistance of the steel and to control the phase composition of the microstructure in the final product.

Most commercial stainless and heat resistant steels are found in the following range of standardized compositions, table 4.1:

Structure of the steel product	C	Cr	Ni %
Ferritic	−0,08	12−14	
	−0,10	16−19	
	−0,25	24−28	
Martensitic	−0,08	12−14	3−6
	0,09−	12−14	
	0,15−	16−18	1,3−2,5
Ferritic-austenitic	−0,10	18−30	4,5−14
Austenitic	−0,50	16−26	7−35

Table 4.1 Classification of stainless and heat resistant steels

The structure of the final product should not be confused with the structures present during and immediately after solidification. Many austenitic steels for instance contain considerable quantities of ferrite in their solidification structure.

Other common alloying elements are molybdenum up to 5% and copper up to 3%. Nitrogen, which is usually present at residual levels of about 0,03−0,06%, can also be used as an alloying addition of up to 0,2%.

Austenitic steels are produced as castings, ingots of all sizes and as continuously cast billets and slabs. The other types of stainless and heat resistant materials mentioned in table 4.1 are cast predominantly as ingots of a moderate size, although martensitic and ferritic-austenitic steels are also commonly used as castings.

The solidification behaviour is governed by the proportions of austenite- and ferrite-forming elements present. The first group comprises carbon, nitrogen, nickel, manganese, copper and cobalt. (At high concentrations manganese has been reported to be a ferrite former, [66].)

The most important ferrite formers are chromium, silicon, molybdenum, niobium, titanium and aluminium. The ferritic and martensitic grades have already been described in chapter 3. The alloys of the present section, belonging to the ferritic-austenitic and the austenitic groups were chosen to give examples of the different solidification paths. The alloys are listed in table 4.2 in order of increasing tendency to solidify as austenite:

No.	C	Si	Mn	Cr	Ni	Mo	Others %
401	0,04	0,9	0,8	25,1	4,7	1,2	
402	0,01	0,3	1,8	19,8	9,9	–	
403	0,02	0,3	0,9	19,5	10,3	–	
404	0,04	0,4	1,2	18,4	9,1	0,4	
405	0,07	0,6	1,4	17,2	10,3	0,5	0,5 Ti
406	0,05	0,4	1,7	17,2	12,6	2,8	0,5 Nb
407	0,02	0,5	1,6	17,2	13,5	2,6	
408	0,05	0,6	1,7	17,7	13,4	2,7	
409	0,02	0,6	1,8	17,4	12,8	2,8	0,19 N
410	0,01	0,2	1,8	25,1	22,2	2,3	
411	0,06	1,2	1,8	24,2	20,4	–	
412	0,13	0,5	1,7	24,3	20,5	–	
413	0,01	0,5	1,7	19,2	25,1	4,4	1,5 Cu
414	0,41	1,0	1,3	25,2	20,6	–	
415	0,07	0,6	0,6	21,1	31,0	–	

Table 4.2 Stainless and heat resistant steels

The choice of these alloys was based on the solidification modes indicated by the pseudobinary phase diagrams, such as that shown in figure 4.1.

The types of solidification are:

- primary ferrite formation
- primary ferrite formation followed by a three-phase reaction between liquid, δ and γ.
- primary ferrite and austenite formation
- primary austenite formation

In this work the transition δ + liquid → γ is called peritectic *reaction* as long as the δ- phase is in direct contact with the liquid. When δ is completely surrounded by γ -phase and the reaction rate is governed by solid state diffusion of the alloying elements through γ, the process is denoted peritectic *transformation*.

The relative amount of austenite usually increases below the solidus temperature, i.e. the remaining δ-ferrite content is dependent on temperature. In alloys with a high carbon content carbides precipitate during solidification.

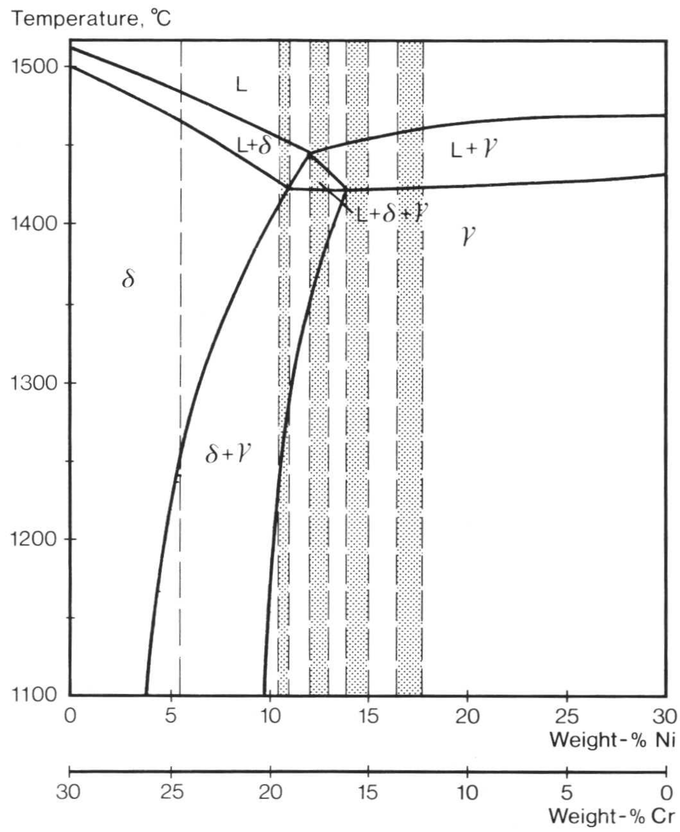


Figure 4.1 Phase diagram Fe-Cr-Ni at 70% Fe. (After Metals Handbook, Vol 8, 1973, 424−425)

References

The solidification of stainless and heat resistant alloys has been the subject of many research reports. Papers on general aspects of solidification and phase equilibria include references [65−77]. Quantitative discussions of microsegregation have been presented, [68, 69, 71, 73, 77−82].

Finally, solidification under welding conditions has also received attention, [72, 79, 83−86].

STEEL 401. 0,04 % C 25 % Cr 5 % Ni Mo STAINLESS STEEL

Designations

SIS	AISI	Werkstoff Nr
2324	(329)	(1.4460)

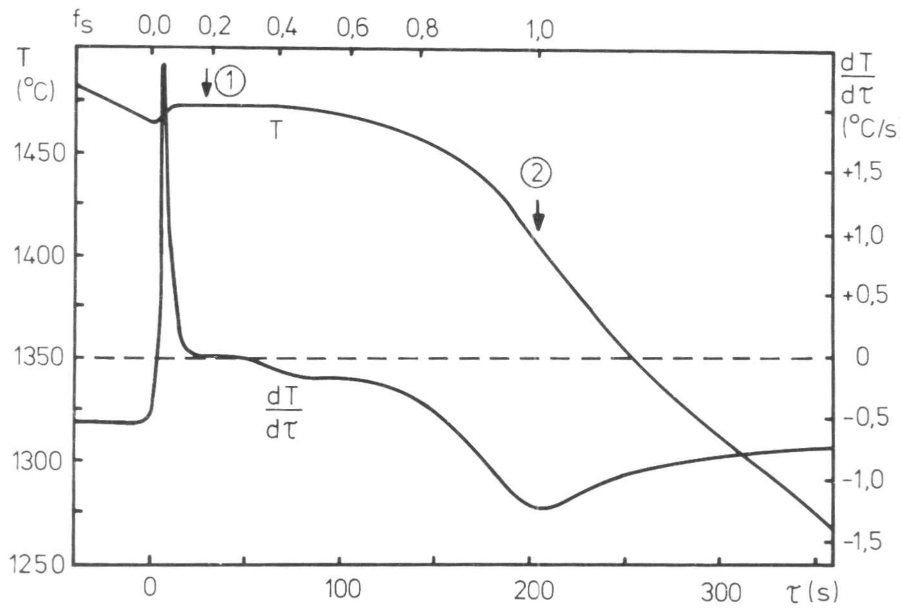
Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Co	Al_{tot}	N
0,042	0,86	0,76	0,031	0,010	25,1	4,7	1,22	0,08	0,08	≤0,002	0,077

$\frac{Cr_{eq}}{Ni_{eq}} = 4,01$

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate,R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1465	1471	1469
Solidus temperature, °C (2)	1390	1410	1420
Solidification range, °C	75	60	50
Solidification time, s	80	205	770
Fraction solidified as ferrite, %	100	100	100

Precipitates

$M_{23}C_6$ particles and austenite in grain boundaries and $M_{23}C_6$ particles in the matrix, (see figures 5–8).
The carbide and austenite were precipitated during quenching from 1360°C.

Microsegregation

Element	Mn	Cr	Ni	Mo
I	1,3	1,0	1,2	1,3

R = 0,5 °C/s
Tq = 1360 °C

Partly solidified

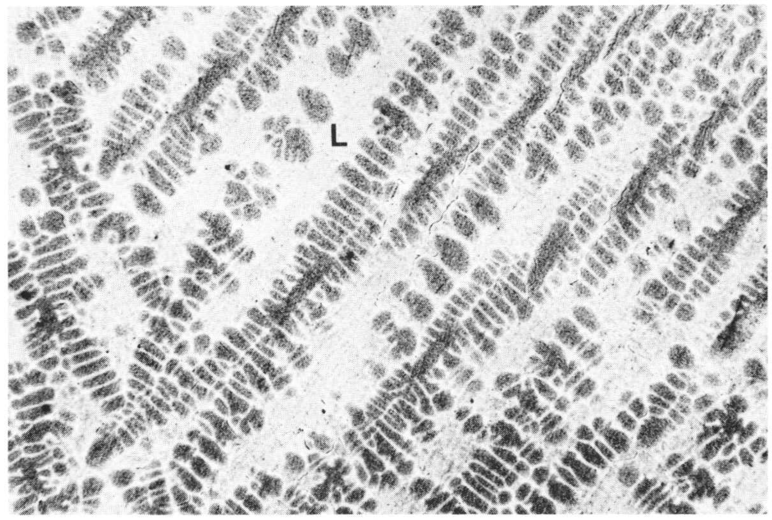


Figure 1
R = 0,5°C/s
Tq = 1468°C
d = 70 μm
δ-dendrites and quenched liquid (L).

× 25 400 μm

Completely solidified

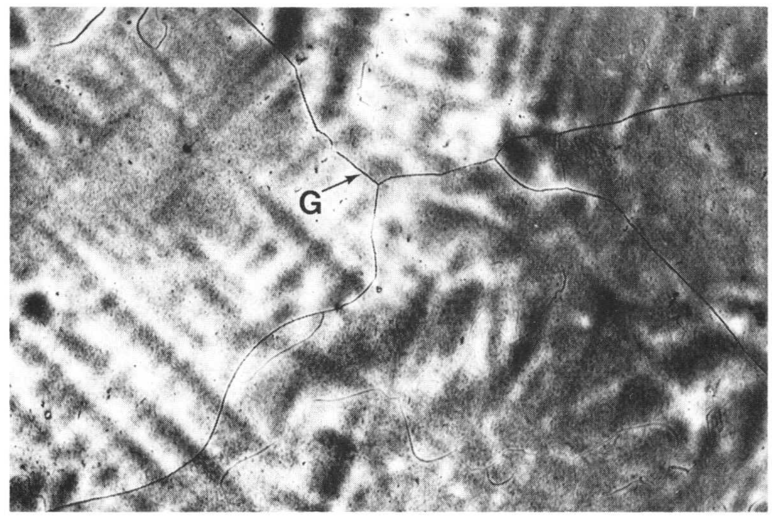


Figure 2
R = 2,0°C/s
Tq = 1360°C
d = 115 μm
Figures 2–4: δ-dendrites.
White interdendritic areas (ID). Grain boundaries (G) also visible.

× 25 400 μm

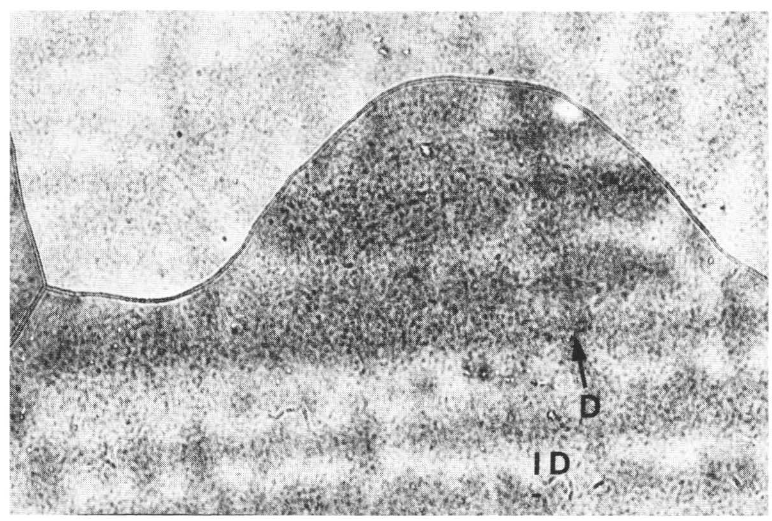


Figure 3
R = 0,5°C/s
Tq = 1360°C
d = 280 μm

× 25 400 μm

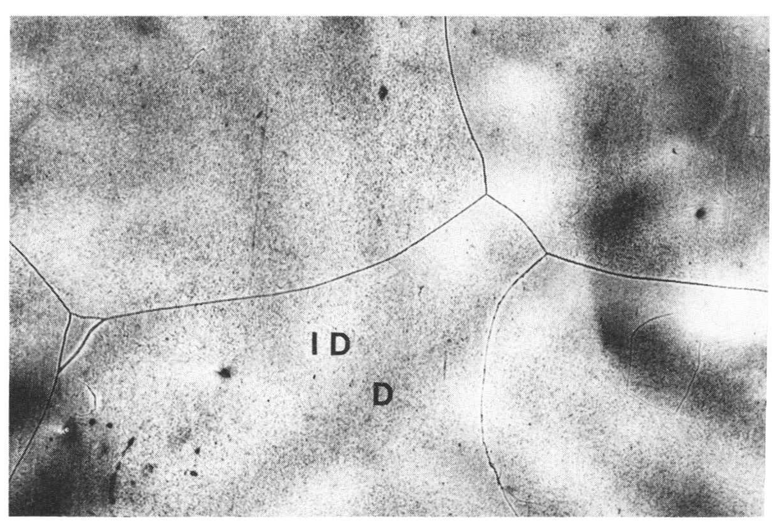


Figure 4
R = 0,1°C/s
Tq = 1360°C
d = 550 μm

× 25 400 μm

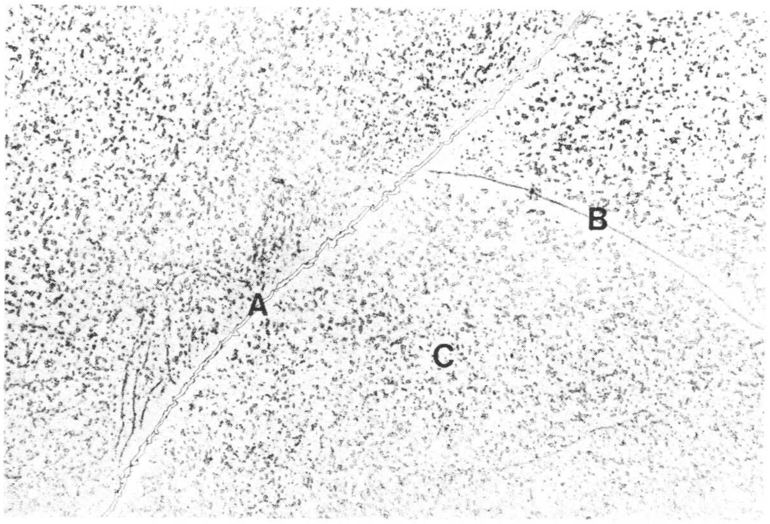


Figure 5
R = 0,5°C/s
Tq = 1360°C
A = grain boundary with austenite.
B = grain boundary with carbide particles.
C = ferritic matrix with carbide and austenite precipitates.

100 μm × 150

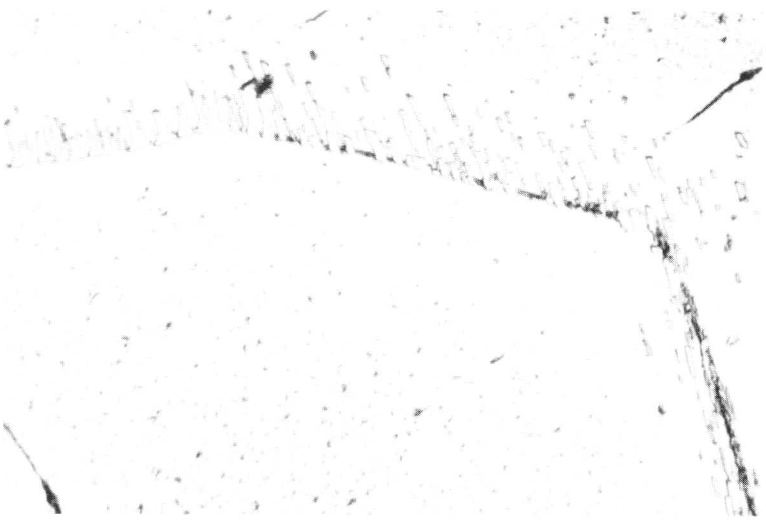


Figure 6
R = 0,5°C/s
Tq = 1360°C
Austenite, formed during quenching, in grain boundary as in fig 5 at A.

10 μm × 1000

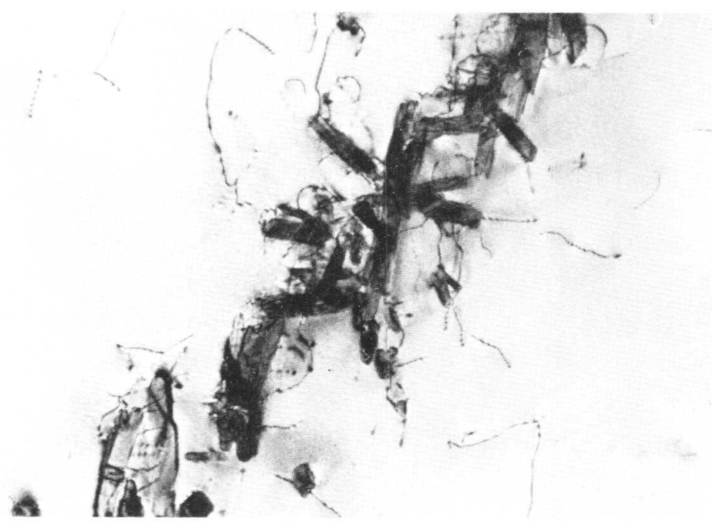


Figure 7
R = 0,5°C/s
Tq = 1360°C
Carbide particles ($M_{23}C_6$), formed during quenching, in a grain boundary as in fig 5 at B. Electron micrograph of thin foil (TEM).

0,5 μm × 30 000

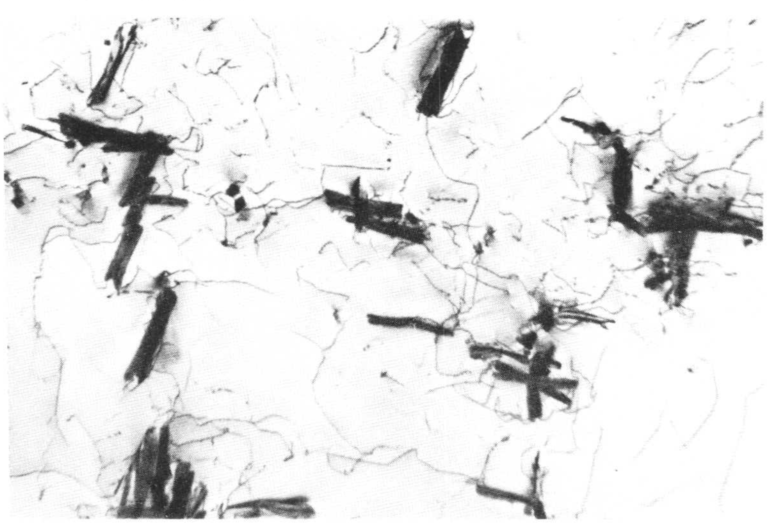


Figure 8
R = 0,5°C/s
Tq = 1360°C
Carbide particles ($M_{23}C_6$), formed during quenching, in the ferritic matrix as in fig 5 at C. Electron micrograph of thin foil (TEM).

1 μm × 15 000

STEEL 402. 0,01 % C 20 % Cr 10 % Ni STAINLESS STEEL

Designations

SIS	AISI	Werkstoff Nr
—	308L	1.4316

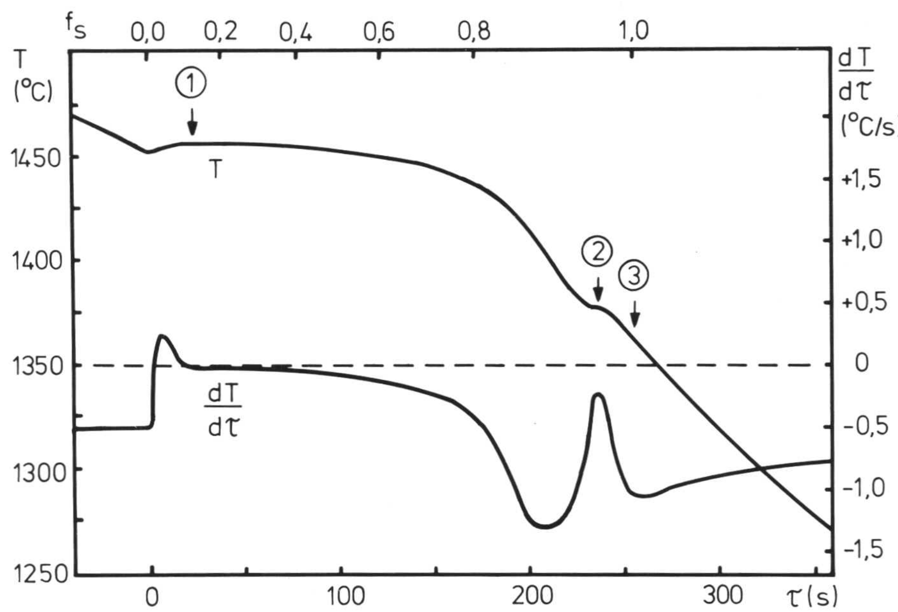
Composition (wt–%)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Co	Al_{tot}	N
0,012	0,31	1,76	0,008	0,008	19,8	9,9	0,10	0,04	0,02	0,004	0,031

$\frac{Cr_{eq}}{Ni_{eq}} = 1,82$

Thermal Analysis

R = 0,5°C/s



	Average Cooling Rate, R, (°C/s)		
	2,0	0,5	0,1
Liquidus temperature, ferritic primary phase, °C (1)	1447	1454	1449
Temperature of austenite formation, °C (2)	1366	1391	1405
Solidus temperature, °C (3)	1325	1360	1390
Solidification range, °C	120	95	60
Solidification time, s	105	255	690
Fraction solidified as ferrite, %	92	91	97

Precipitates

—

Microsegregation

Element	Si	Mn	Cr	Ni

R = 0,5 °C/s

Partly solidified

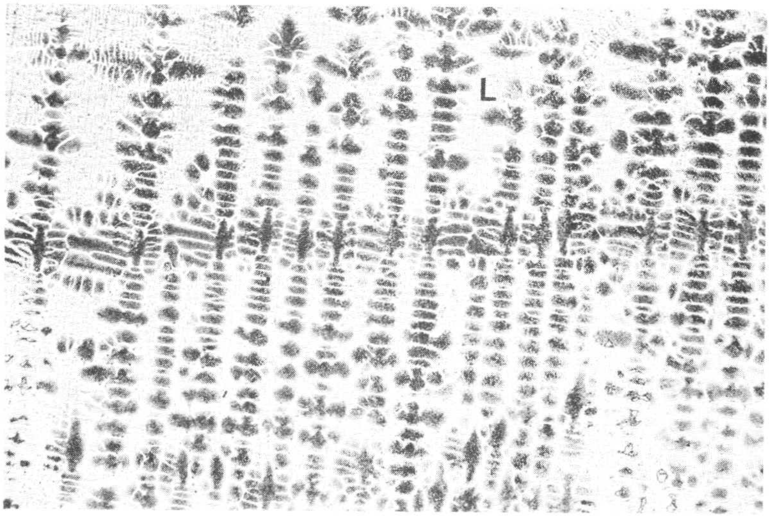


Figure 1

R = 0,5°C/s
Tq = 1450°C
d = 60 μm
δ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

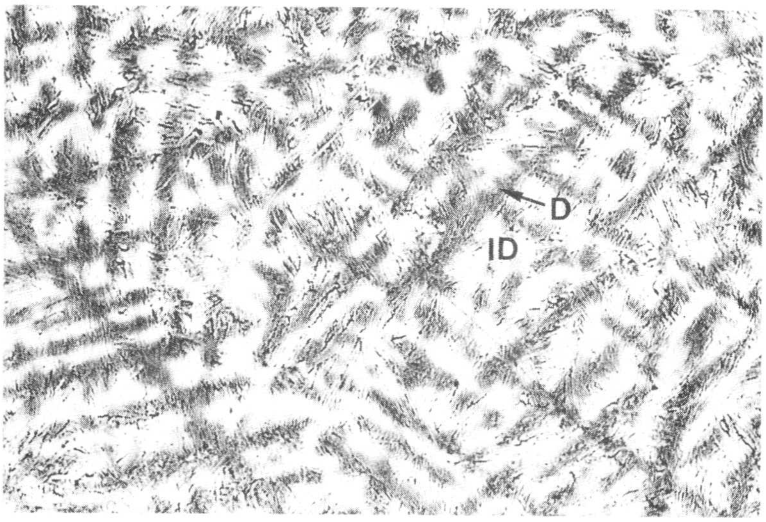


Figure 2

R = 2,0°C/s
Tq = 1325°C
d = 150 μm
Figures 2–4: Former δ-dendrites (D).
White interdendritic areas (ID).
(Most of the δ transformed to γ by the peritectic reaction and transformation.)

400 μm × 25

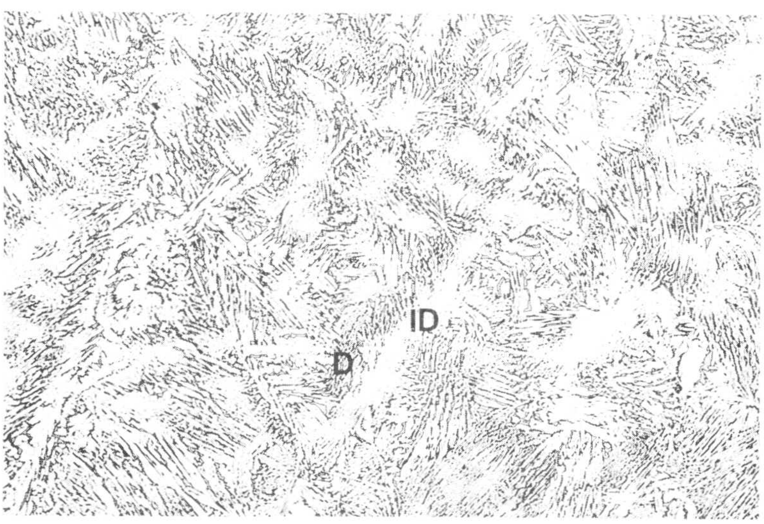


Figure 3

R = 0,5°C/s
Tq = 1325°C
d = 270 μm

400 μm × 25

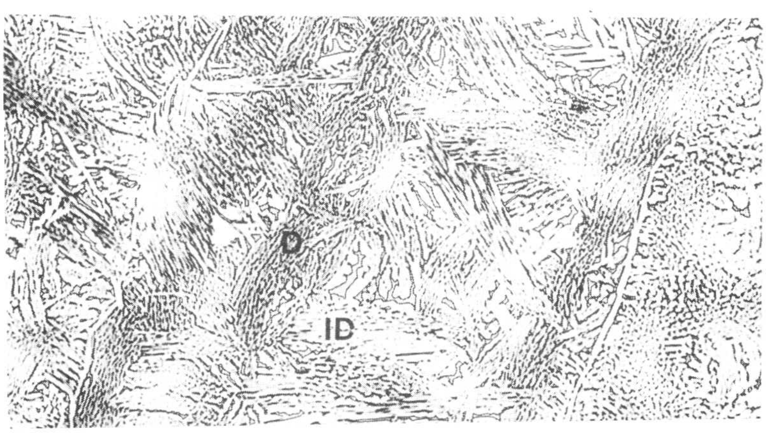


Figure 4

R = 0,1°C/s
Tq = 1325°C