ISOTHERMAL TRANSFORMATION DIAGRAMS OF NICKEL ALLOY STEELS

INCO

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Location of I-T Diagrams

[a] The AISI-SAE system for numbering steels is used if applicable.
[b] AISI-SAE Standard Steel, "1965 SAE Handbook."
[c] Aerospace Materials Specification.
[d] AISI Standard Tool Steel, "Tool Steels," April 1963.
[e] Tool steel designation used in Metals Handbook.[6]

Isothermal Transformation Diagrams of Nickel Alloy Steels

INTRODUCTION

The I-T diagrams presented in this bulletin come from several sources. In the interest of uniformity, all have been redrawn on a standard form. Dashed lines are used for those portions of the curves about which the investigators are uncertain. Investigators differ as to the proper criterion for establishing the beginning of transformation; consequently, the criterion used is shown on each diagram for which it could be obtained.

CRITICAL AND MARTENSITE FORMATION TEMPERATURES

Equilibrium temperatures Ae_1 and Ae_3, shown on the diagrams, were determined usually by metallographic observations on a series of specimens austenitized in the usual manner, quenched to produce a fully martensite structure, reheated to different temperatures in the vicinity of Ae_1 and Ae_3, and quenched in water after holding long enough to establish equilibrium. The Ac_1 and Ac_3 temperatures given on a few diagrams are for variable, but slow, heating rates.

The M_s, M_{50} and M_{90} temperatures are those furnished by the laboratory which did the work for the I-T diagram. If they are not given, they can be calculated, using the methods of Grange and Stewart[1] or Steven and Haynes.[2]

GRAIN SIZE

The information on grain size is for the austenite grain size developed in the steel by the austenitizing temperature shown. In some early charts grain size was not reported because its importance was not recognized.

WROUGHT AND CAST STEELS

All of the diagrams are based on wrought steels, except that one is for weld metal. However, data for cast steels are included on the diagrams for 2330 and 4330.* The similarity indicates that wrought steel diagrams can be used for cast steels, keeping in mind that segregation is usually greater in the cast steels.

APPROXIMATE NATURE OF I-T DIAGRAMS

In using I-T diagrams to establish suitable heat treatments, the approximate nature of the curves should be clearly recognized. Each diagram is based on the investigation of a single heat of steel. Normal variations in steels of the same type, particularly chemical composition, segregation, and austenite grain size may greatly influence transformation characteristics.

USE OF I-T DIAGRAMS TO ESTIMATE TRANSFORMATION UNDER CONTINUOUS COOLING CONDITIONS

The transformation behavior of a steel during continuous cooling, such as exists in normal quenching operations, is represented most accurately by continuous cooling transformation (C-T) diagrams, as shown in another bulletin.** Relatively few C-T diagrams are available but useful practical estimates of continuous cooling transformation can be deduced from I-T diagrams by use of the cooling curve adapter. The use of this device is described in Appendix I.

* The AISI-SAE system for numbering steels is used if applicable.

** Bulletin 6-A, "Hardenability of Nickel Alloy Steels."

APPENDIX I. COOLING CURVE ADAPTER

(Located inside back cover)

The cooling curve adapter comprises a series of continuous cooling rate curves drawn to the same temperature-log time scale as used in the I-T diagrams. Therefore, when such continuous cooling rate curves are superimposed on an I-T diagram, an indication can be obtained of the times and temperatures at which transformation will start and finish.

It must be emphasized, however, that the indications are only approximate because cooling tends to shift the time-temperature-transformation relationships of the I-T diagram downward and to the right. The extent of the displacement is a function of the cooling rate.

Use of the Adapter

The adapter is placed on the diagram with the vertical straight lines superimposed upon the vertical (left and right) boundaries of the diagram. The device is positioned with the horizontal reference line (near the top of the adapter) located at the temperature from which controlled cooling begins, ordinarily this will be the Ae_1 temperature.

As an example, suppose it is desired to anneal 8640 steel to a hardness of about Rockwell C 12 by controlled furnace cooling. The adapter is superimposed on the I-T diagram for 8640 with the horizontal reference line set at 1300 F (the Ae_1 temperature). Inspection shows immediately that the cooling rate that intersects the end of transformation curve at Rockwell C 12 (by interpolation) is 50°F per hour and the temperature is about 1230 F. To allow for displacement of the reaction curve on the diagram caused by continuous cooling, the controlled cooling should be continued to 50 F below the indicated temperature, i.e. to 1180 F. Following the 50°F per hour cooling curve to 1180 F and reading the time scale at that temperature shows that the total time required from 1300 F is 2 hours.

With the same setting, the adapter shows that complete transformation to pearlite can be secured by cooling from 1300 F at any cooling rate up to nearly 500°F per hour, the maximum rate that will intersect the line representing the end of the pearlite transformation. However, increased cooling rates intersect the line at progressively lower temperatures and the resulting structures will be progressively harder. If moderately higher hardnesses can be tolerated, considerable furnace time can be saved. At a cooling rate of 200°F per hour, the adapter shows that cooling to 1150 F (50 F below the intersection) requires about 40 minutes and yields a product with a hardness of Rockwell C 19 (by interpolation).

The same setting of the adapter shows that a cooling rate of 50°F per minute is sufficiently fast to avoid the pearlite nose and therefore avoid the formation of any pearlite transformation product, whereas a rate of 100°F per second will avoid both pearlite and bainite noses and insure a fully martensitic structure.

Prediction of Microstructure

The adapter also can be used to predict the structures that will be obtained at various cooling rates. Table I gives the approximate cooling rates between 1300 and 1000 F at various positions from center to surface of round steel bars quenched in water, oil, or air. If the horizontal reference line of the adapter is set at 1300 F, a rough translation can be made, by using the table, from the uniform cooling curves of the adapter to the actual cooling rates of various sizes of steel bars. The results are approximate, but they can furnish useful information, if their limitations are recognized.

Applying table and adapter to steel 8640 with the horizontal reference line set to 1300 F* indicates, for example, that sections of the steel up to 1 inch in diameter should harden fully in a water quench. The table shows that the center of a 1-inch round has an approximate cooling rate of 75°F per second in the 1300 to 1000 F range and the cooling curve for this rate on the adapter (interpolated) just avoids intercepting the start of transformation curve on the diagram. Hence, this or any faster rate should retain the austenitic structure until the martensitic transformation temperature is reached. The final structure should be composed entirely of martensite (plus some retained austenite).

* The use of the adapter with the table requires setting the horizontal reference line at 1300 F because the conversions in the table are based on cooling rates from that temperature. This temperature was selected, partly because it is fairly representative of the Ae_1 temperature and partly because many data are available on cooling rates at this temperature because of the general custom of using it as a reference temperature for cooling rates.

On the other hand, the center of a 2-inch round quenched in water or a 1-inch round quenched in oil (for both, the table indicates a 25°F per second cooling rate) will probably not harden fully because the adapter curve for 25°F per second intersects the line on the diagram indicating start of the bainite transformation. The final structure will consist of martensite and bainite. There will be no pearlite because the line representing start of the pearlite transformation is not intercepted.

A normalized 12-inch diameter bar, for which the table indicates a surface cooling rate of 500°F per hour, should have a structure consisting almost entirely of pearlite and ferrite because the adapter curve for 500°F per hour is nearly tangent to the line representing the end of pearlite transformation.

TABLE I

Approximate Average Cooling Rates Between 1300 and 1000 F of Round Steel Bars Cooled in Various Media

Diameter, in.	Water Quench*				Oil Quench*				Air Cool*	
	Center	0.5 Radius	0.75 Radius	0.9† Radius	Center	0.5 Radius	0.75 Radius	Surface	Center	Surface
1	75-S	90-S	105-S	135-S	25-S	28-S	30-S	35-S	100-M	100-M
1½	40-S	50-S	60-S	95-S	20-S	22-S	23-S	26-S	65-M	65-M
2	25-S	30-S	40-S	65-S	750-M	900-M	1000-M	21-S	50-M	50-M
2½	1050-M	22-S	30-S	50-S	550-M	650-M	775-M	1100-M	38-M	40-M
3	800-M	1000-M	25-S	43-S	400-M	500-M	650-M	1000-M	31-M	33-M
3½	600-M	800-M	20-S	35-S	325-M	400-M	500-M	900-M	27-M	29-M
4	500-M	625-M	1000-M	32-S	275-M	350-M	450-M	825-M	23-M	25-M
5	350-M	450-M	750-M	25-S	200-M	250-M	350-M	725-M	19-M	20-M
6	250-M	325-M	575-M	21-S	150-M	200-M	275-M	650-M	900-H	1000-H
7	200-M	260-M	450-M	1050-M	110-M	150-M	225-M	600-M	785-H	875-H
8	160-M	225-M	400-M	900-M	90-M	125-M	200-M	550-M	675-H	750-H
9	130-M	175-M	325-M	800-M	75-M	110-M	175-M	500-M	600-H	675-H
10	110-M	150-M	300-M	700-M	65-M	95-M	150-M	475-M	525-H	600-H
12	85-M	110-M	225-M	600-M	50-M	65-M	125-M	425-M	425-H	500-H

* S = °F per Second.
M = °F per Minute.
H = °F per Hour.

† The cooling rates at the extreme surface in water will exceed 1000-S for the complete range of sizes included in this table. This is practically a skin phenomenon, however, as the rates fall very rapidly immediately below the surface. Therefore, the rates for 0.9 radius position are probably of more practical value.

I-T DIAGRAMS

STANDARD NICKEL ALLOY STEELS

This section presents data on nickel alloy steels which are standard compositions in one of the following specification systems:

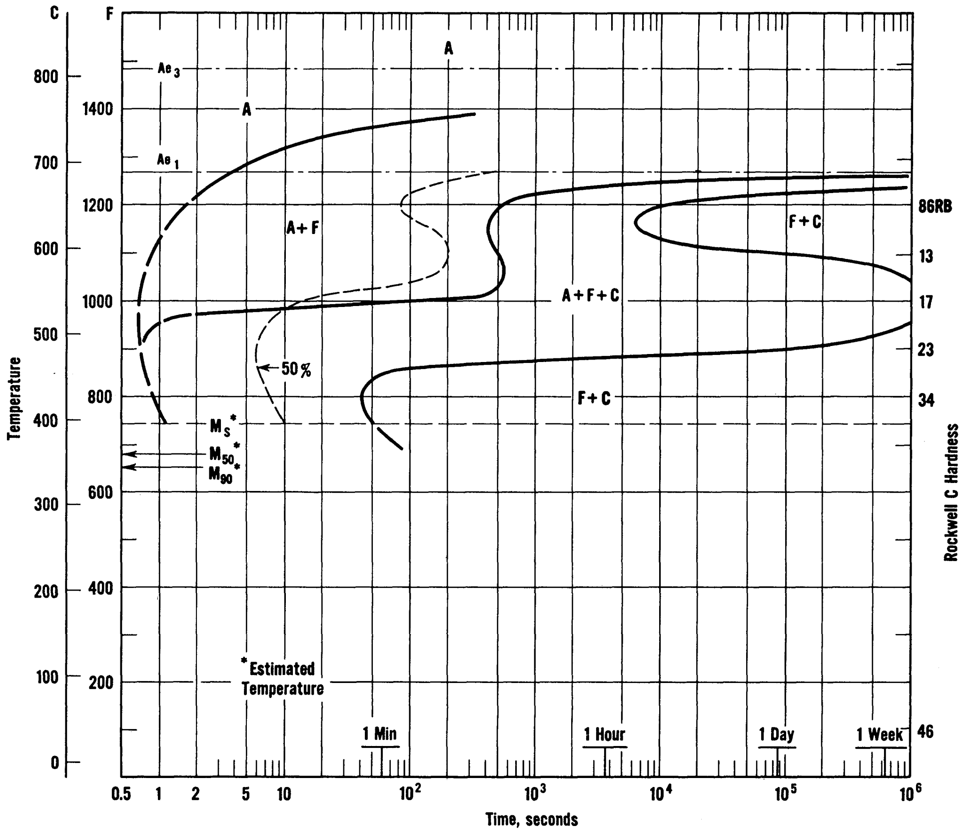
- AISI-SAE Standard Steels, "1965 SAE Handbook," the AISI-SAE prefix being omitted for brevity.
- AMS (Aerospace Materials Specification) Standard Steels.
- AISI Standard Tool Steel, "Tool Steels," April 1963.

Page No.	Steel Type [a]	Composition, %[b]								
		C	Mn	P	S	Si	Ni	Cr	Mo	Other
7	**4320**	0.17	0.57	.016	.023	0.27	1.87	0.45	0.24	—
7	**4340**	0.42	0.78	.018	.027	0.24	1.79	0.80	0.33	—
8	**4615**	0.15	0.63	.019	.026	0.28	1.90	.05	0.24	—
8	**4626** (0.70-1.00 Ni)	0.24	0.59	.011	.023	0.22	0.99	—	0.17	—
9	**4815**	0.16	0.52	.009	.010	0.27	3.36	.09	0.19	Cu-.04
9	**4815** (1.0 C), carburized	0.99	0.52	.009	.010	0.27	3.36	.09	0.19	Cu-.04
10	**8620**	0.18	0.79	.021	.023	0.21	0.52	0.56	0.19	—
10	**8630**	0.30	0.80	.010	.015	0.29	0.54	0.55	0.21	—
11	**8640 & 8740**	0.42	0.89	.018	.015	0.30	0.58	0.52	0.24	—
11	**8645**	0.44	0.90	.019	.031	0.25	0.45	0.54	0.22	—
12	**8660**	0.59	0.89	.017	.016	0.24	0.53	0.64	0.22	—
12	**AMS 6416** (300-M)	0.43	0.83	.021	.009	1.55	1.84	0.91	0.40	V-0.12
13	**AMS 6418**	0.22	1.30	—	—	1.36	1.88	0.22	0.38	—
13	**AMS 6428 & 6434**	0.32	0.72	.012	.021	0.19	1.70	0.82	0.31	Cu-0.12, V-0.17
14	**AISI L6 Tool**	0.72	0.35	.018	.010	0.23	1.75	0.94	—	—
14	**AISI L6 Tool**	0.75	0.70	—	—	0.25	1.35	0.75	0.30	V-0.15
15	**AISI L6 Tool**	0.75	0.40	—	—	—	1.50	1.00	—	—
15	**AISI A10 Tool** (graphitic)	1.36	1.84	—	—	1.14	1.81	0.15	1.41	Graphite-0.38

[a] All heats are commercial type but vary greatly in size. All material was reduced greatly from ingot form by hot working.

[b] Composition of the material used in developing the I-T diagram.

4320



C-0.17 Mn-0.57
Ni-1.87 Cr-0.45
Mo-0.24

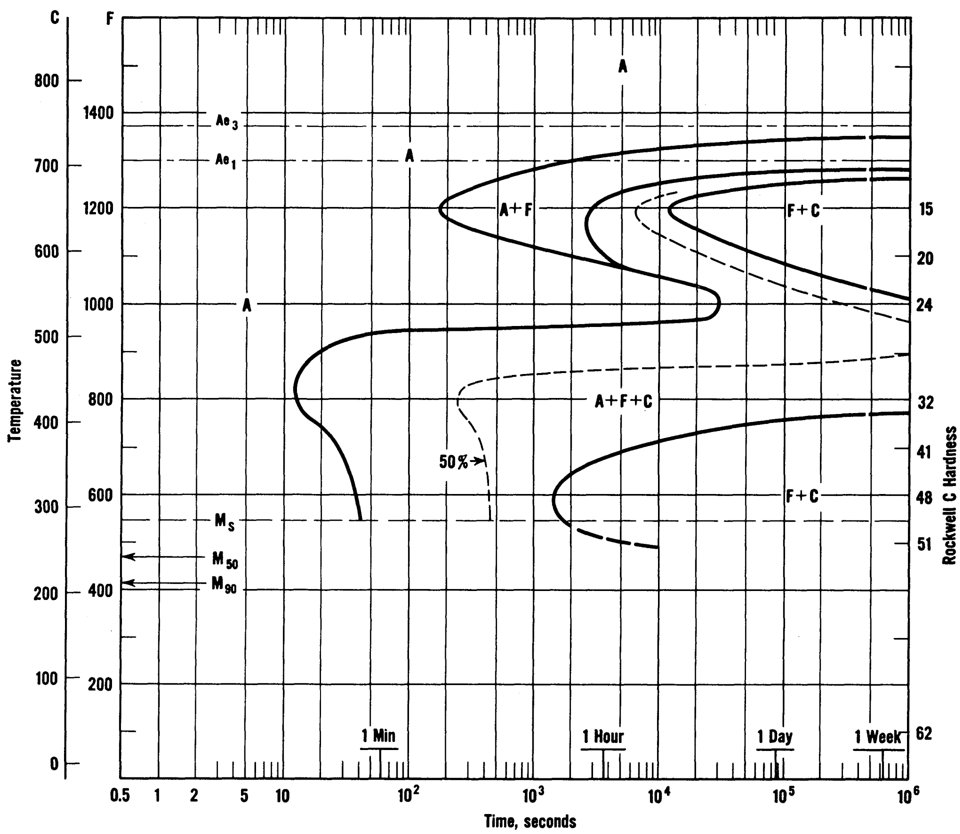
Austenitized at 1700 F
Grain Size: 7

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]

4340



C-0.42 Mn-0.78
Ni-1.79 Cr-0.80
Mo-0.33

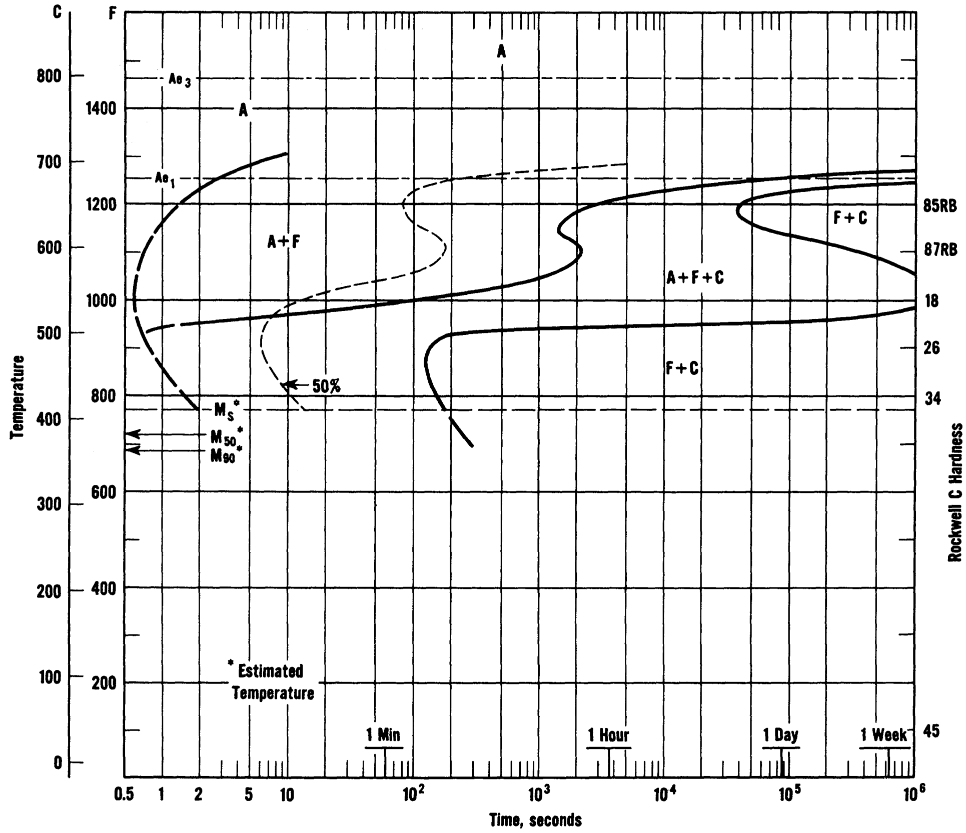
Austenitized at 1550 F
Grain Size: 7-8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]

4615



C-0.15 Mn-0.63
Ni-1.90 Mo-0.24

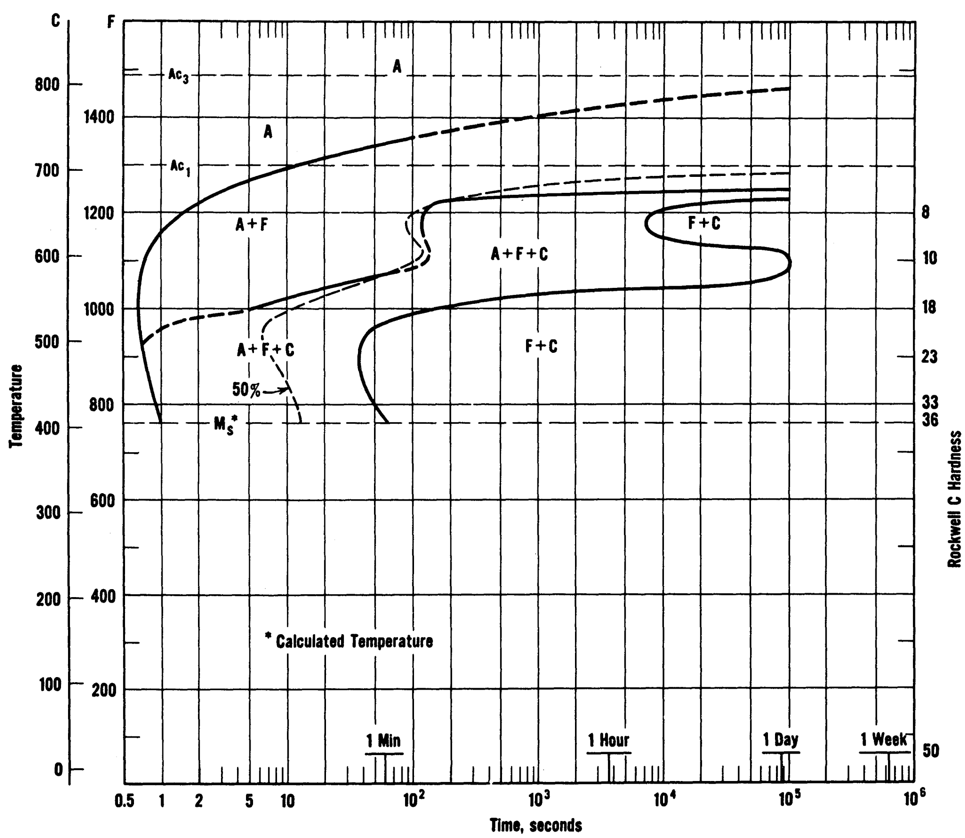
Austenitized at 1700 F
Grain Size: 8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]

4626
(0.70-1.00 Ni)



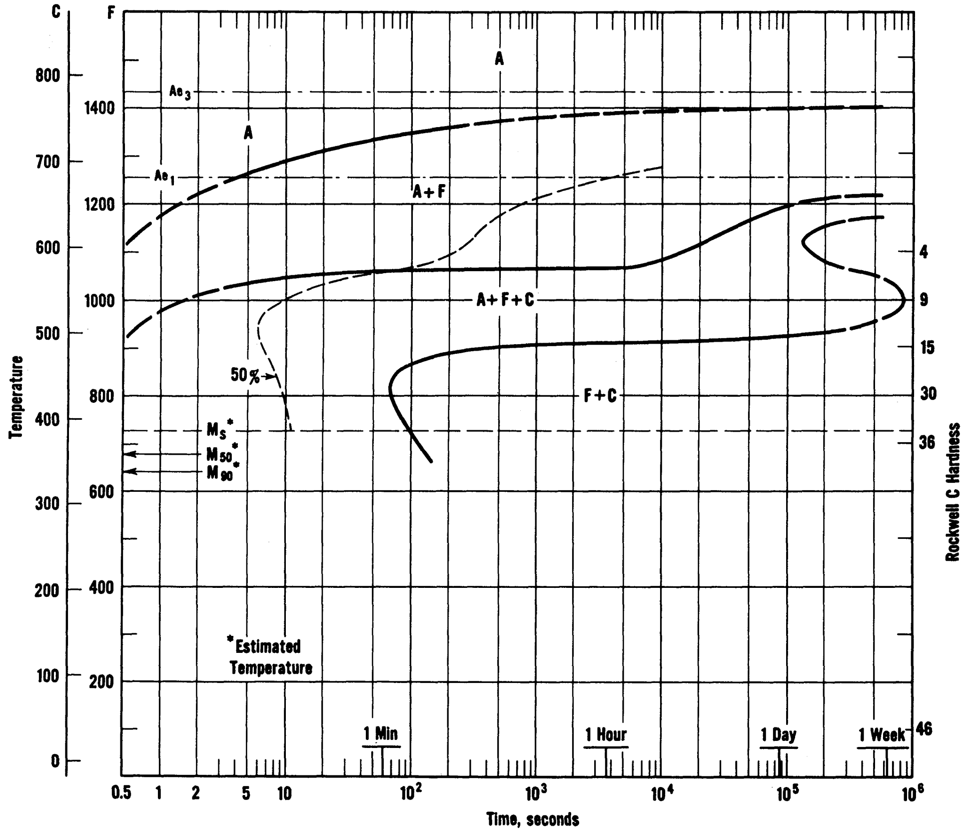
C-0.24 Mn-0.59
Ni-0.99 Mo-0.17

Austenitized at 1700 F
Grain Size: 5-6

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
International
Nickel Limited



4815

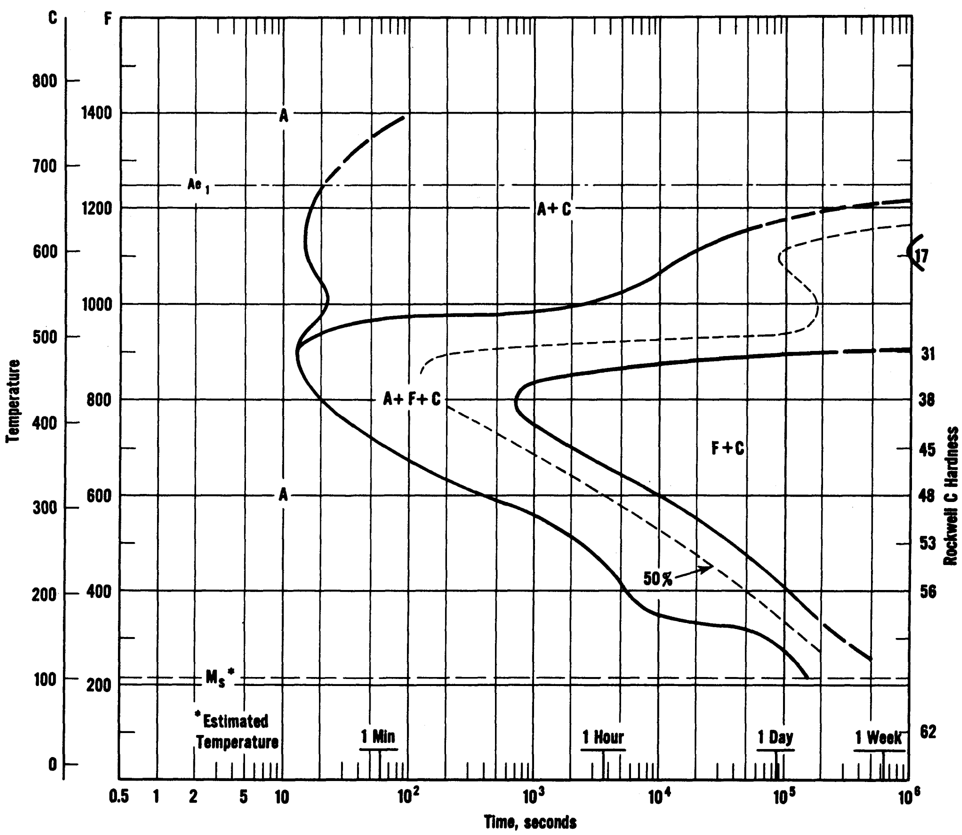
C-0.16 Mn-0.52
Ni-3.36 Mo-0.19

Austenitized at 1650 F
Grain Size: 8-9

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas[3]



4815 (1.0 C) Carburized

C-0.97 Mn-0.52
Ni-3.36 Mo-0.19

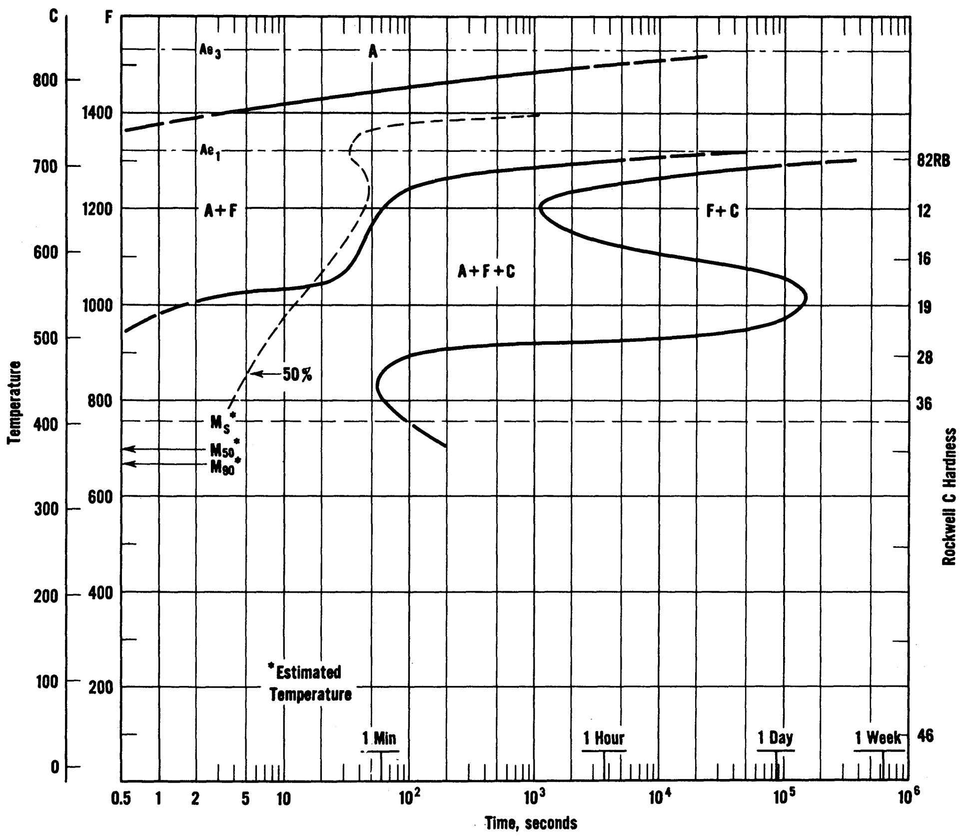
Austenitized at 1800 F
Grain Size: 7

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas[3]

8620



C-0.18 Mn-0.79
Ni-0.52 Cr-0.56
Mo-0.19

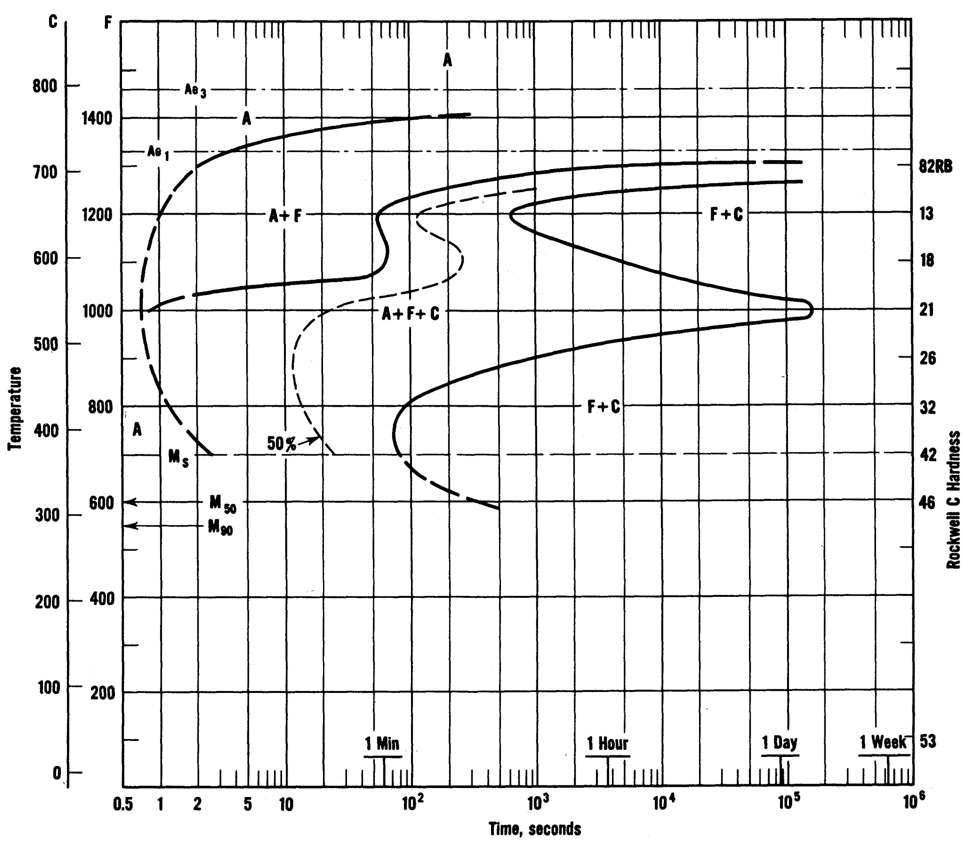
Austenitized at 1650 F
Grain Size: 9-10

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]

8630



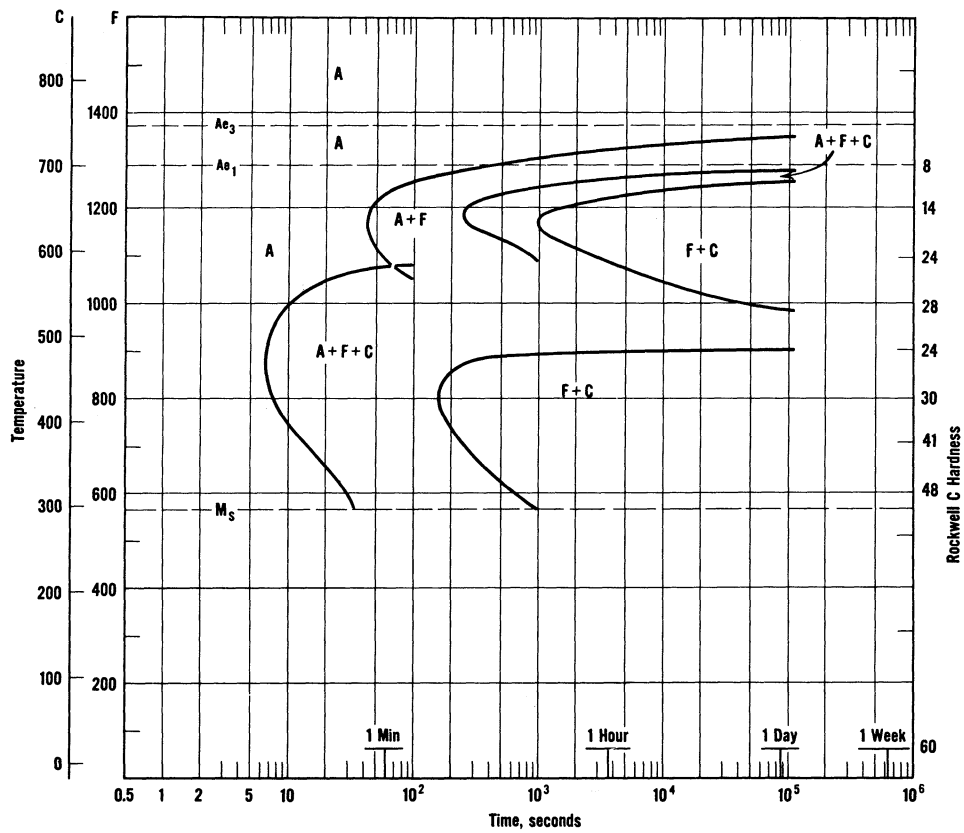
C-0.30 Mn-0.80
Ni-0.54 Cr-0.55
Mo-0.21

Austenitized at 1600 F
Grain Size: 9

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]



8640 & 8740

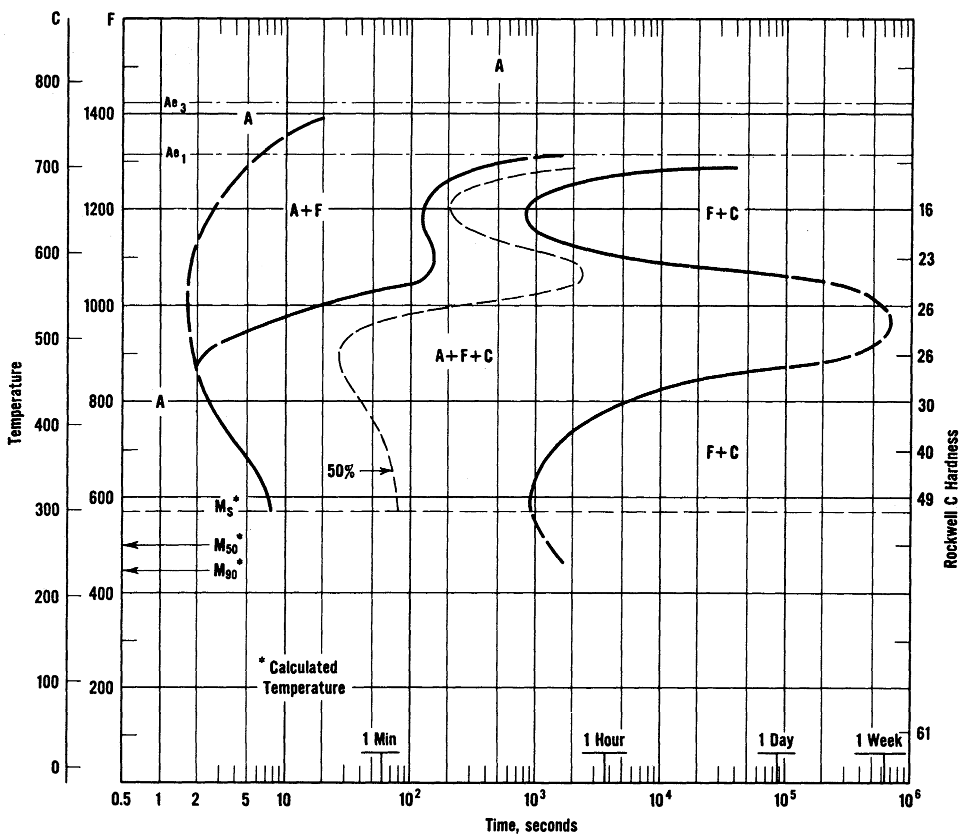
C-0.42 Mn-0.89
Ni-0.58 Cr-0.52
Mo-0.24

Austenitized at 1650 F
Grain Size: 8-9

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Battelle Memorial Inst.
for
The International
Nickel Company, Inc.



8645 & 8745

C-0.44 Mn-0.90
Ni-0.45 Cr-0.54
Mo-0.22

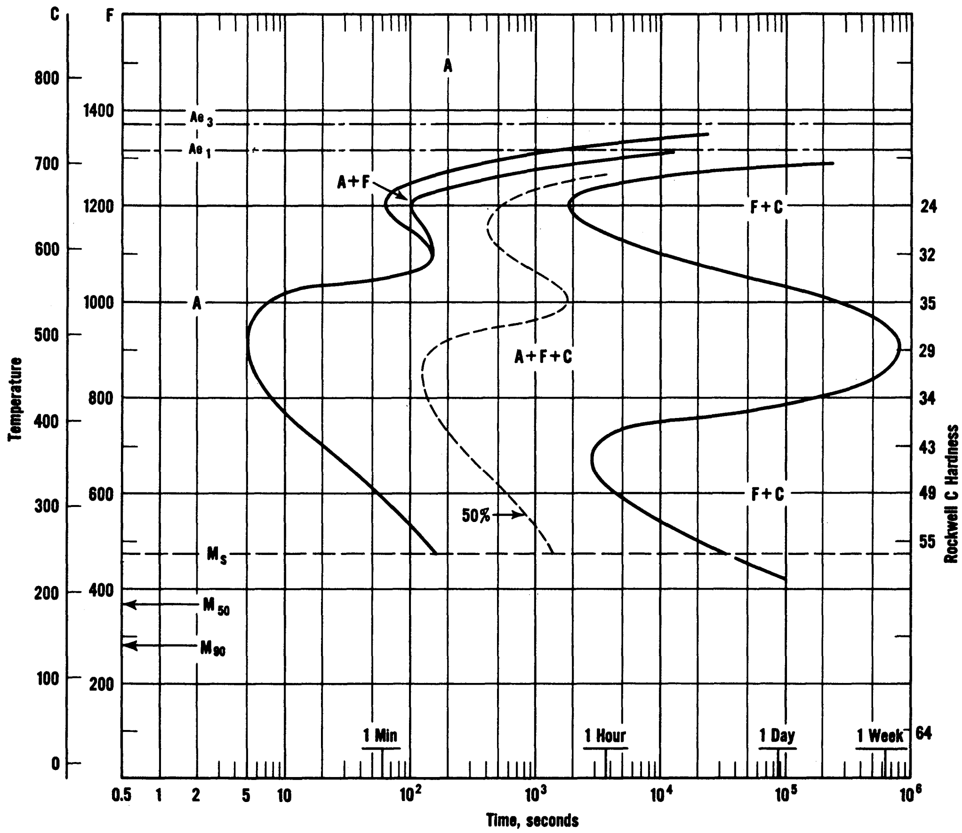
Austenitized at 1550 F
Grain Size: 9-10

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]

8660



C-0.59 Mn-0.89
Ni-0.53 Cr-0.64
Mo-0.22

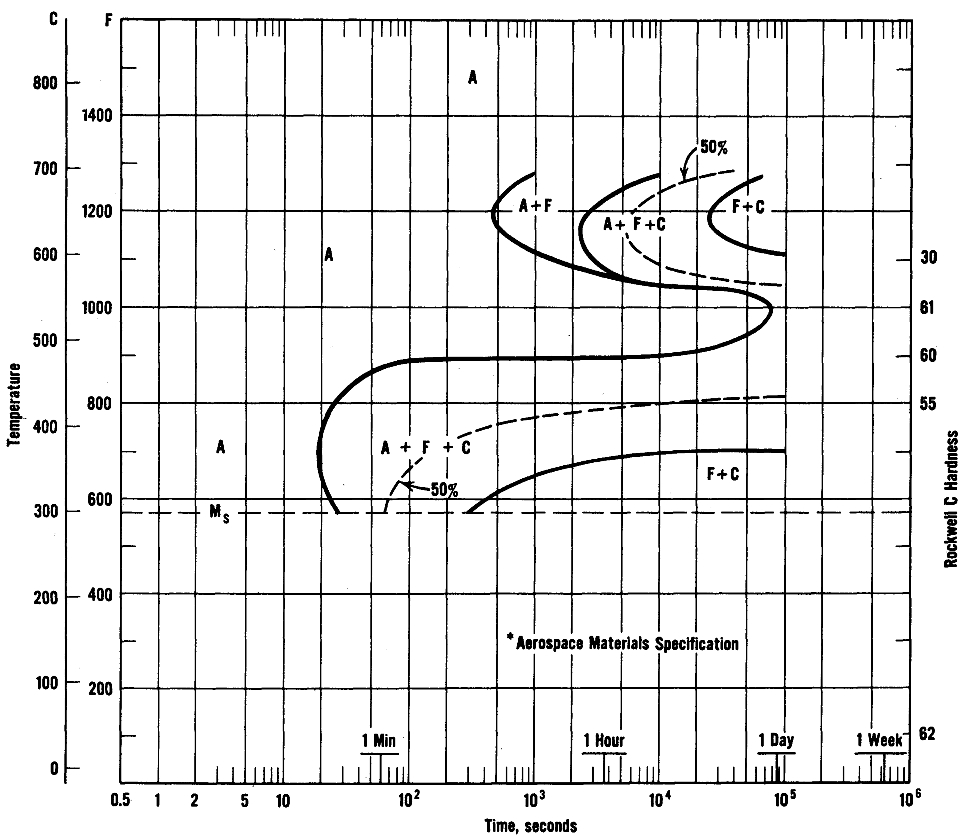
Austenitized at 1550 F
Grain Size: 8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]

AMS* 6416
(300-M)



C-0.43 Mn-0.83
Si-1.55 Ni-1.84
Cr-0.91 Mo-0.40
V-0.12

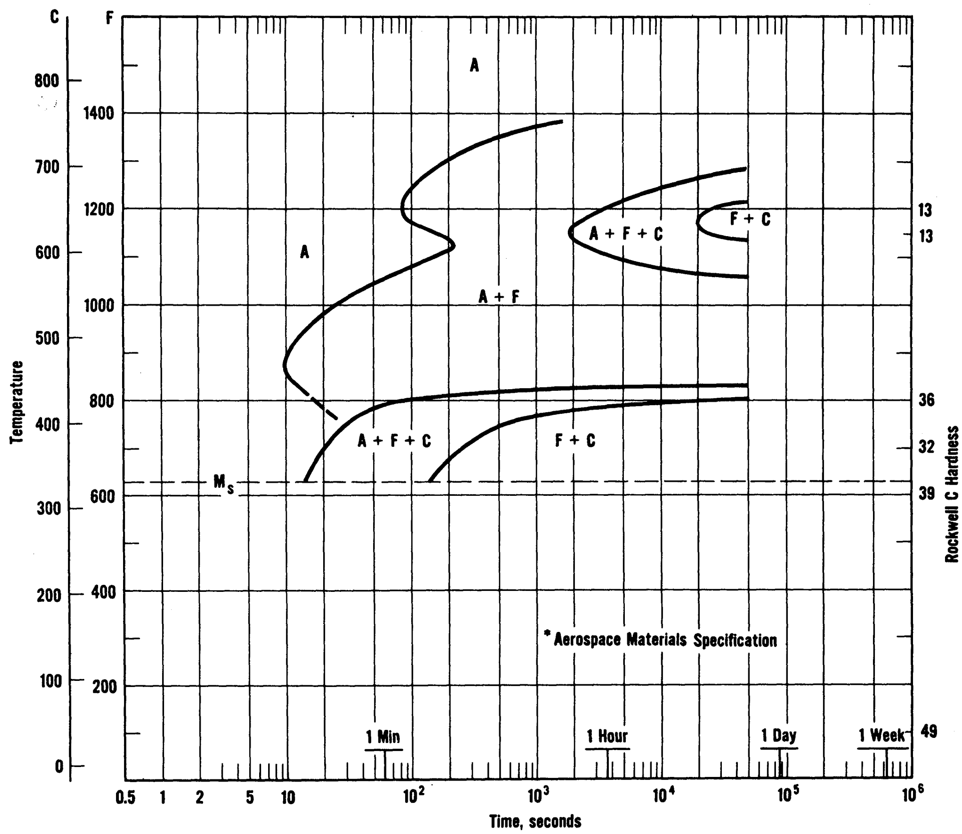
Austenitized at 1575 F
Grain Size: 5-7

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Bethlehem Steel Co.

AMS* 6418



C-0.22 Mn-1.30
Si-1.36 Ni-1.88
Cr-0.22 Mo-0.38

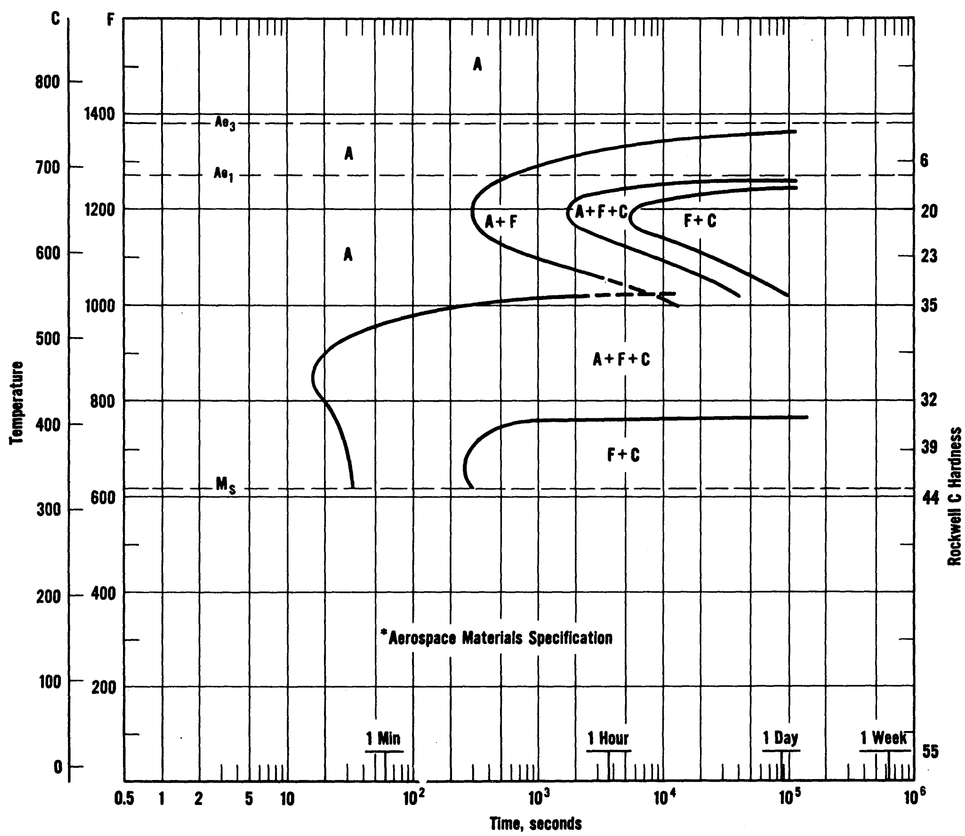
Austenitized at 1600 F

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Crucible Steel Co.
of America

AMS* 6428 & 6434



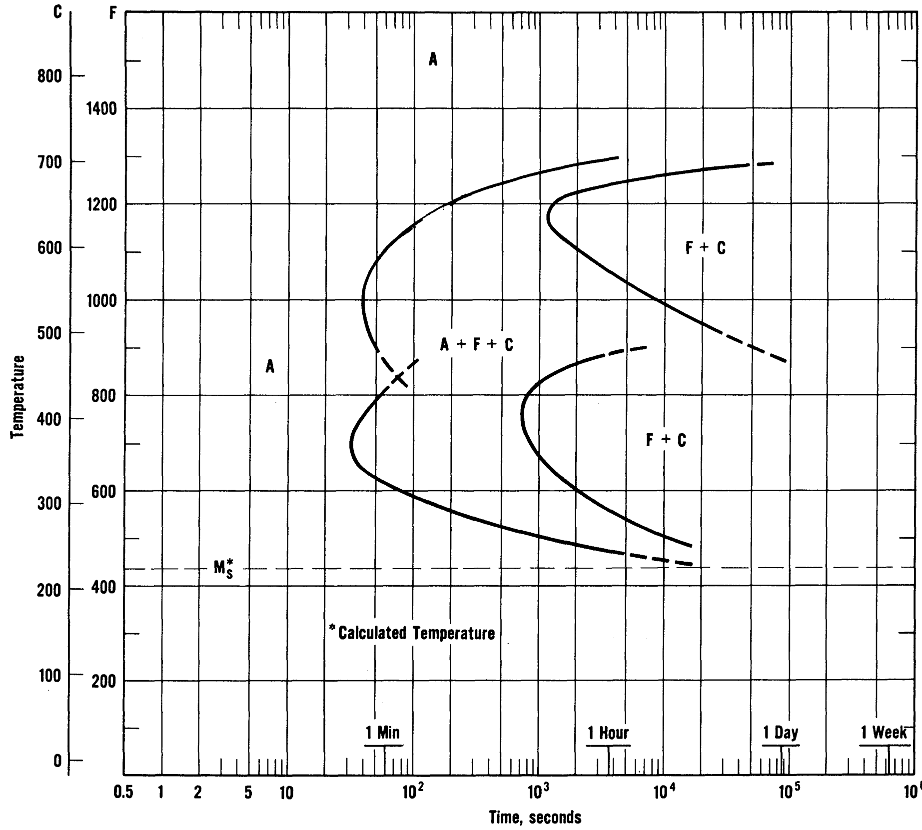
C-0.32 Mn-0.72
Ni-1.70 Cr-0.82
Mo-0.31 V-0.17

Austenitized at 1650 F
Grain Size: 7-8

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Battelle Memorial
Institute for
The International
Nickel Company, Inc.



L6 Tool

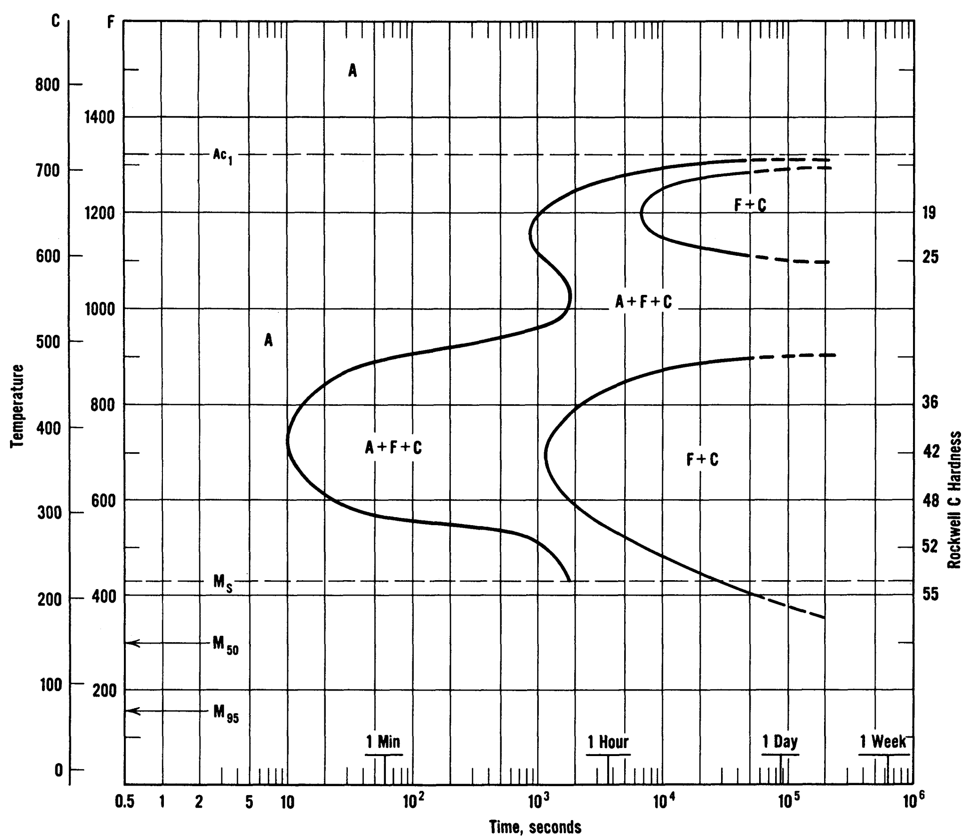
C-0.72 Mn-0.35
Ni-1.75 Cr-0.94

Austenitized at 1525 F
Grain Size: 9

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Carpenter Steel Co.



L6 Tool

C-0.75 Mn-0.70
Ni-1.35 Cr-0.75
Mo-0.30 V-0.15

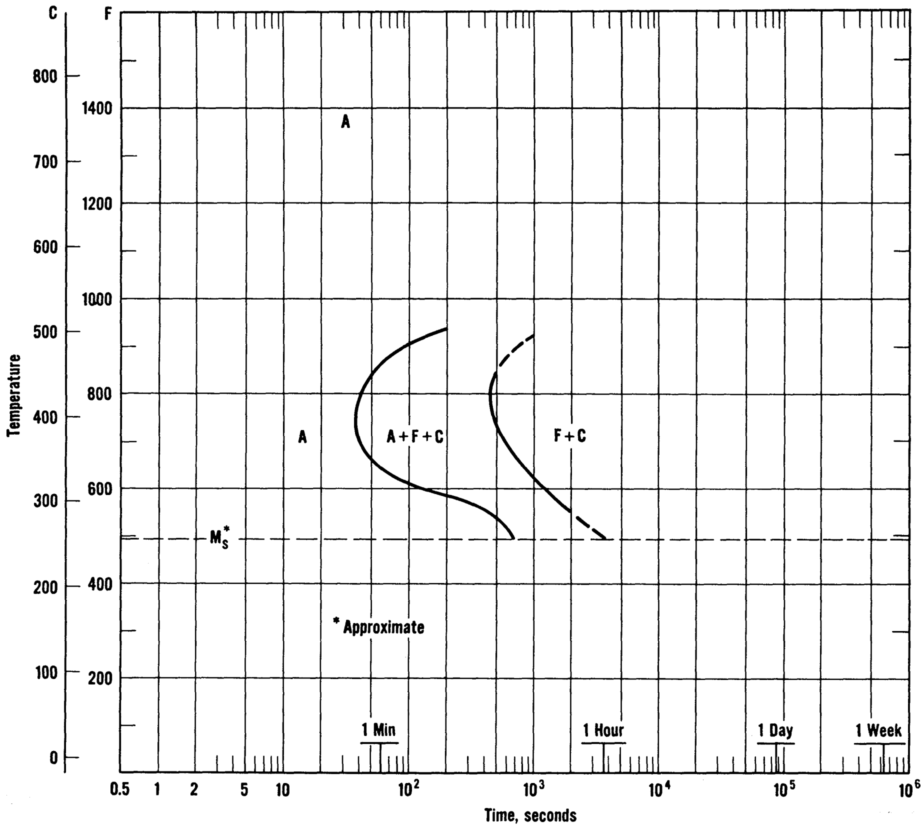
Austenitized at 1550 F

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Crucible Steel Co.
of America

L6 Tool



C-0.75 Mn-0.40
Ni-1.50 Cr-1.00

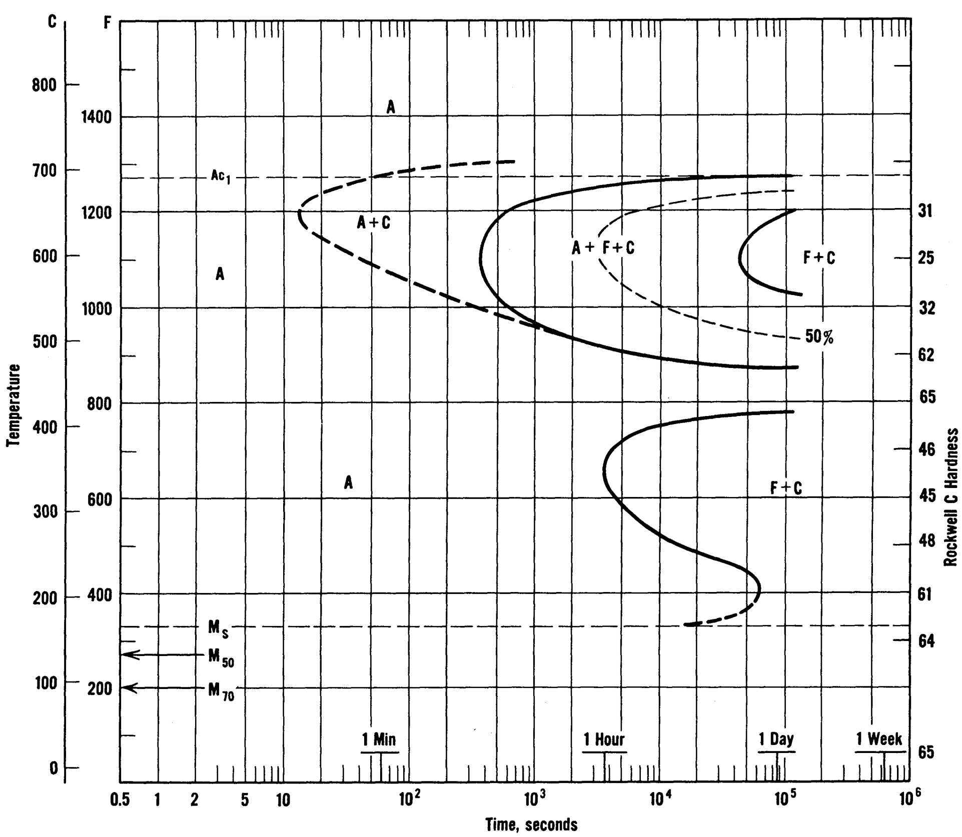
Austenitized at 1690 F

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Universal-Cyclops
Steel Corp.

A10 Tool
(Graphitic)



C-1.36 Mn-1.84
Si-1.14 Ni-1.81
Cr-0.15 Mo-1.41
Graphite-0.38

Austenitized at 1460 F

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Timken Roller
Bearing Co.

I-T DIAGRAMS

CARBON STEELS AND NONSTANDARD NICKEL ALLOY STEELS

This section provides data on AISI-SAE standard carbon steels and nickel alloy steels which are classified as follows:

- Types numbered by the AISI-SAE system but not listed as standard compositions in the "1965 SAE Handbook." Many formerly were AISI-SAE designations.
- Steels with SAE temporary number, SAE EX-1 and SAE EX-2.
- Tool steel designations used in Metals Handbook[6], 6F4 and 6F5.
- Types identified by nominal alloy content such as "2¾ Nickel Forging" or by early sponsor's name such as "Krupp."

Page No.	Steel Type [a]	Composition, % [d]									
		C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Other
18	**1021**	0.20	0.81	—	—	0.16	—	—	—	—	—
18	**1035** Modified Mn (Nonst'd)	0.35	0.37	.009	.012	0.21	0.06	.05	.00	0.7	—
19	**1050**	0.50	0.91	.046	.041	0.13	—	—	—	—	—
19	**2315**	0.19	0.57	.015	.023	0.22	3.60	.09	.05	—	—
20	**2330** (Cast & Wrought)	0.28	0.69	.043	.028	0.41	3.30	0.12	.03	—	—
20	**2340**	0.40	0.89	.021	.011	0.31	3.34	0.11	—	—	—
21	**23110**[b]	1.12	0.55	.007	.014	0.28	3.56	—	—	—	—
21	**2512**	0.10	0.52	.007	.016	0.28	5.00	.07	.03	—	—
22	**2512** (0.4 C), carburized	0.4[c]	0.52	.007	.016	0.28	5.00	.07	.03	—	—
22	**2512** (0.6 C), carburized	0.6[c]	0.52	.007	.016	0.28	5.00	.07	.03	—	—
23	**2512** (0.8 C), carburized	0.8[c]	0.52	.007	.016	0.28	5.00	.07	.03	—	—
23	**2512** (1.0 C), carburized	1.0[c]	0.52	.007	.016	0.28	5.00	.07	.03	—	—
24	**2512** (1.2 C), carburized	1.2[c]	0.52	.007	.016	0.28	5.00	.07	.03	0.10	—
24	**9 Nickel**	0.10	0.77	.010	.024	0.28	8.56	.05	.02	—	—
25	**3120**	0.21	0.61	.017	.016	0.24	1.35	0.67	.02	.04	—
25	**3140**	0.38	0.72	.019	.033	0.21	1.32	0.49	.00	.02	—
26	**3190**[b]	0.91	0.65	.013	.026	0.23	1.35	0.60	—	.03	—
26	**3240**	0.43	0.52	.025	.021	0.29	1.76	1.19	.05	.06	—
27	**3310**	0.11	0.45	.017	.009	0.18	3.33	1.52	.03	—	—
27	**3310** (0.4 C), carburized	0.4[c]	0.45	.017	.009	0.18	3.33	1.52	.03	—	—
28	**3310** (0.6 C), carburized	0.6[c]	0.45	.017	.009	0.18	3.33	1.52	.03	—	—

(Continued on p. 17)

Page No.	Steel Type [a]	Composition, % [d]									
		C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Other
28	**3310** (0.8 C), carburized	0.8 [c]	0.45	.017	.009	0.18	3.33	1.52	.03	—	—
29	**3310** (1.0 C), carburized	1.0 [c]	0.45	.017	.009	0.18	3.33	1.52	.03	—	—
29	**3330**	0.29	0.21	.026	.017	.06	3.25	1.45	—	—	—
30	**Krupp,** 0.15 C	0.15	0.45	.013	.020	0.20	4.03	1.54	.03	—	—
30	**Krupp,** 0.90 C [b]	0.87	0.39	—	—	0.19	4.00	1.58	—	—	—
31	**4330** (Cast & Wrought)	0.33	0.69	.043	.028	0.41	1.41	0.72	0.28	—	—
31	**4360**	0.62	0.64	—	—	0.67	1.79	0.60	0.32	—	—
32	**4330** Modified (Si + V)	0.34	0.98	.015	.005	1.37	1.82	0.95	0.42	—	V-0.14
32	**4630**	0.32	0.74	.015	.014	0.31	1.70	0.12	0.23	—	—
33	**4640**	0.36	0.63	.018	.021	0.19	1.84	.06	0.23	—	—
33	**4695** [b]	0.95	0.58	—	—	0.24	1.79	—	0.25	—	—
34	**SAE EX-2**	0.69	0.42	—	—	—	0.80	0.20	0.13	—	—
34	**4840**	0.41	0.60	—	—	—	3.51	—	0.21	—	—
35	**SAE EX-1**	0.17	0.49	.010	.015	0.29	5.07	0.18	0.24	0.10	—
35	**8695** [b]	0.95	0.82	—	—	0.23	0.56	0.52	0.19	—	—
11	**8745**	0.44	0.90	.019	.031	0.25	0.45	0.54	0.22	—	—
36	**9315** [b]	0.17	0.59	—	—	0.30	3.18	1.12	0.13	—	—
36	**9395** [b]	0.95	0.60	—	—	0.22	3.27	1.23	0.13	—	—
37	**6F4 Tool**	0.22	0.50	.016	.026	0.30	2.80	—	2.95	—	—
37	**6F5 Tool**	0.55	0.90	—	—	1.00	2.75	0.40	0.45	—	V-0.13
38	**Ni-Cr-Mo-V-Cu-B**	0.15	0.92	.014	.020	0.26	0.88	0.50	0.46	0.32	V- .06, B-.003
38	**2¾ Nickel Forging**	0.29	0.77	.034	.031	0.23	2.72	.04	.05	—	—
39	**2½ Nickel Saw**	0.76	0.41	.012	.023	0.20	2.50	0.13	.08	0.12	—
39	**VCM Nitriding**	0.32	0.76	.014	.018	—	0.70	1.06	1.01	—	—
40	**2½ Ni-½ Mo-V Turbine Rotor**	0.34	0.71	.039	.028	0.22	2.52	0.14	0.42	—	V- .02
40	**5¼ Ni-¼ Mo-V** [b]	0.23	0.52	—	—	0.25	5.35	0.20	0.27	—	V- .08
41	**Ni-Cr-Mo-V** (Weld Metal)	.08	1.05	.014	.015	0.45	2.00	0.20	0.75	—	V-0.25
41	**3¼ Ni-Cr-Mo**	0.33	0.57	.005	.007	0.23	3.26	0.85	0.09	—	—
42	**3 Ni-Cr-Mo-V**	0.32	0.51	.013	.009	0.19	3.02	1.37	0.48	—	V-0.18
42	**4¼ Ni-1½ Cr-1/10 Mo**	0.35	0.44	.016	.008	0.14	4.23	1.43	0.13	—	—
43	**4¼ Ni-1½ Cr-1/3 Mo**	0.33	0.51	.013	.009	0.17	4.16	1.44	0.31	—	—

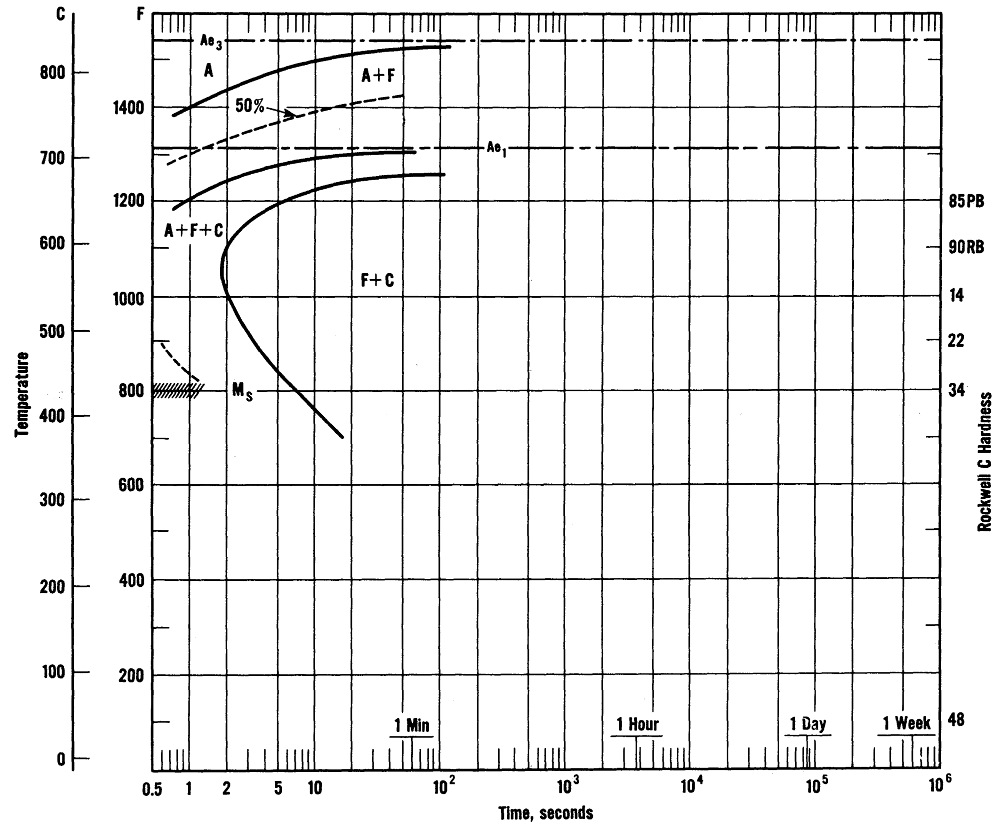
[a] All heats are commercial type, unless otherwise noted, but vary greatly in size. All material, if not otherwise noted, was reduced greatly from ingot form by hot working.

[b] Small laboratory heat.

[c] Based upon a measured distance from the surface of a carburized specimen whose carbon gradient was measured; estimated carbon was 0.40%, 0.60%, etc., but method of determination precludes accuracy in the second decimal place.

[d] Composition of the material used in developing the I-T diagram.

1021



C-0.20
Mn-0.81

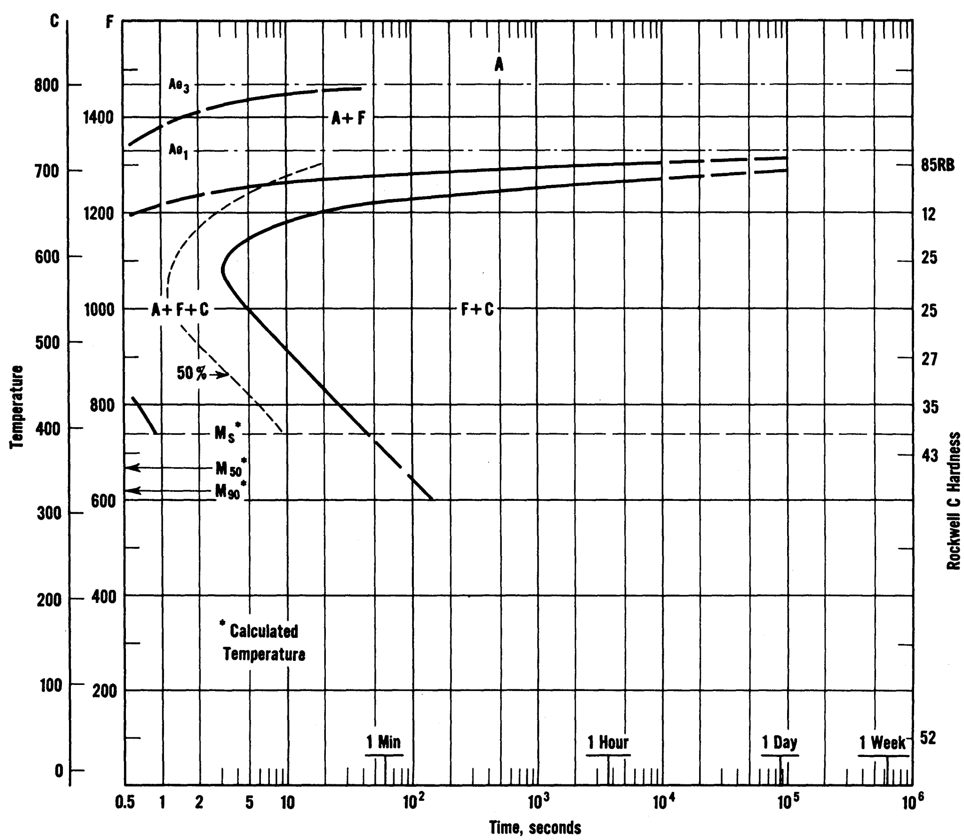
Austenitized at 1700 F
Grain Size: 8-9

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas[3]

1035 (Modified Mn)



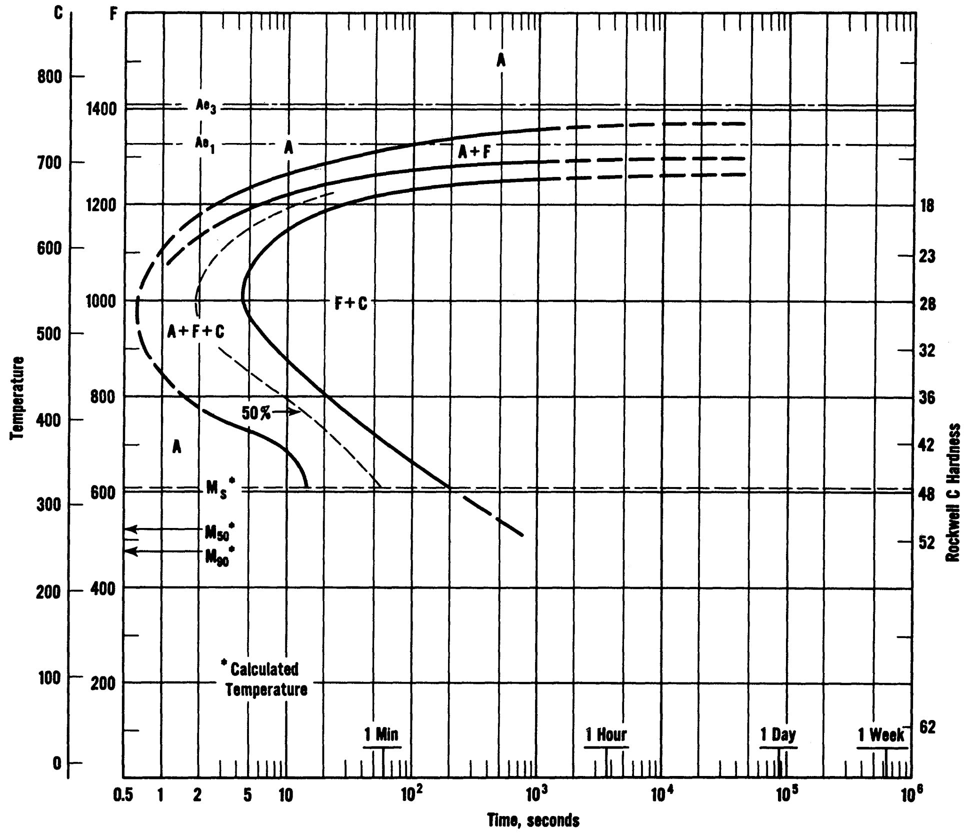
C-0.35
Mn-0.37

Austenitized at 1550 F
Grain Size:
75% 2-3, 25% 7-8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas[3]



1050

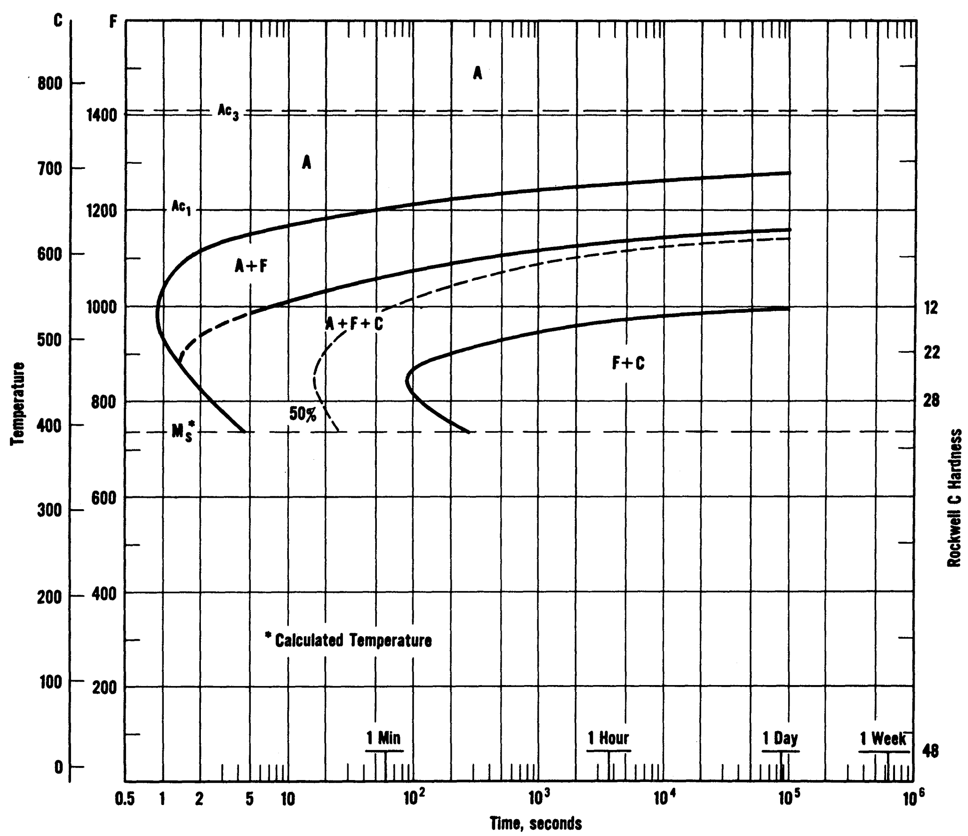
C-0.50
Mn-0.91

Austenitized at 1670 F
Grain Size: 7-8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]



2315

C-0.19 Mn-0.57
Ni-3.60

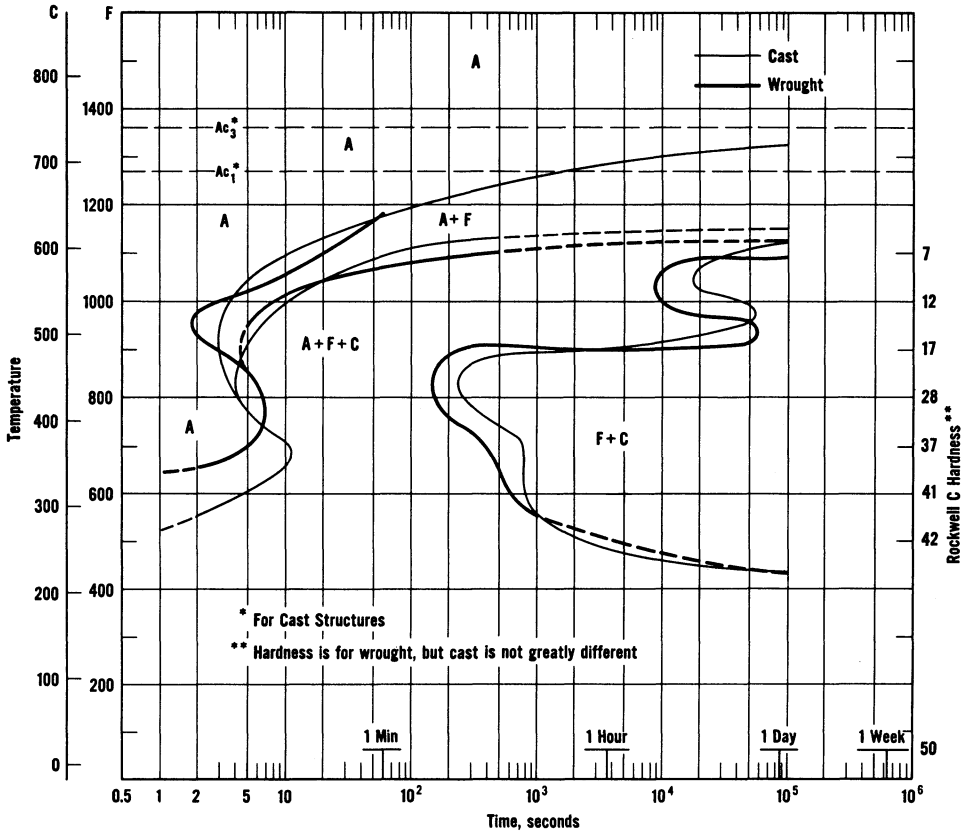
Austenitized at 1650 F
Grain Size: 5-6

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
International
Nickel Limited

2330



C-0.28 Mn-0.69
Ni-3.30

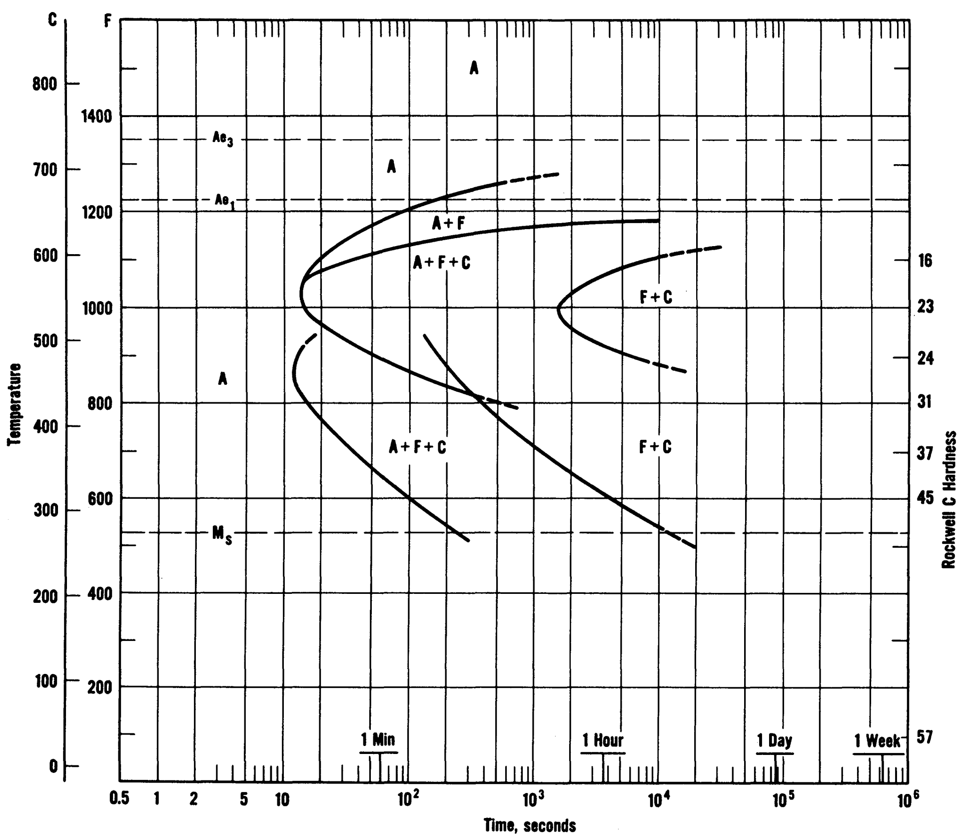
Austenitized at 1660 F
Grain Size: 7-8

Starting Criterion:
1 % Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Eddy, Marcotte & Smith,
Trans. AIME, *162*, 1945,
p 250

2340



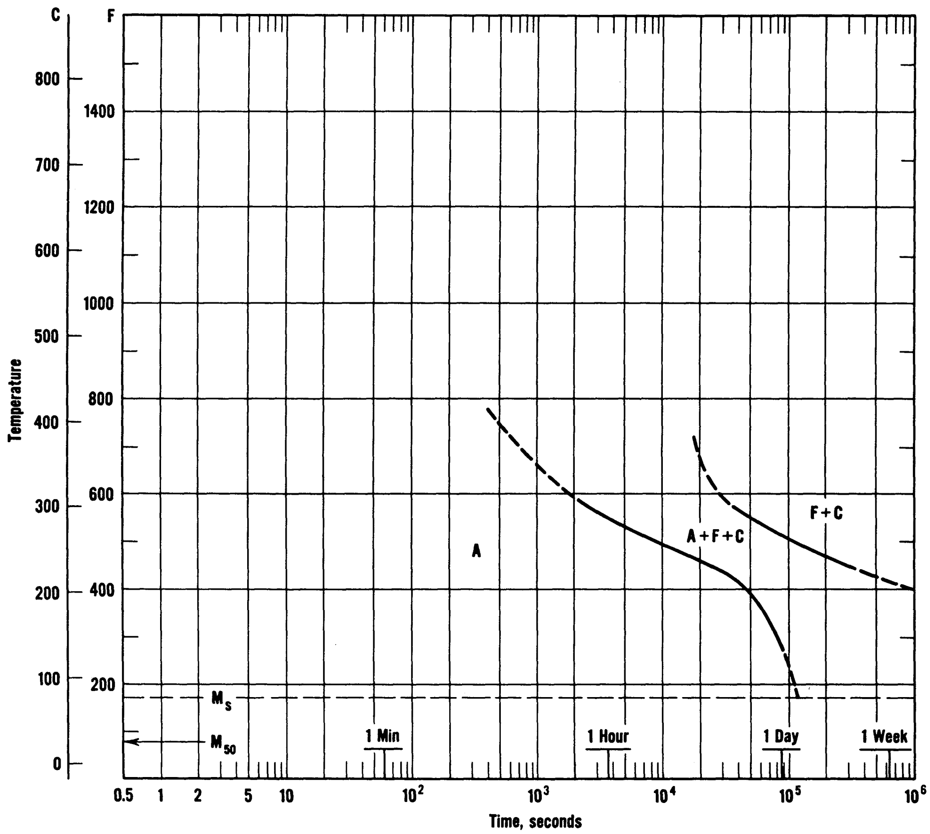
C-0.40 Mn-0.89
Ni-3.34

Austenitized at 1500 F
Grain Size: 8

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
A. R. Troiano for
The International
Nickel Company, Inc.



23110

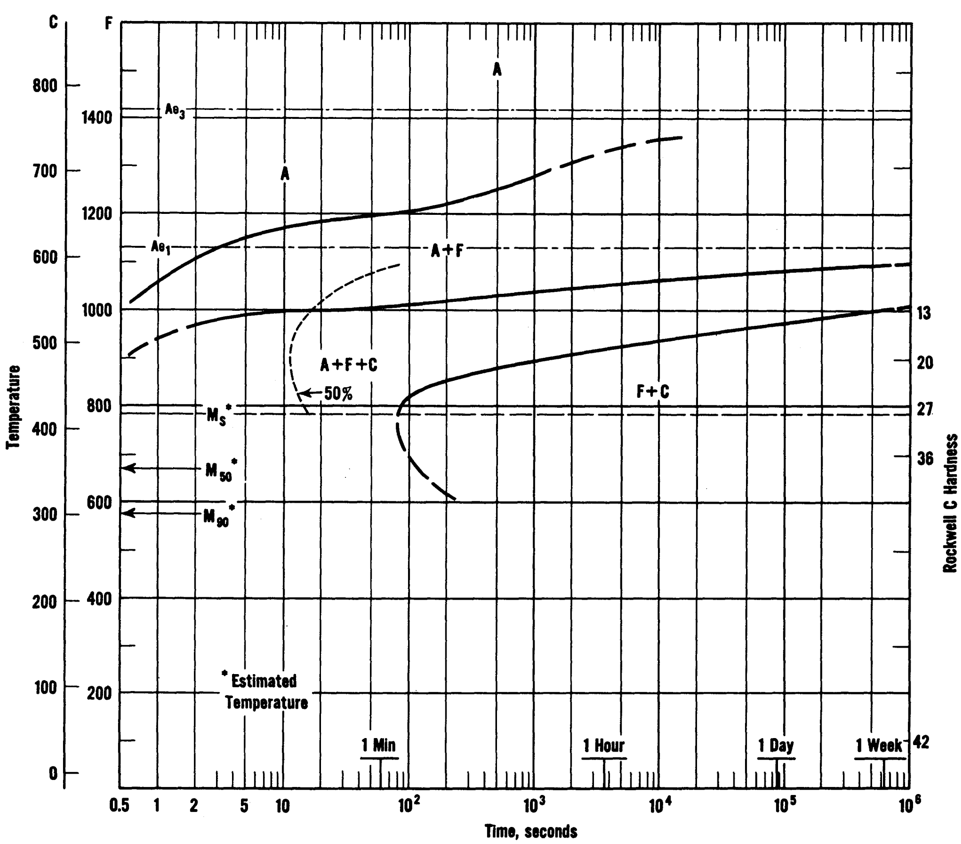
C-1.12 Mn-0.55
Ni-3.56

Austenitized at 1750 F

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Howard & Cohen
Trans. AIME, *176*,
1948, p 374



2512

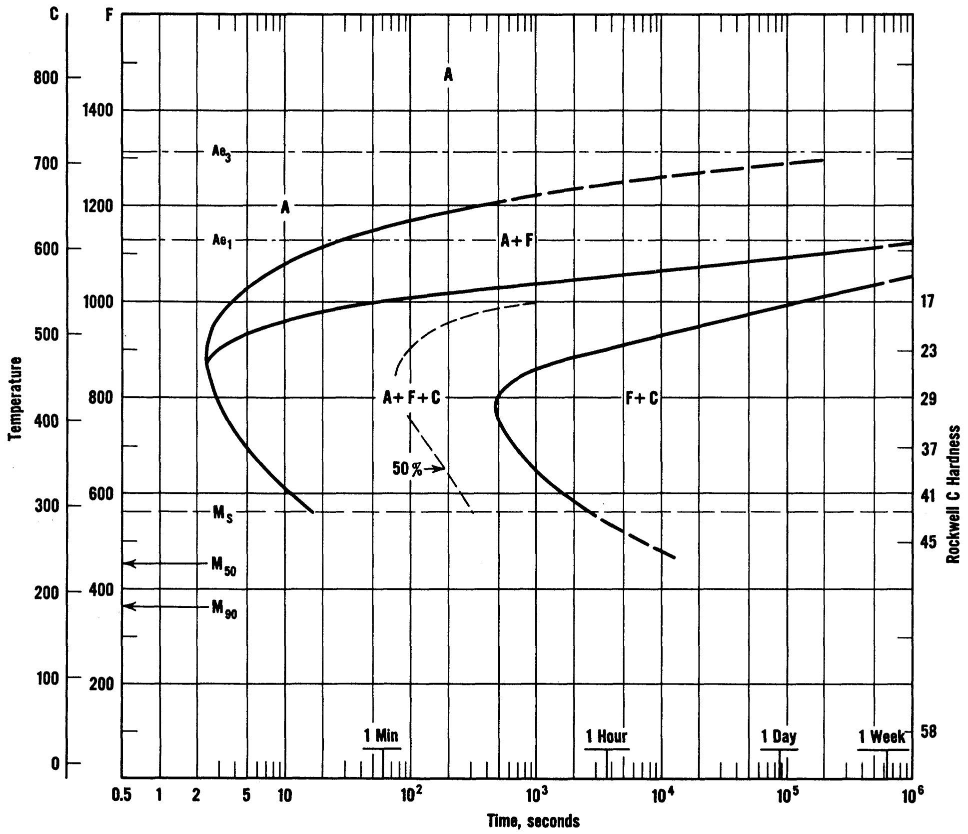
C-0.10 Mn-0.52
Ni-5.00

Austenitized at 1700 F
Grain Size: 7-8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]



2512
(0.4 C)
Carburized

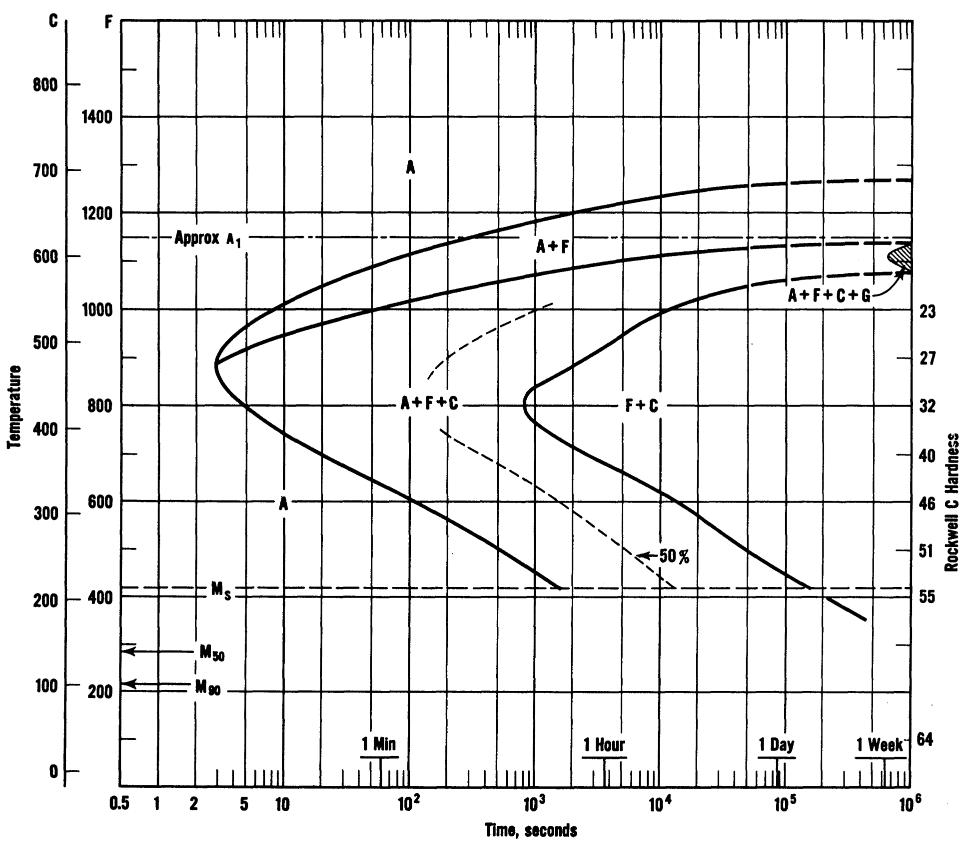
C-0.4 Mn-0.52
Ni-5.00

Austenitized at 1700 F
Grain Size:
25% 3, 75% 7-8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]



2512
(0.6 C)
Carburized

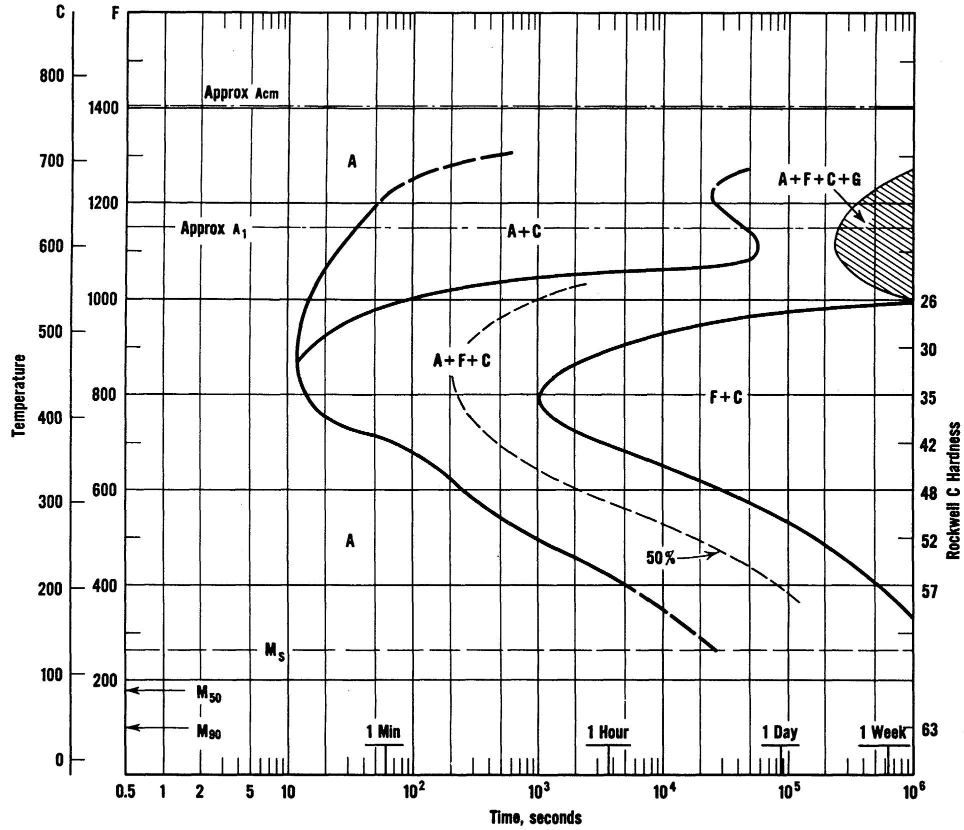
C-0.6 Mn-0.52
Ni-5.00

Austenitized at 1700 F
Grain Size:
80% 4-5, 20% 7

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
Cross-hatched areas represent region in which graphite (G) formed.
M = Martensite

Data from
U.S. Steel Atlas [3]



2512
(0.8 C)
Carburized

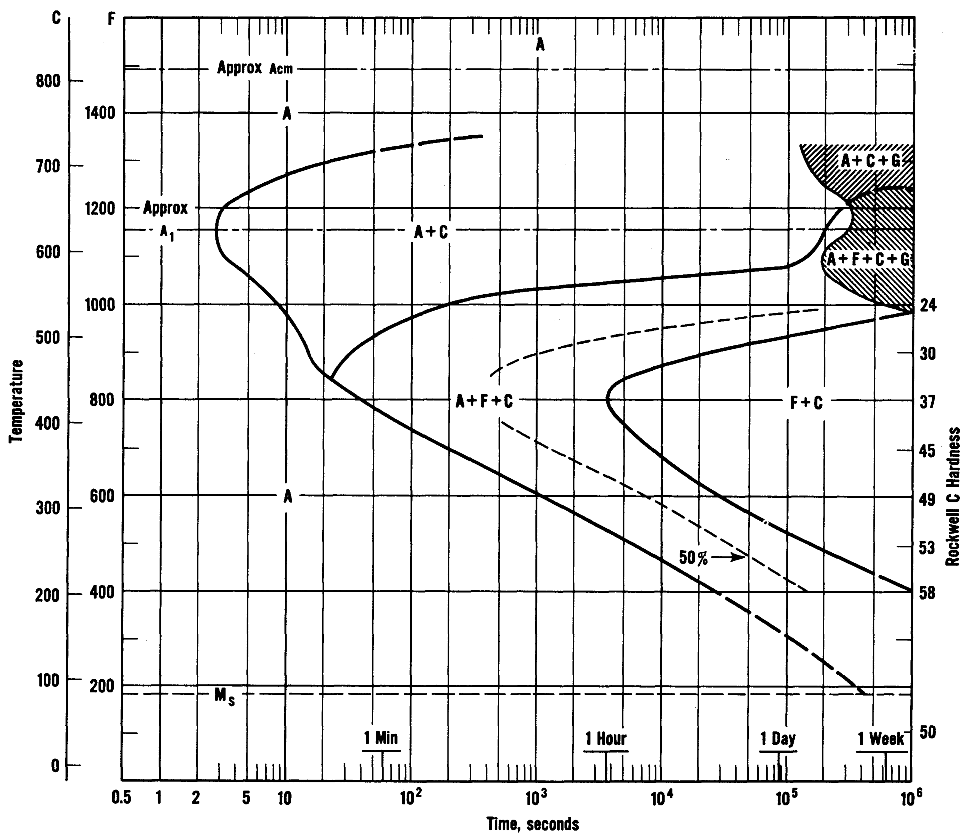
C-0.8 Mn-0.52
Ni-5.00

Austenitized at 1700 F
Grain Size: 6

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
Cross-hatched areas represent region in which graphite (G) formed.
M = Martensite

Data from U.S. Steel Supplement to Atlas[4]



2512
(1.0 C)
Carburized

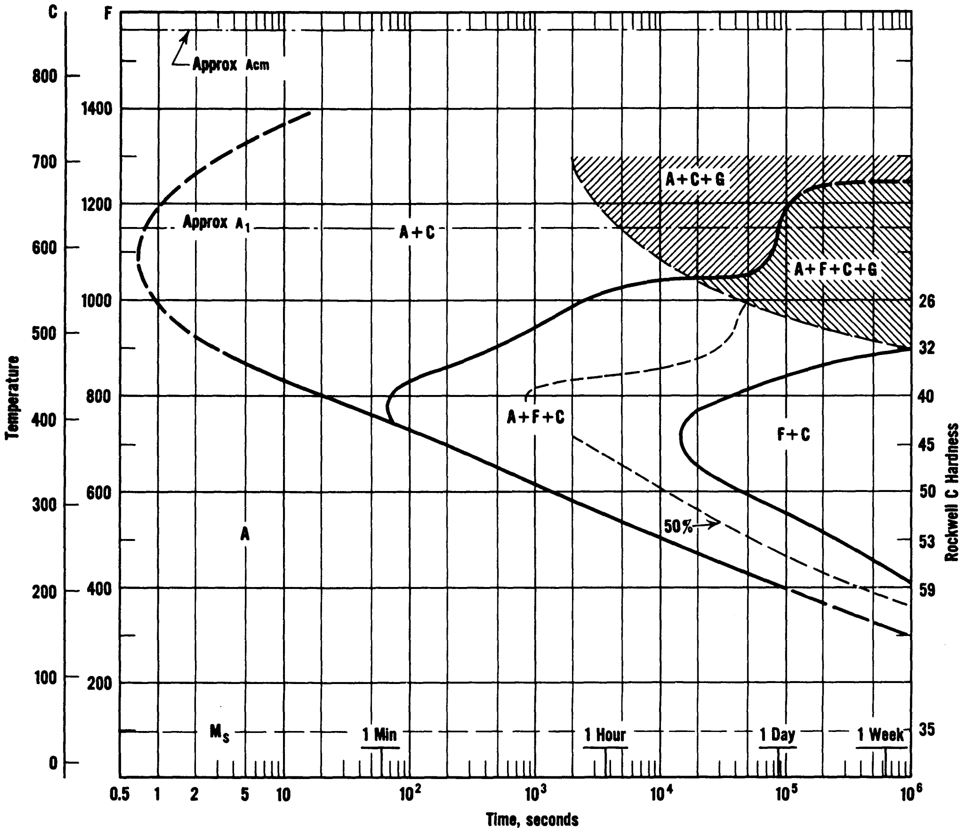
C-1.0 Mn-0.52
Ni-5.00

Austenitized at 1700 F
Grain Size: 6-7

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
Cross-hatched areas represent region in which graphite (G) formed.
M = Martensite

Data from U.S. Steel Atlas[3]



2512
(1.2 C)
Carburized

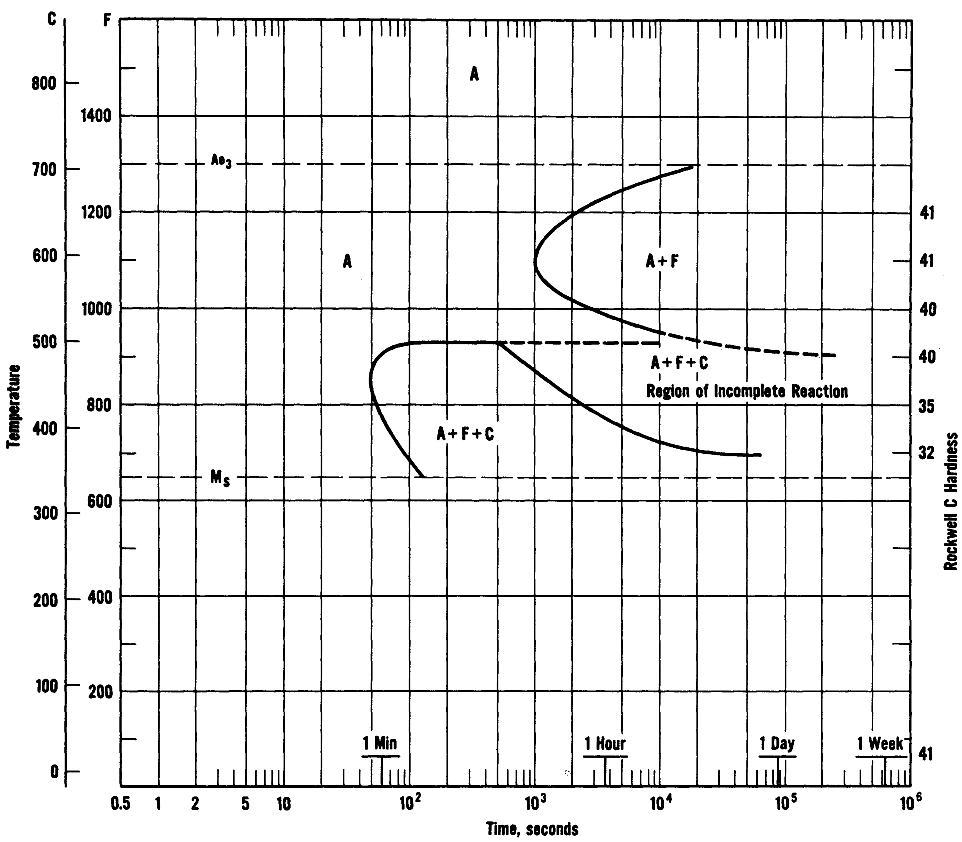
C-1.2 Mn-0.52
Ni-5.00

Austenitized at 1700 F
Grain Size: 7

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
Cross-hatched areas represent region in which graphite (G) formed.
M = Martensite

Data from U.S. Steel Supplement to Atlas[4]



9 Nickel

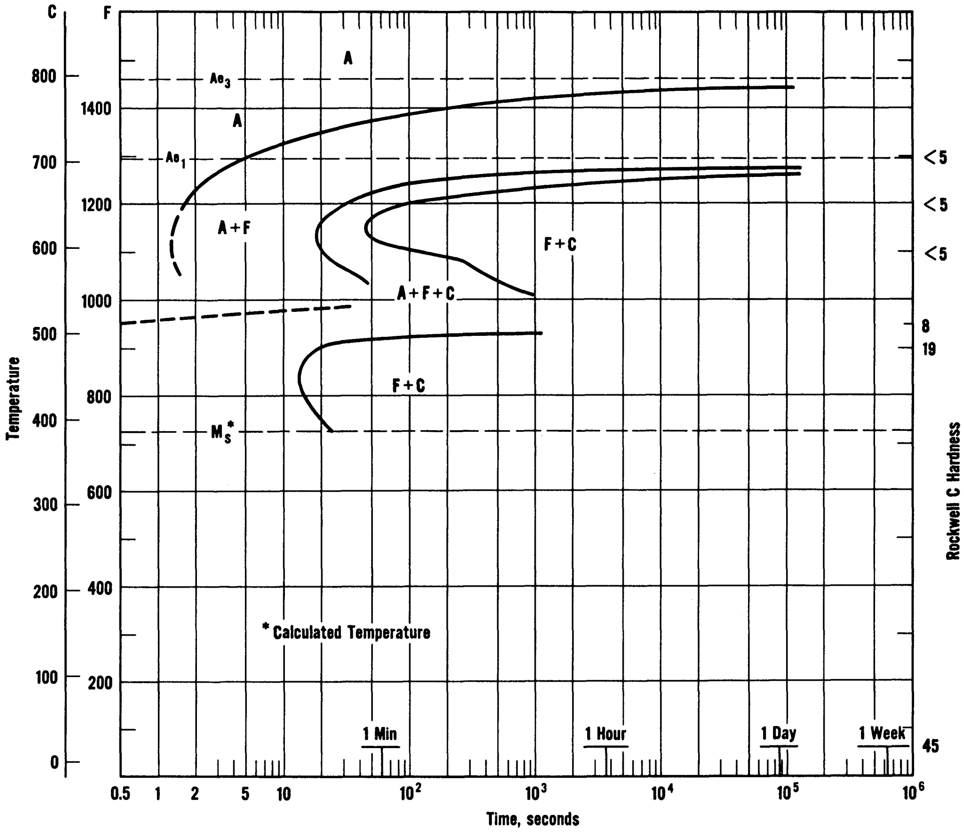
C-0.10 Mn-0.77
Ni-8.56

Austenitized at 1475 F
Grain Size: 9-10

Starting Criterion:
1 % Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
A. R. Troiano for
The International
Nickel Company, Inc.



3120

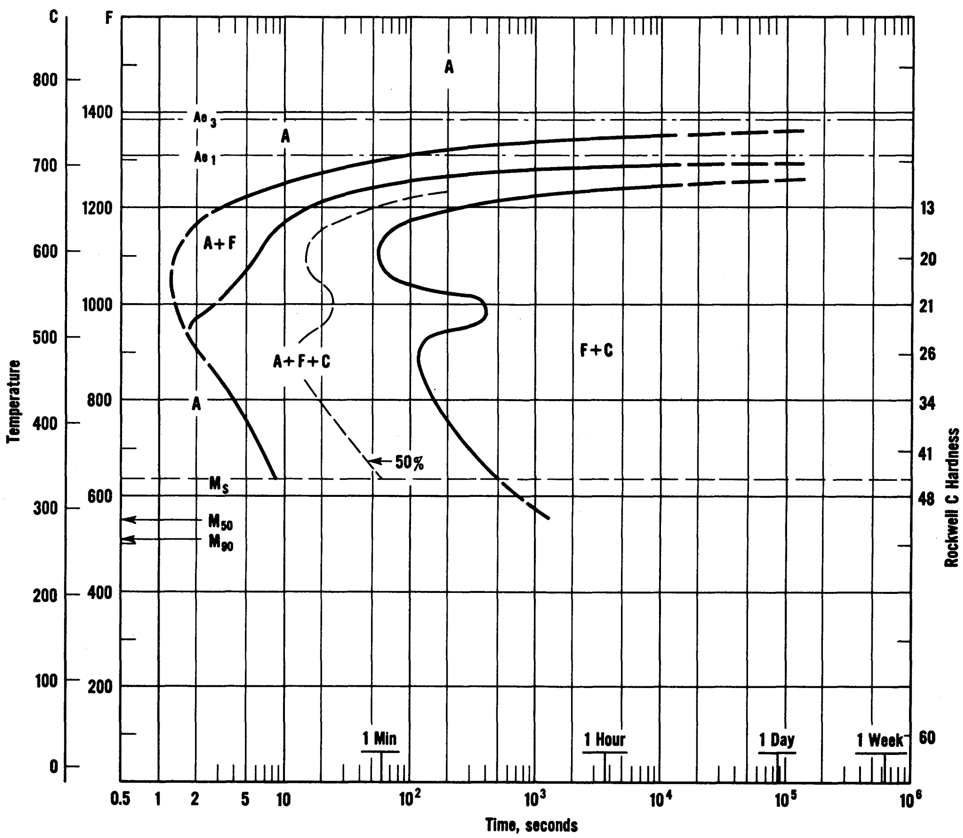
C-0.21 Mn-0.61
Ni-1.35 Cr-0.67

Austenitized at 1650 F
Grain Size:
80% 7-8, 20% 4-5

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Battelle Memorial Inst.
for
The International
Nickel Company, Inc.



3140

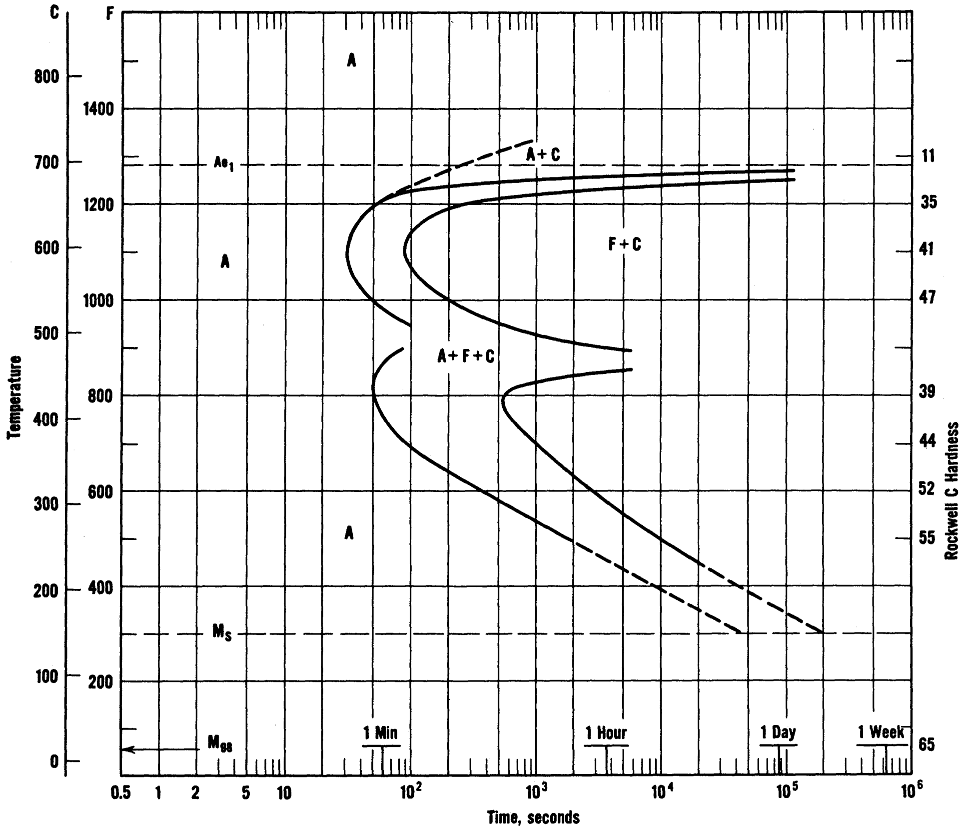
C-0.38 Mn-0.72
Ni-1.32 Cr-0.49

Austenitized at 1550 F
Grain Size: 7-8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]



3190

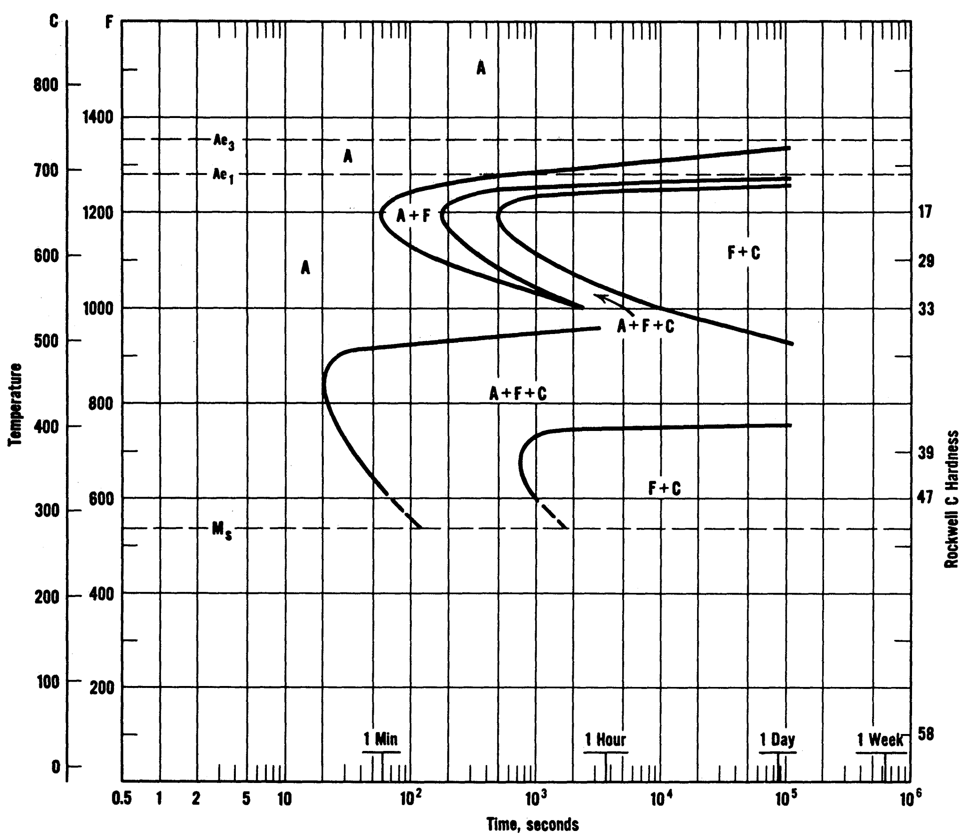
C-0.91 Mn-0.65
Ni-1.35 Cr-0.60

Austenitized at 1650 F
Grain Size: 5-7

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Battelle Memorial
Institute for
The International
Nickel Company, Inc.



3240

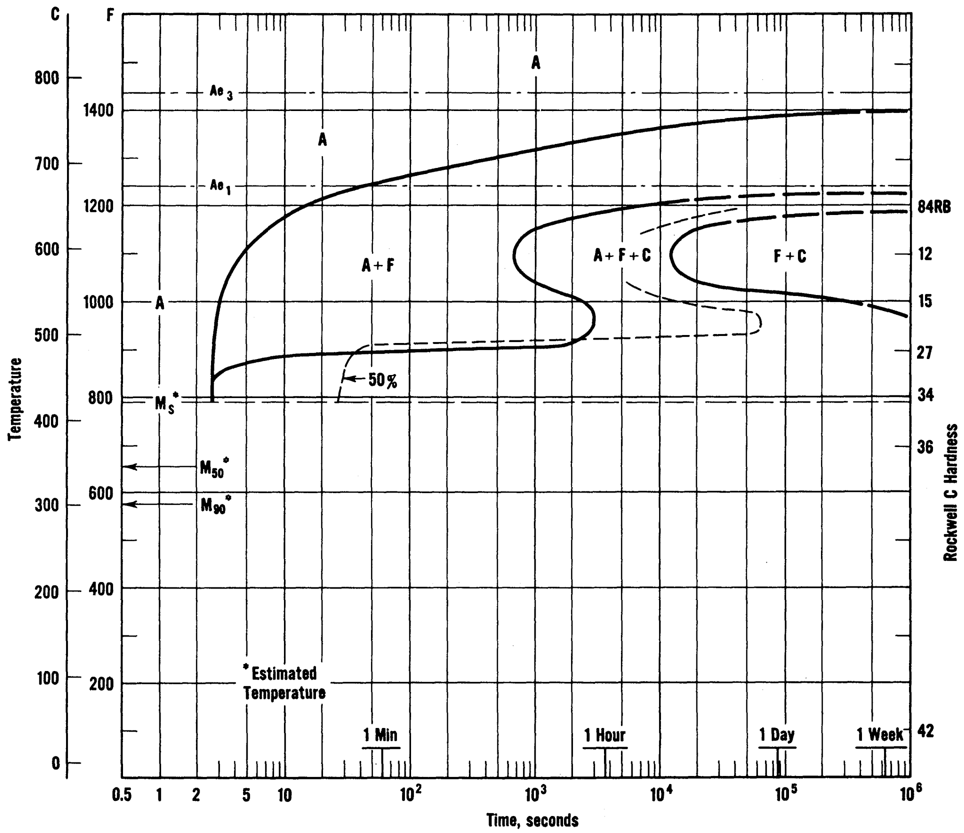
C-0.43 Mn-0.52
Ni-1.76 Cr-1.19

Austenitized at 1650 F
Grain Size: 6-7

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Battelle Memorial
Institute for
The International
Nickel Company, Inc.



3310

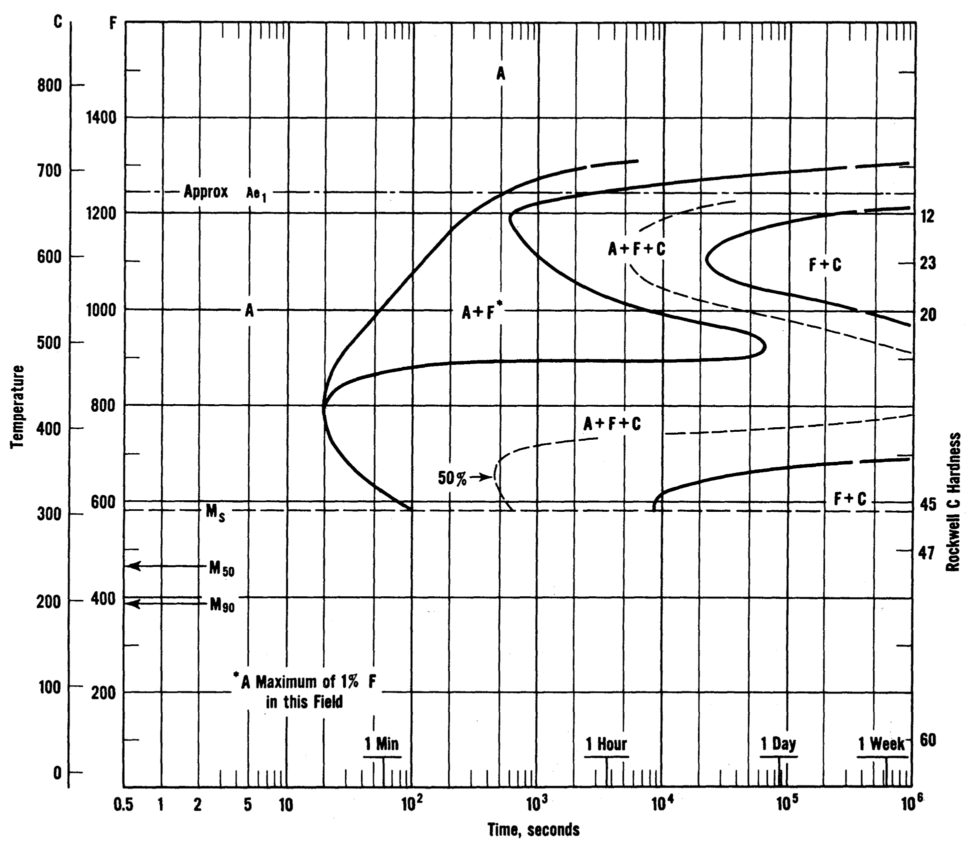
C-0.11 Mn-0.45
Ni-3.33 Cr-1.52

Austenitized at 1650 F
Grain Size: 9

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas[3]



3310 (0.4 C) Carburized

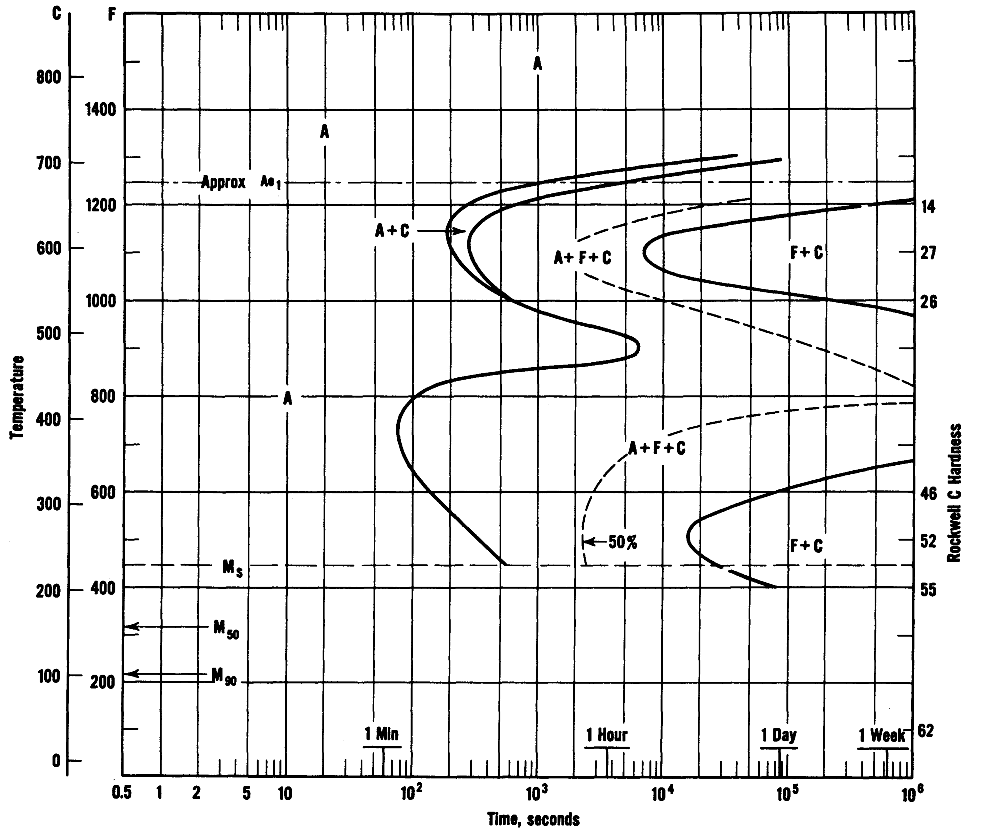
C-0.4 Mn-0.45
Ni-3.33 Cr-1.52

Austenitized at 1700 F
Grain Size:
65% 8, 35% 5

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas[3]



3310
(0.6 C)
Carburized

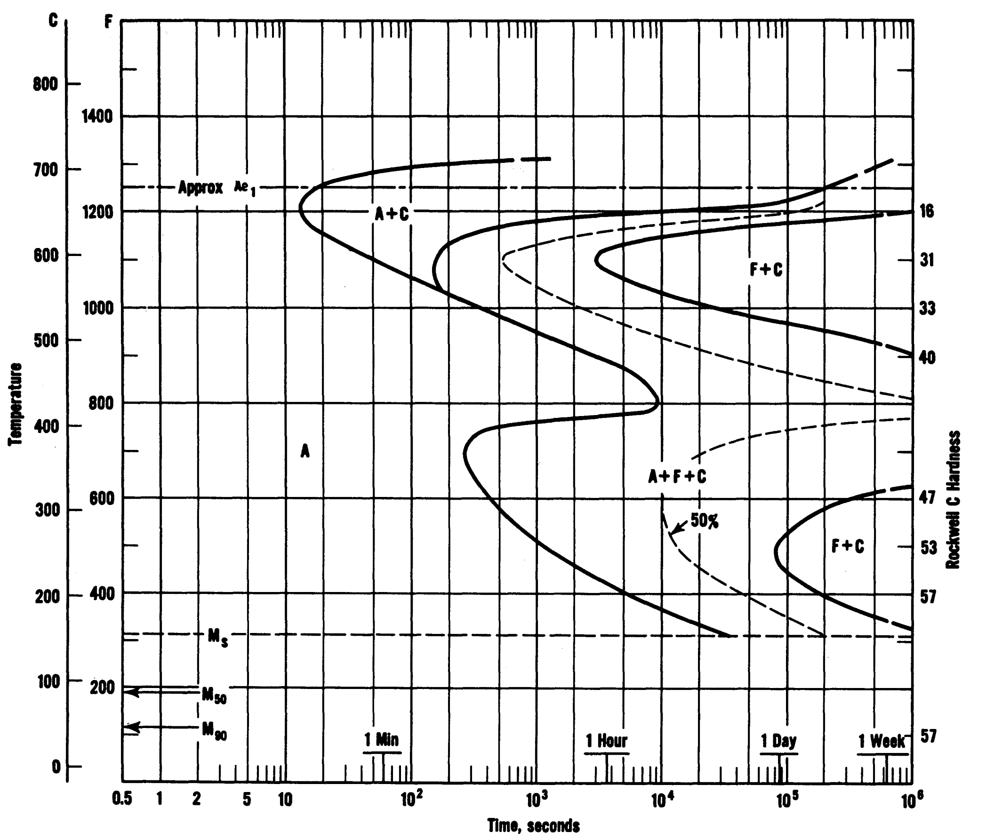
C-0.6 Mn-0.45
Ni-3.33 Cr-1.52

Austenitized at 1700 F
Grain Size: 6

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas[3]



3310
(0.8 C)
Carburized

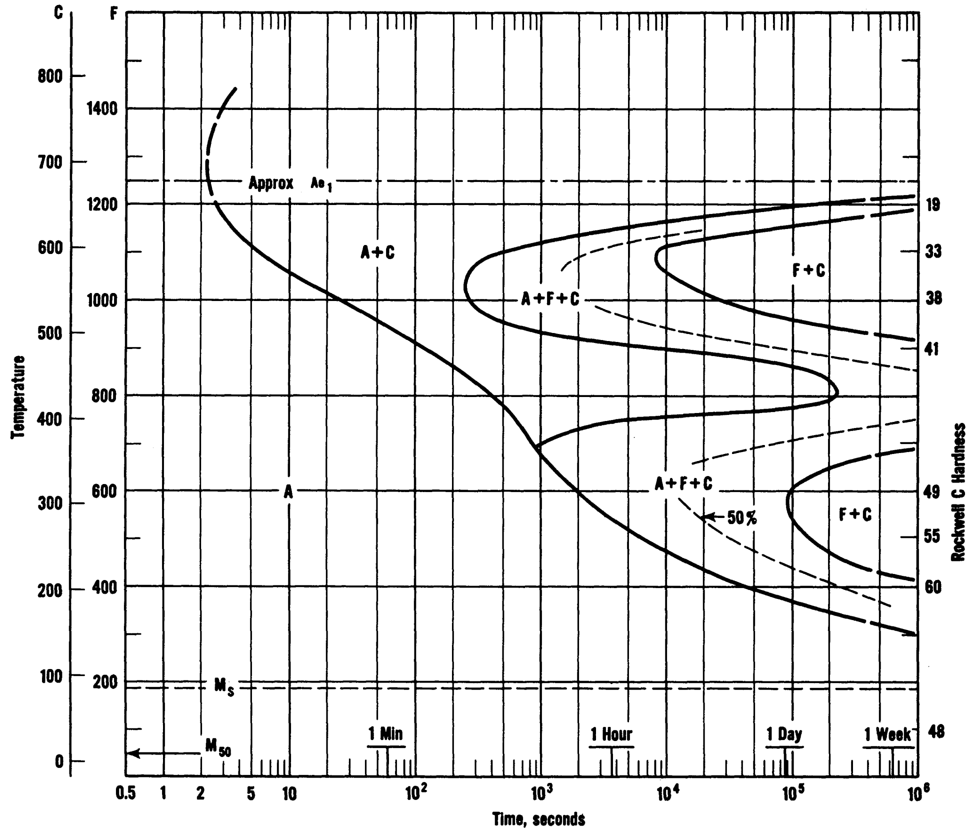
C-0.8 Mn-0.45
Ni-3.33 Cr-1.52

Austenitized at 1700 F
Grain Size: 8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from U.S. Steel
Supplement to Atlas[4]



3310
(1.0 C)
Carburized

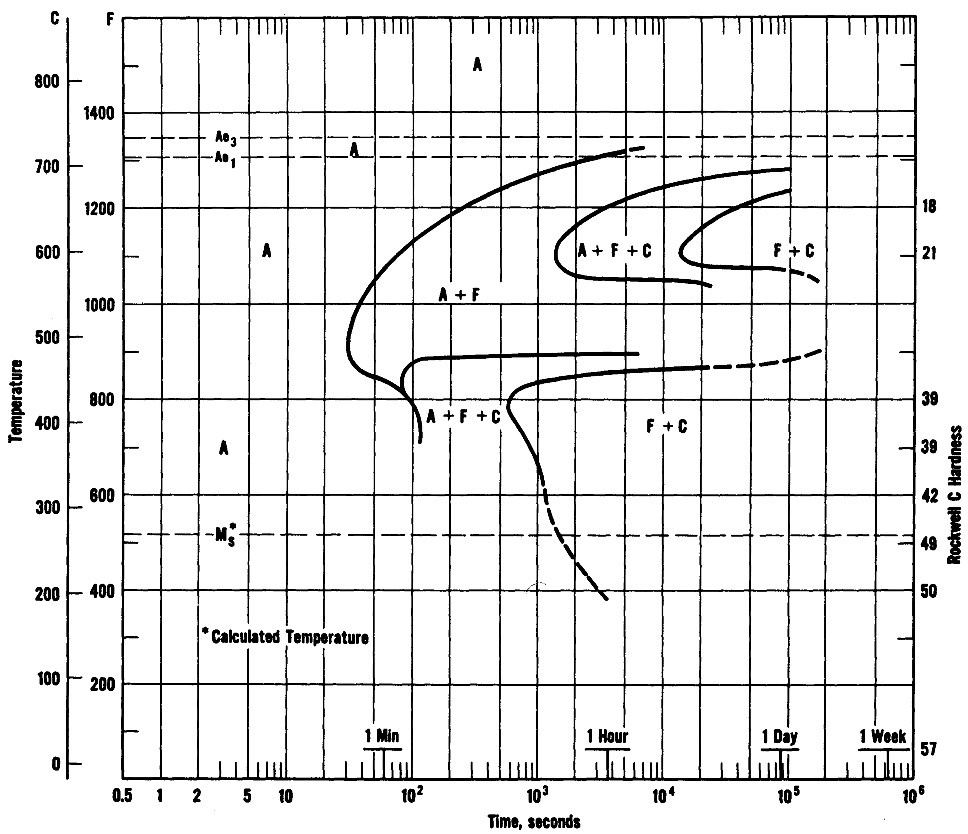
C-1.0 Mn-0.45
Ni-3.33 Cr-1.52

Austenitized at 1700 F
Grain Size: 4-5

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]



3330

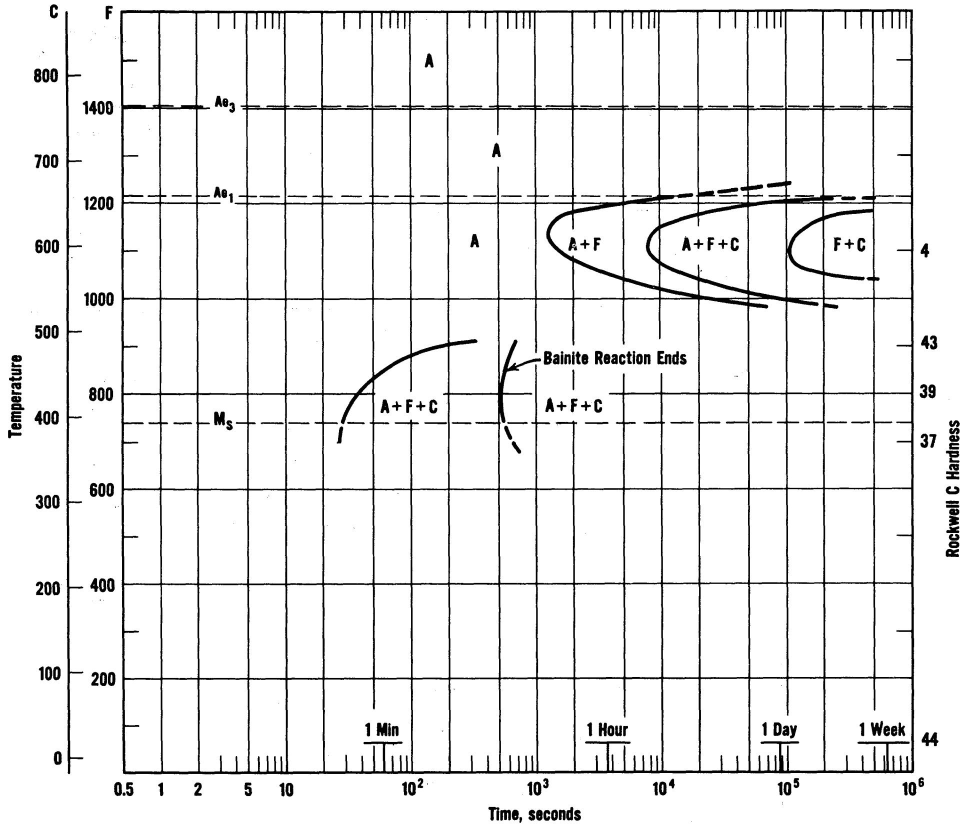
C-0.29 Mn-0.21
Ni-3.25 Cr-1.45

Austenitized at 1550 F
Grain Size: 7

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
B. M. Loring,
Trans. AIME, *150*
1942, p 283



Krupp 0.15 C

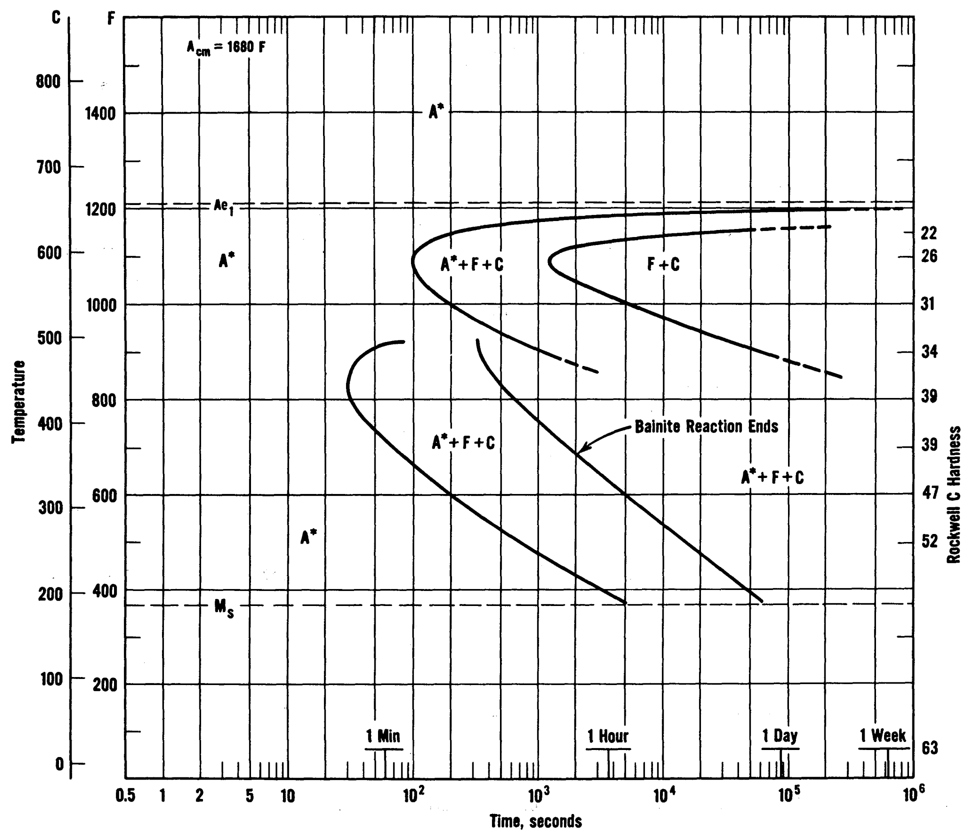
C-0.15 Mn-0.45
Ni-4.03 Cr-1.54

Austenitized at 1650 F
Grain Size: 7-9

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Troiano & DeMoss
for
The International
Nickel Company, Inc.



Krupp 0.90 C

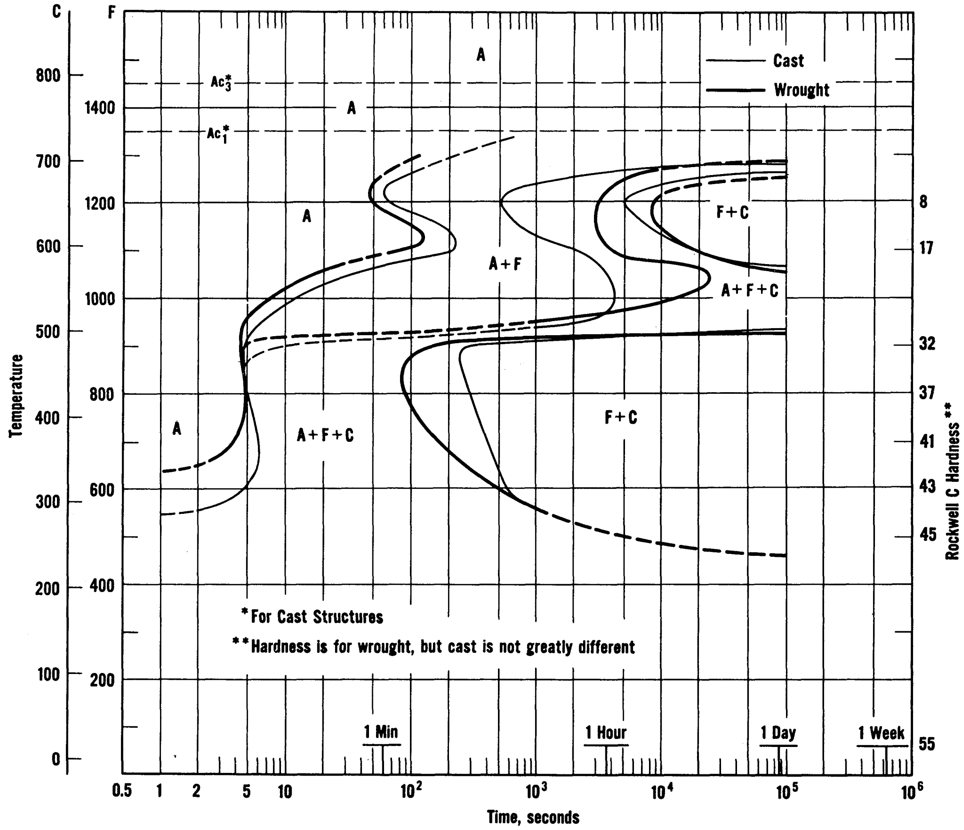
C-0.87 Mn-0.39
Ni-4.00 Cr-1.58

Austenitized at 1475 F
Grain Size: 7-8

Starting Criterion:
1% Transformation

Legend
A* = Austenite + Carbide
F = Ferrite
C = Carbide
M = Martensite

Data by
Troiano & DeMoss
for
The International
Nickel Company, Inc.



4330

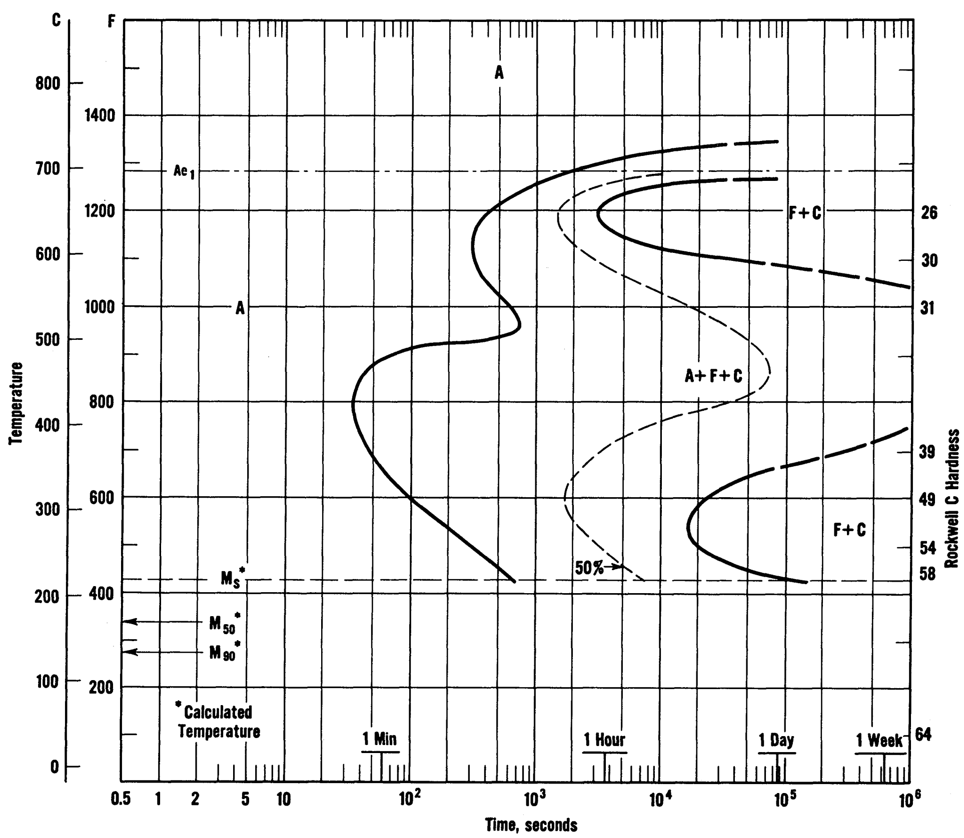
C-0.33 Mn-0.69
Ni-1.41 Cr-0.72
Mo-0.28

Austenitized at 1660 F
Grain Size: 7-8

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Eddy, Marcotte & Smith,
Trans. AIME, *162*, 1945,
p 250



4360

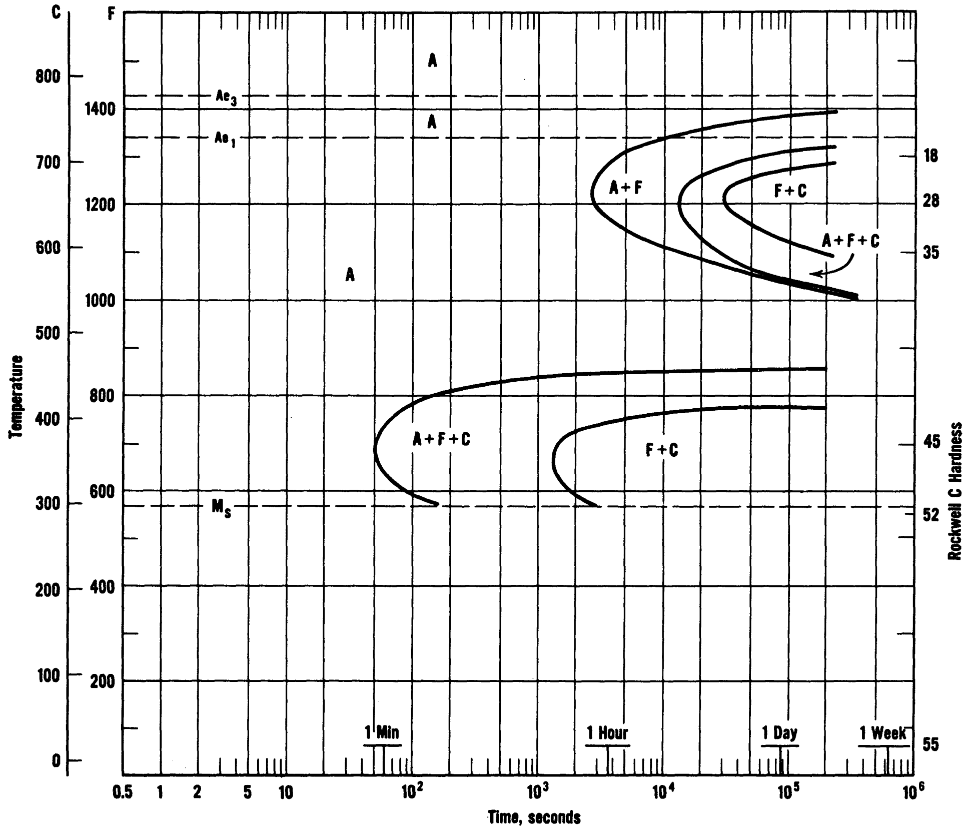
C-0.62 Mn-0.64
Si-0.67 Ni-1.79
Cr-0.60 Mo-0.32

Austenitized at 1800 F
Grain Size: 7-8
(Occasional 4)

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas[3]



4330 Modified (Si+V)

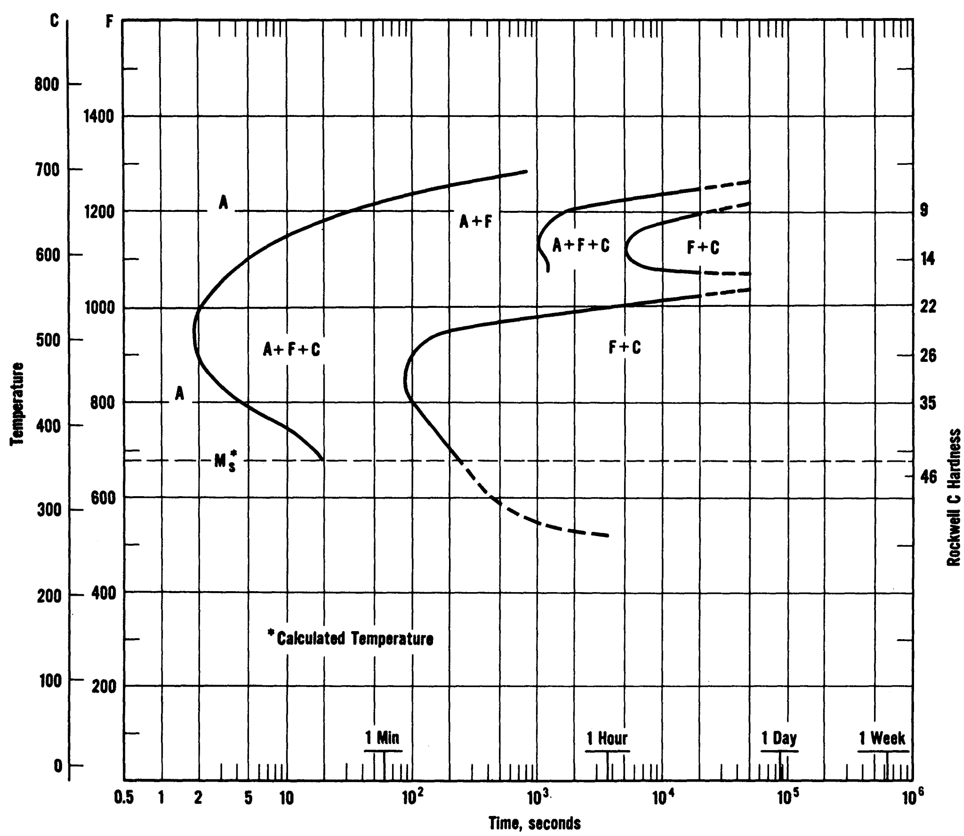
C-0.34 Mn-0.98
Si-1.37 Ni-1.82
Cr-0.95 Mo-0.42
V-0.14

Austenitized at 1650 F
Grain Size: 4

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
J. W. Forney, Frankford Arsenal, Report R-1627, April 1962



4630

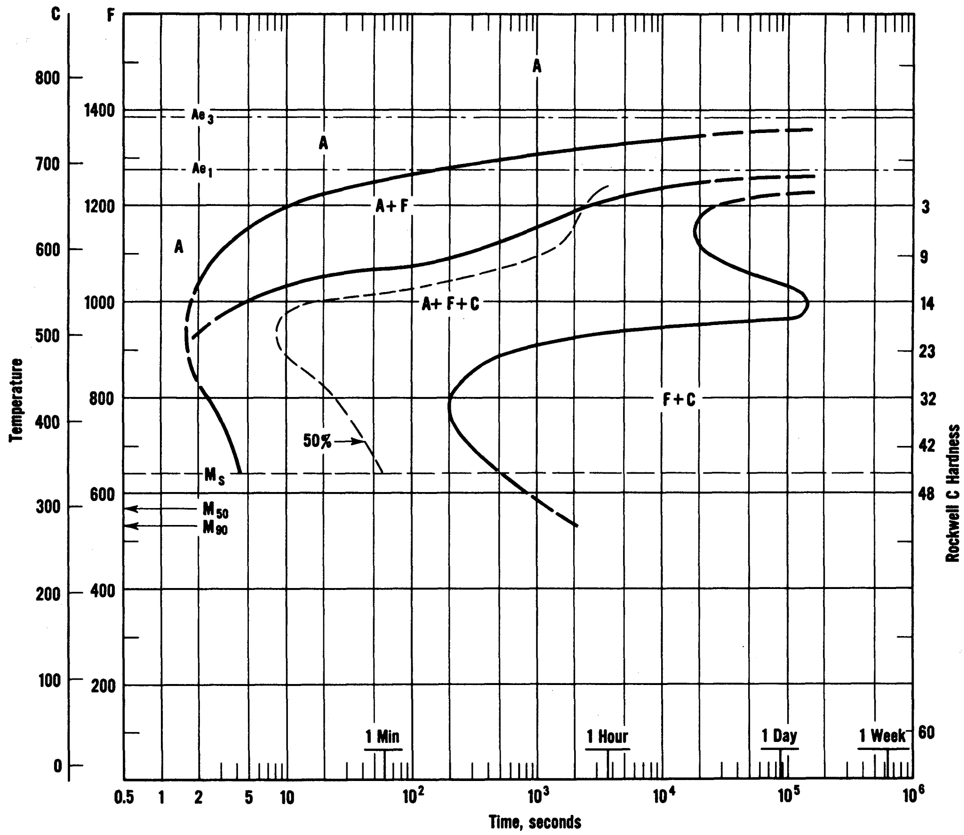
C-0.32 Mn-0.74
Ni-1.70 Mo-0.23

Austenitized at 1550 F
Grain Size: 8

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Parke & Herzig, Metals and Alloys, *11*, 1940, p6

4640



C-0.36 Mn-0.63
Ni-1.84 Mo-0.23

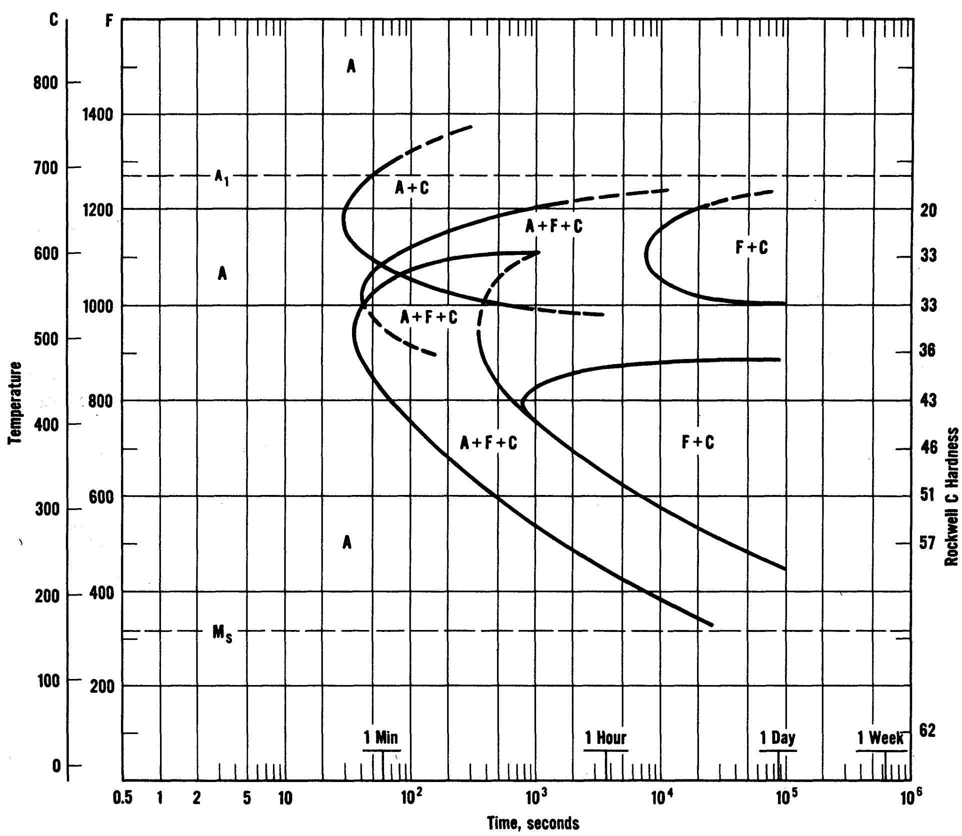
Austenitized at 1550 F
Grain Size: 7-8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]

4695



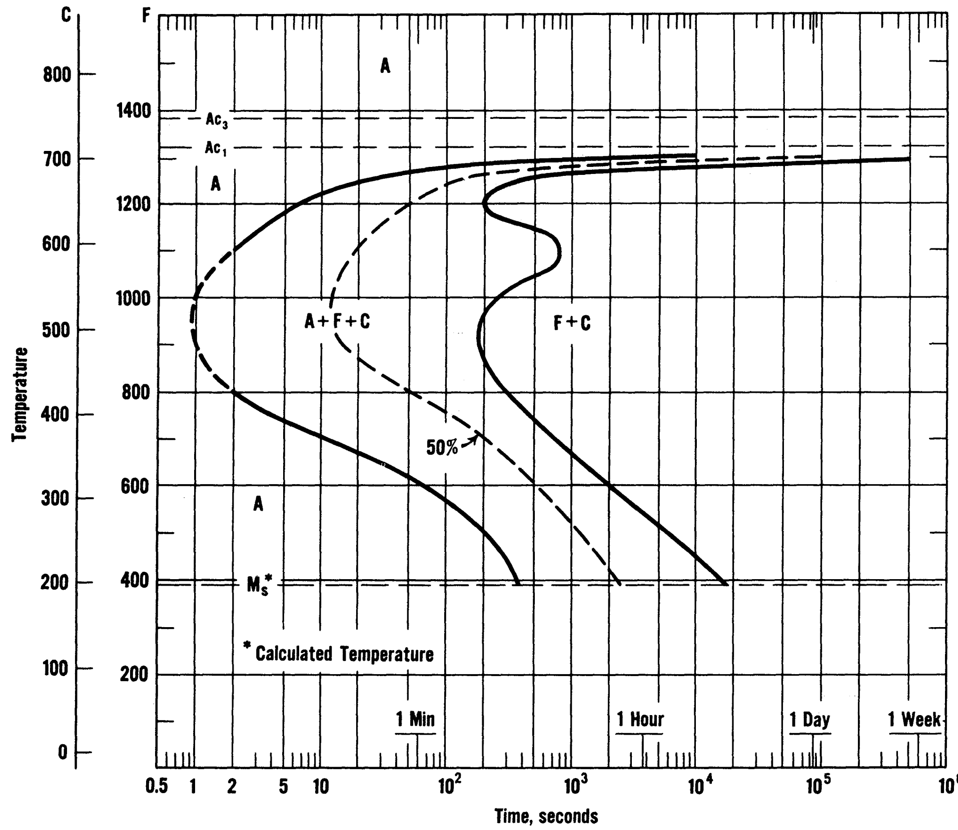
C-0.95 Mn-0.58
Ni-1.79 Mo-0.25

Austenitized at 1700 F
Grain Size:
50% 5-6, 50% 2-3

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
A. R. Troiano for
The International
Nickel Company, Inc.



SAE EX-2

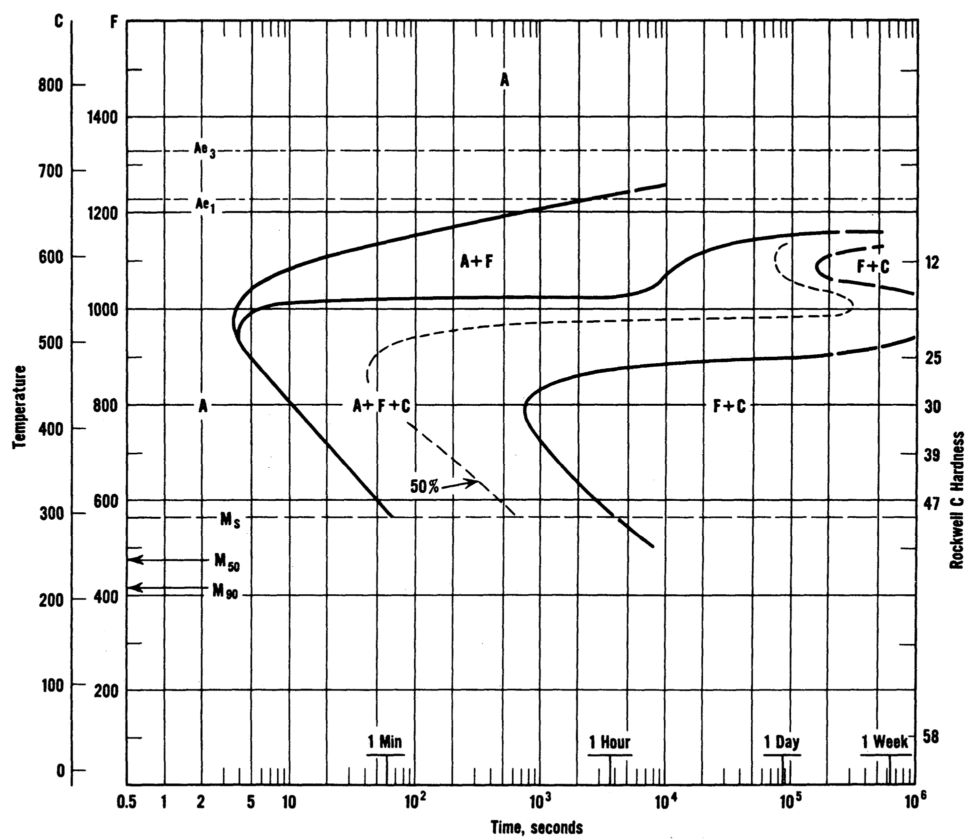
C-0.69 Mn-0.42
Ni-0.80 Cr-0.20
Mo-0.13

Austenitized at 1525 F
Grain Size: 8

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
International
Nickel Limited



4840

C-0.41 Mn-0.60
Ni-3.51 Mo-0.21

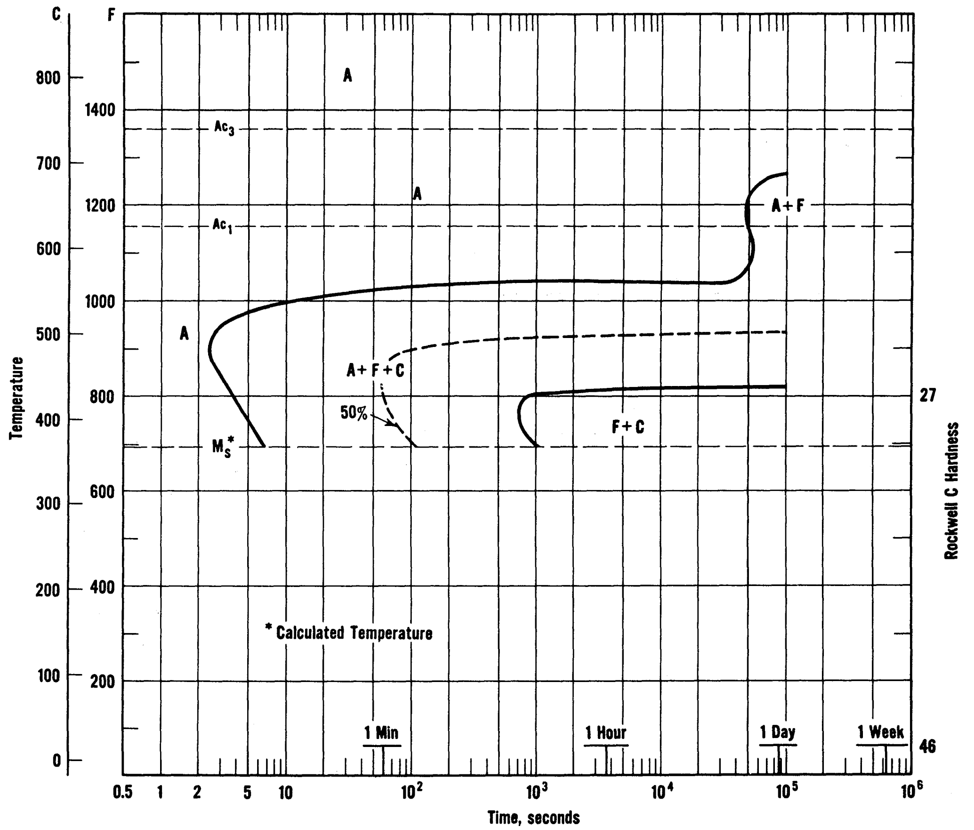
Austenitized at 1600 F
Grain Size: 7-8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
U.S. Steel Atlas [3]

SAE EX-1



C-0.17 Mn-0.49
Ni-5.07 Mo-0.24

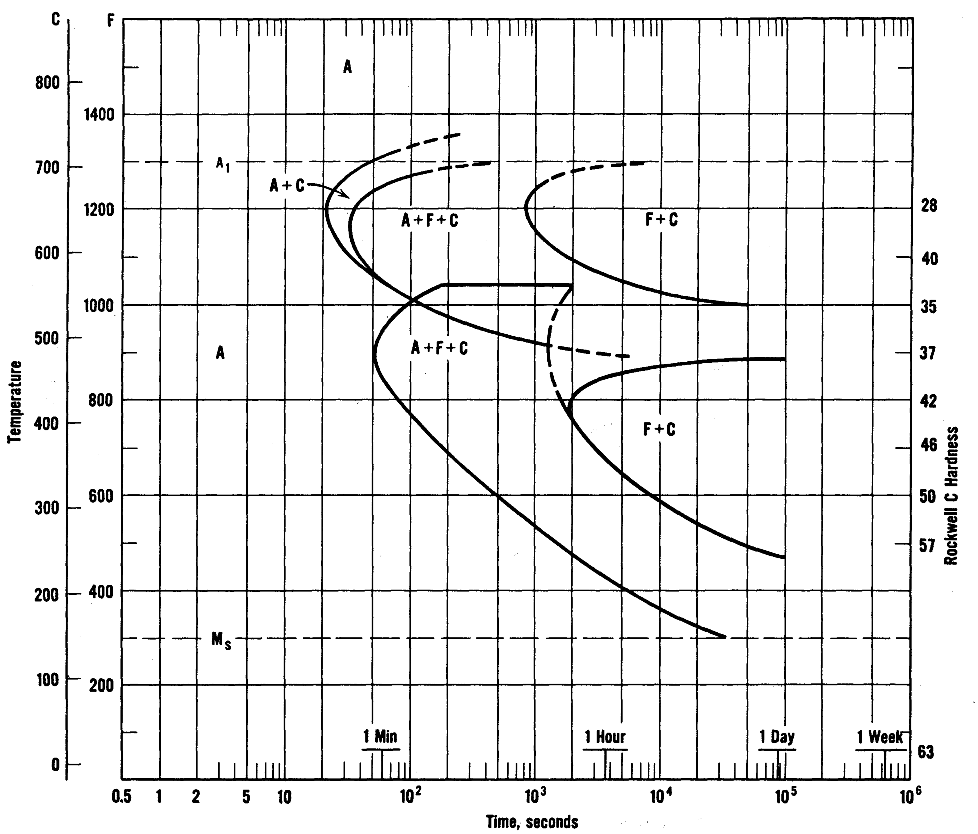
Austenitized at 1700 F
Grain Size: 5-6

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
International
Nickel Limited

8695



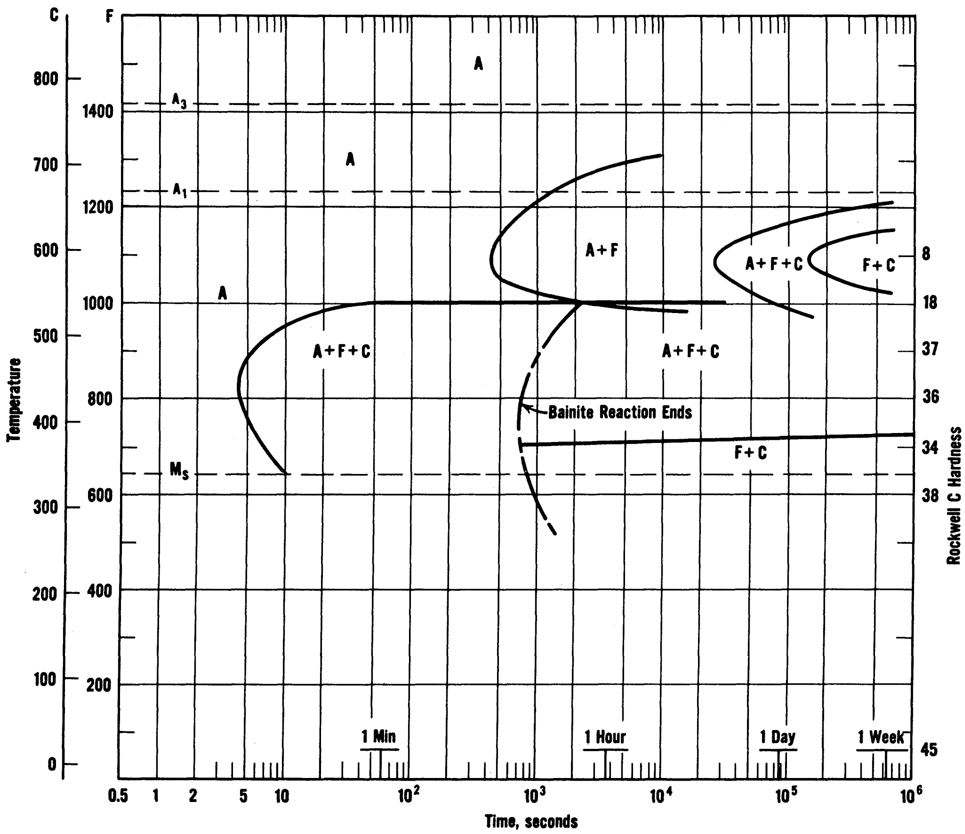
C-0.95 Mn-0.82
Ni-0.56 Cr-0.52
Mo-0.19

Austenitized at 1700 F
Grain Size:
10% 3-4, 90% 6-7

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
A. R. Troiano for
The International
Nickel Company, Inc.



9315

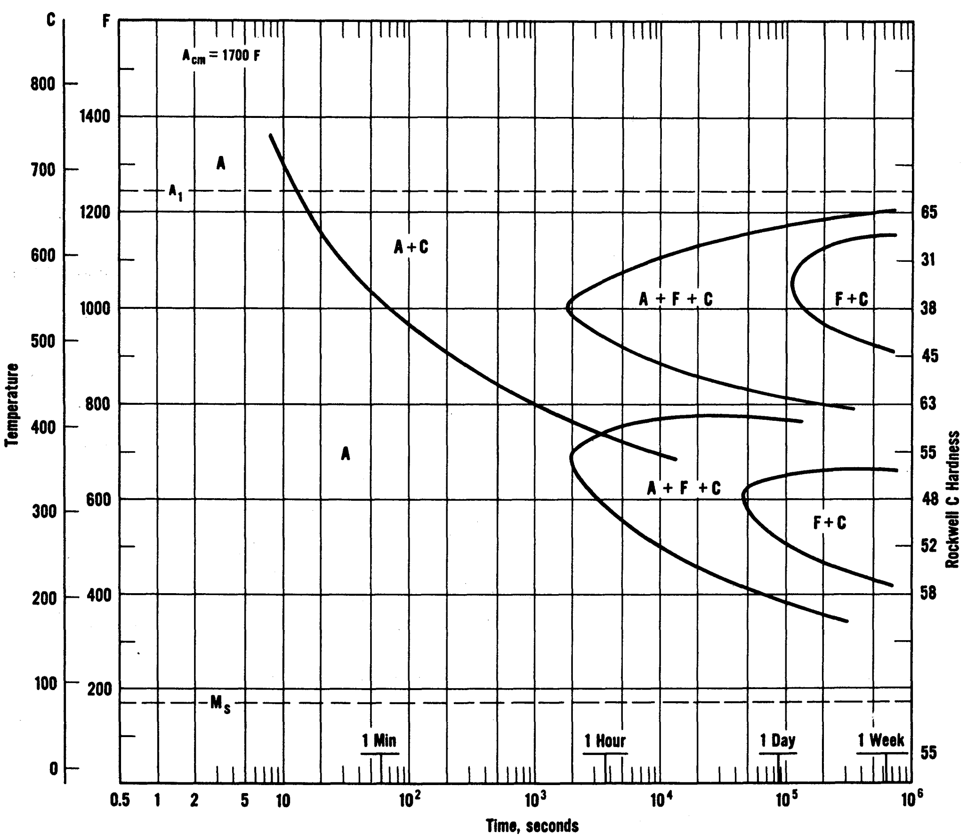
C-0.17 Mn-0.59
Ni-3.18 Cr-1.12
Mo-0.13

Austenitized at 1700 F
Grain Size: 7-8

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Hehemann & Troiano
for
The International
Nickel Company, Inc.



9395

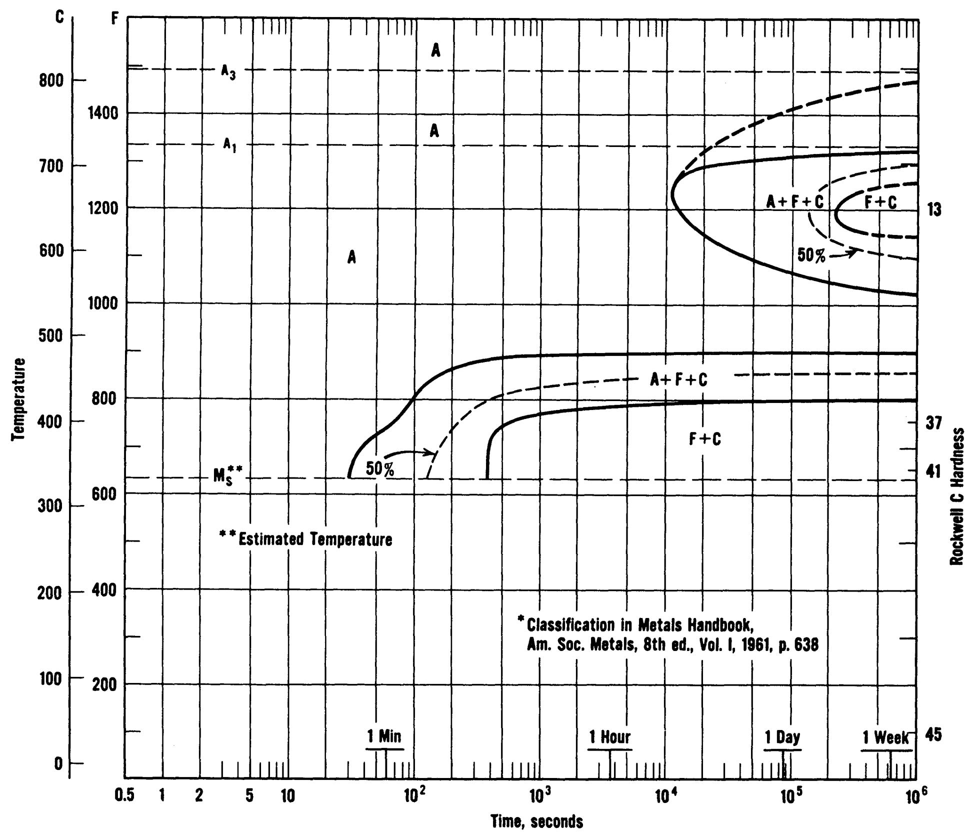
C-0.95 Mn-0.60
Ni-3.27 Cr-1.23
Mo-0.13

Austenitized at 1700 F
Grain Size:
10% 5-6, 90% 7-8

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
A. R. Troiano for
The International
Nickel Company, Inc.



6F4 Tool

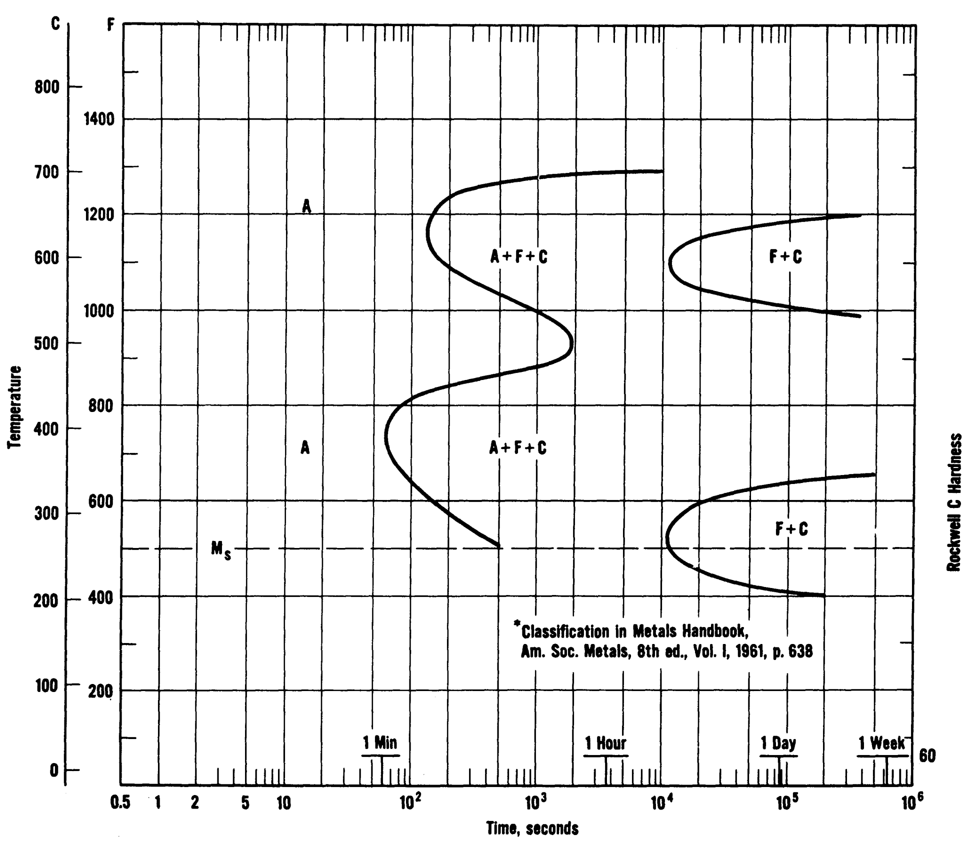
C-0.22 Mn-0.50
Ni-2.80 Mo-2.95

Austenitized at 1900 F
Grain Size: 5

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Heppenstall Co.



6F5 Tool

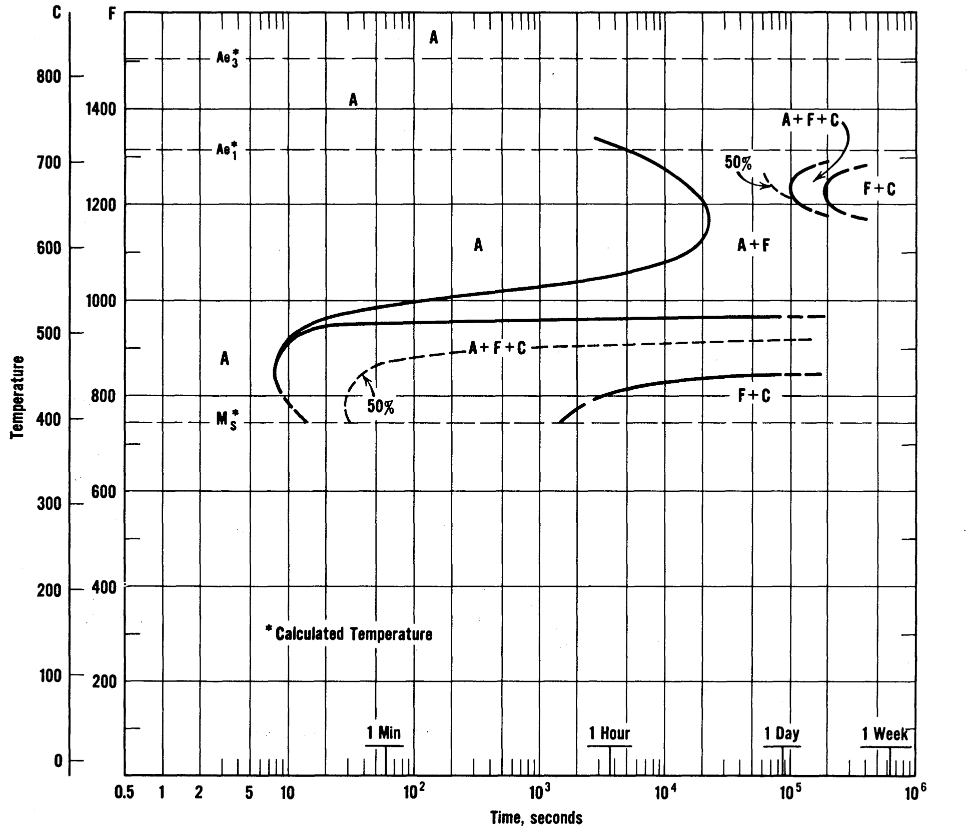
C-0.55 Mn-0.90
Si-1.00 Ni-2.75
Cr-0.40 Mo-0.45
V-0.13

Austenitized at 1600 F

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Latrobe Steel Co.



Ni-Cr-Mo-V-Cu-B

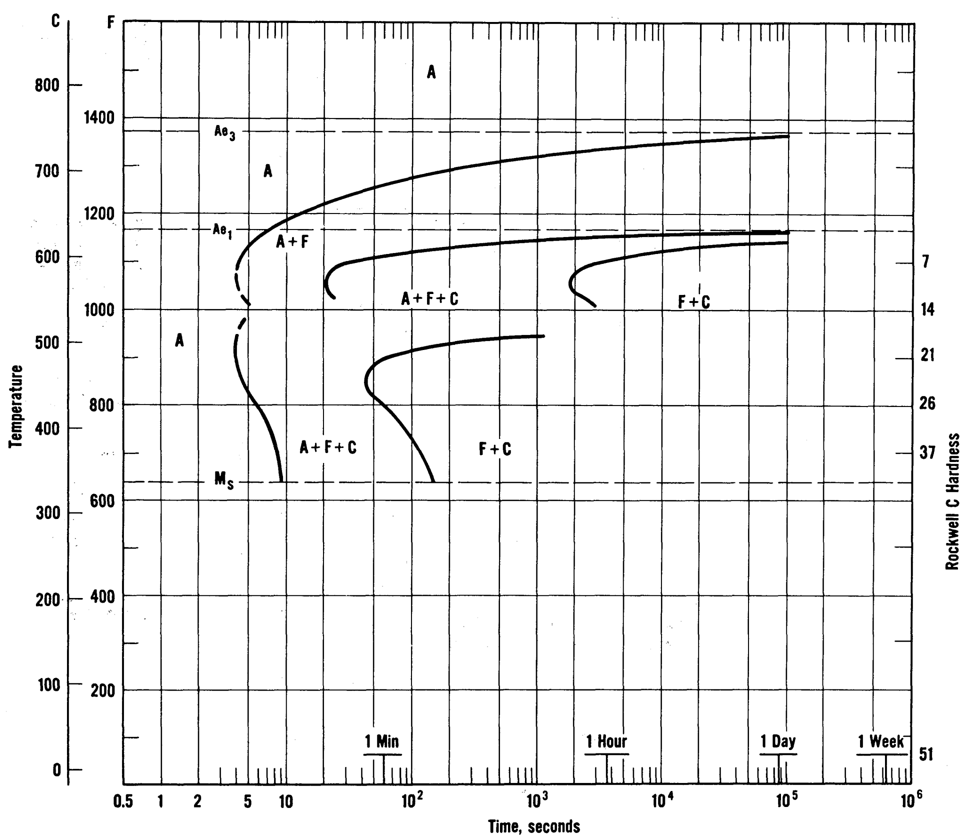
C-0.15 Mn-0.92
Ni-0.88 Cr-0.50
Mo-0.46 V-.06
Cu-0.32 B-.003

Austenitized at 1675 F
Grain Size: 6-7

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
W. D. Doty, Welding
Journal, *34*, 1955,
p425-S



2¾ Nickel Forging

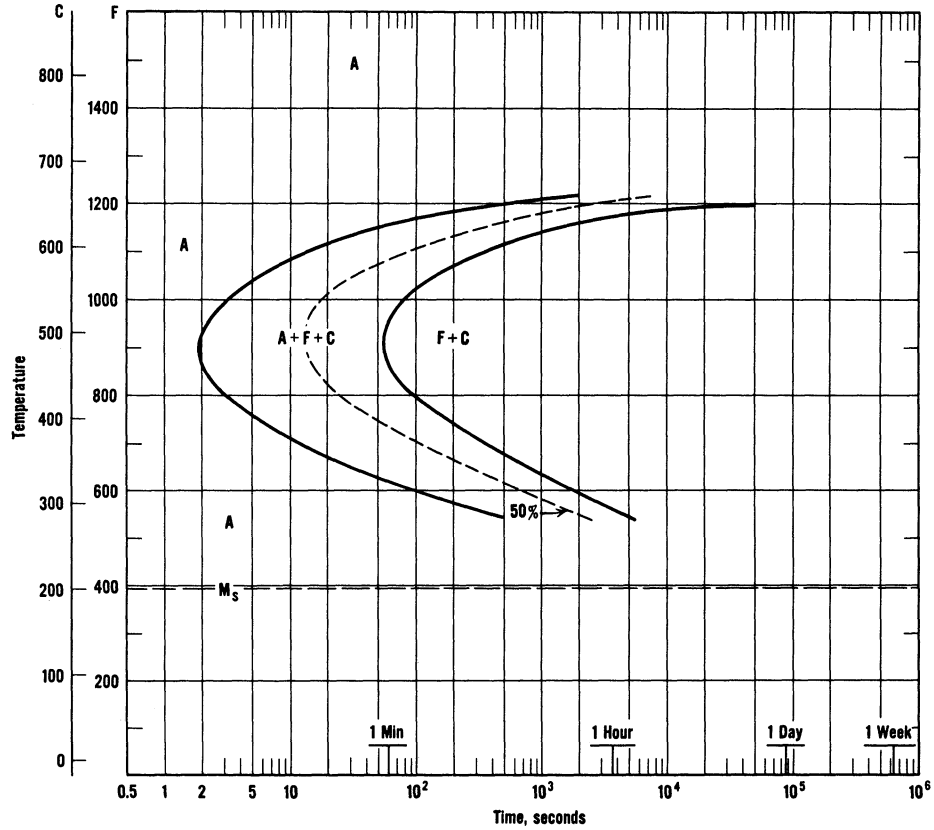
C-0.29 Mn-0.77
Ni-2.72

Austenitized at 1550 F
Grain Size: 6-8

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Battelle Memorial
Institute for
The International
Nickel Company, Inc.



$2\frac{1}{2}$ Nickel Saw

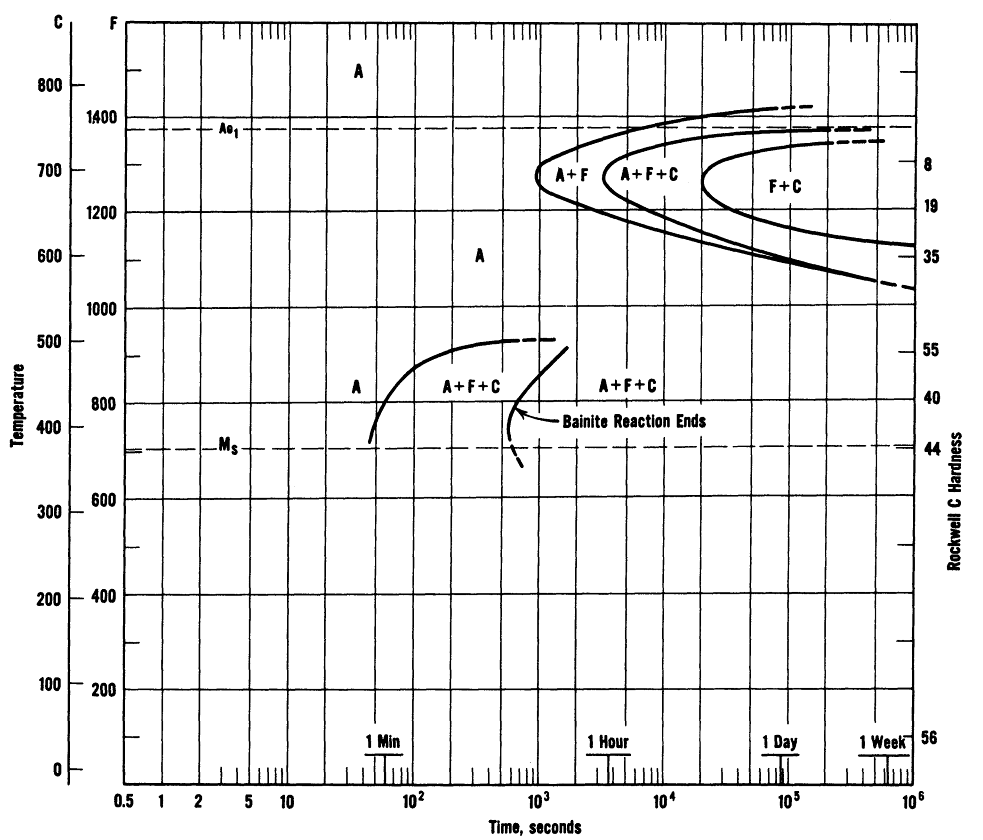
C-0.76 Mn-0.41
Ni-2.50 Mo-.08

Austenitized at 1382 F
Grain Size: 9

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Heal and Mykura,
Metal Treatment and
Drop Forging, *17*, 1950, p 134



VCM Nitriding

C-0.32 Mn-0.76
Ni-0.70 Cr-1.06
Mo-1.01

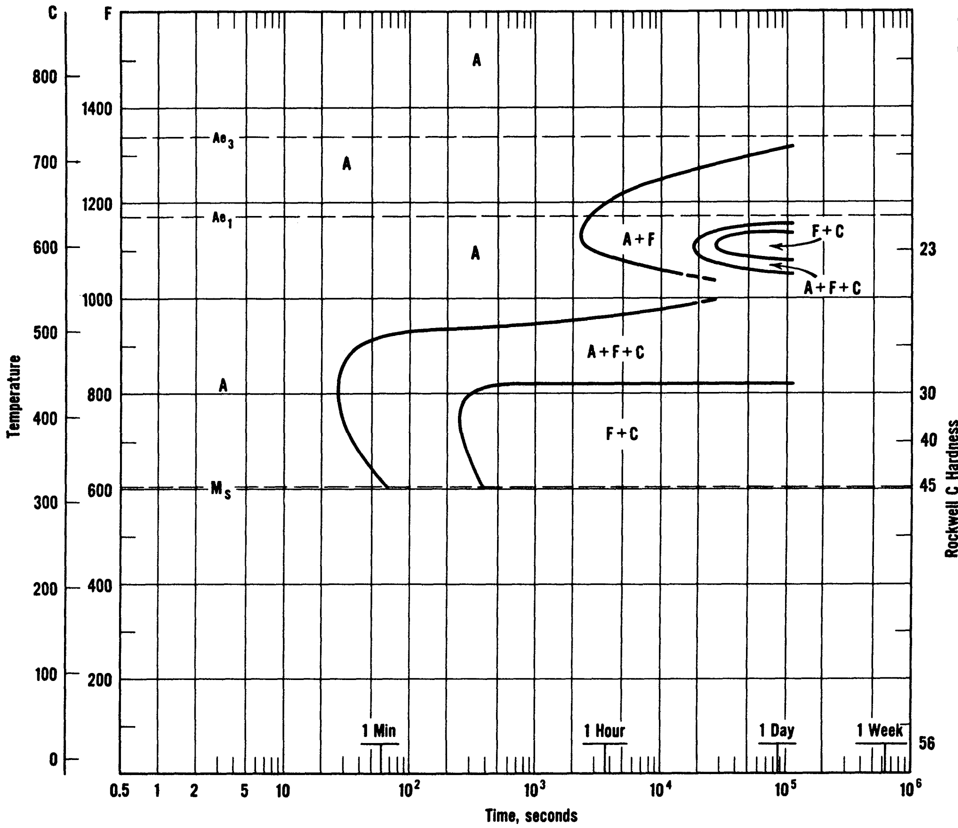
Austenitized at 1650 F
Grain Size: 7-8

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
A. R. Troiano for
The International
Nickel Company, Inc.

2½ Ni-½ Mo-V Turbine Rotor



C-0.34 Mn-0.71
Ni-2.52 Mo-0.42
V-.02

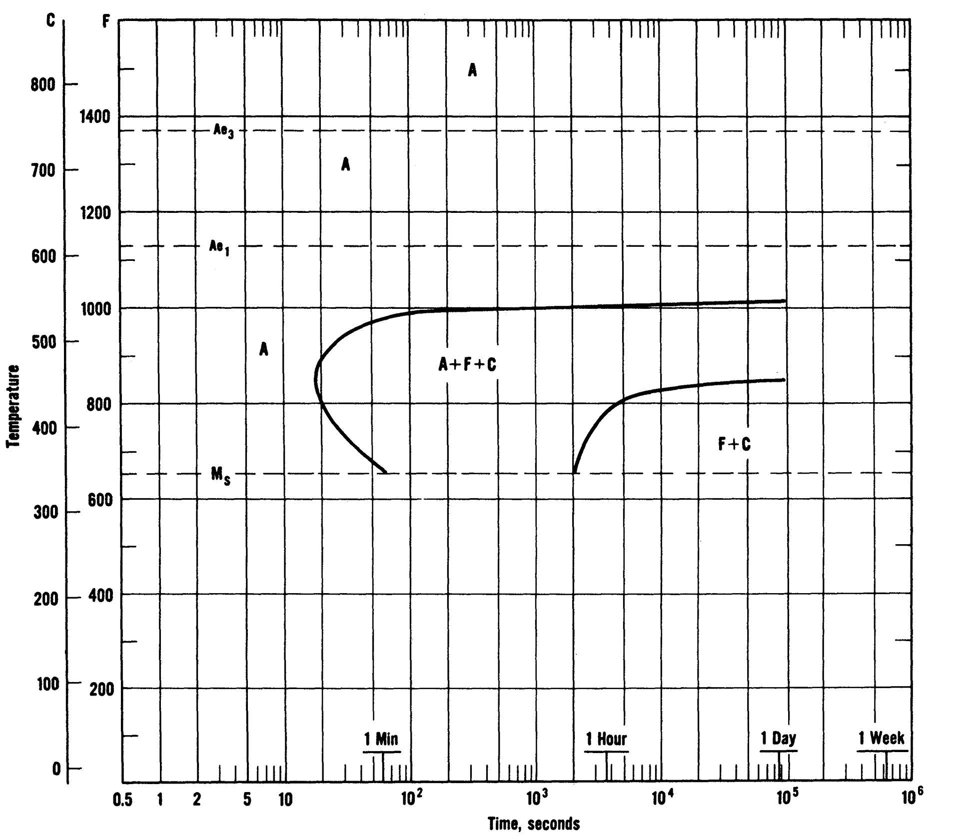
Austenitized at 1650 F
Grain Size: 6-7

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data by
Battelle Memorial
Institute for
The International
Nickel Company, Inc.

5¼ Ni-¼ Mo-V



C-0.22 Mn-0.52
Ni-5.35 Mo-0.27
V-.08

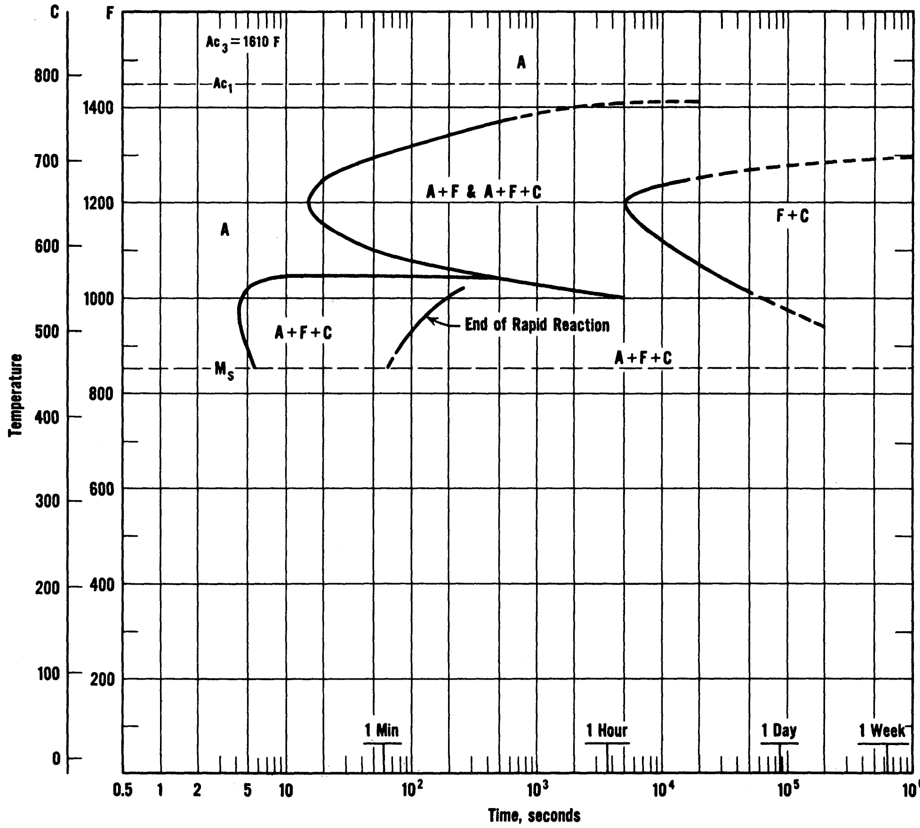
Austenitized at 1650 F (16 hr)
Cooled at 100 F Hr
Reaustenitized at 1450 F (16 hr)
Grain Size: 8

Starting Criterion:
0.1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Yeo & Beasley, U. S.
Patent 2,992,148, July
11, 1961

Ni-Cr-Mo-V (Weld Metal)



C-.08 Mn-1.05
Ni-2.00 Cr-0.20
Mo-0.75 V-0.25

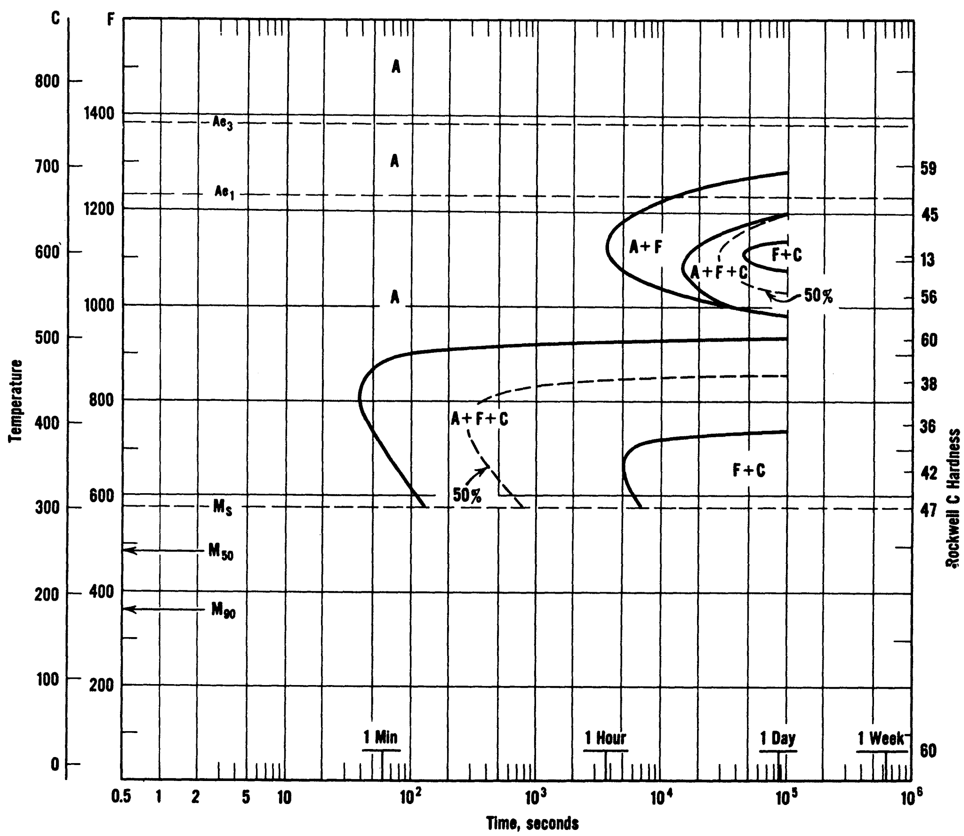
Austenitized at 2000 F
(20 sec)
Grain Size: 6-8

Starting Criterion:
1% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Bailey & Harris, U.S.
Naval Res. Lab. Report
3849, July 7, 1951

3¼ Ni-Cr-Mo



C-0.33 Mn-0.57
Ni-3.26 Cr-0.85
Mo-.09

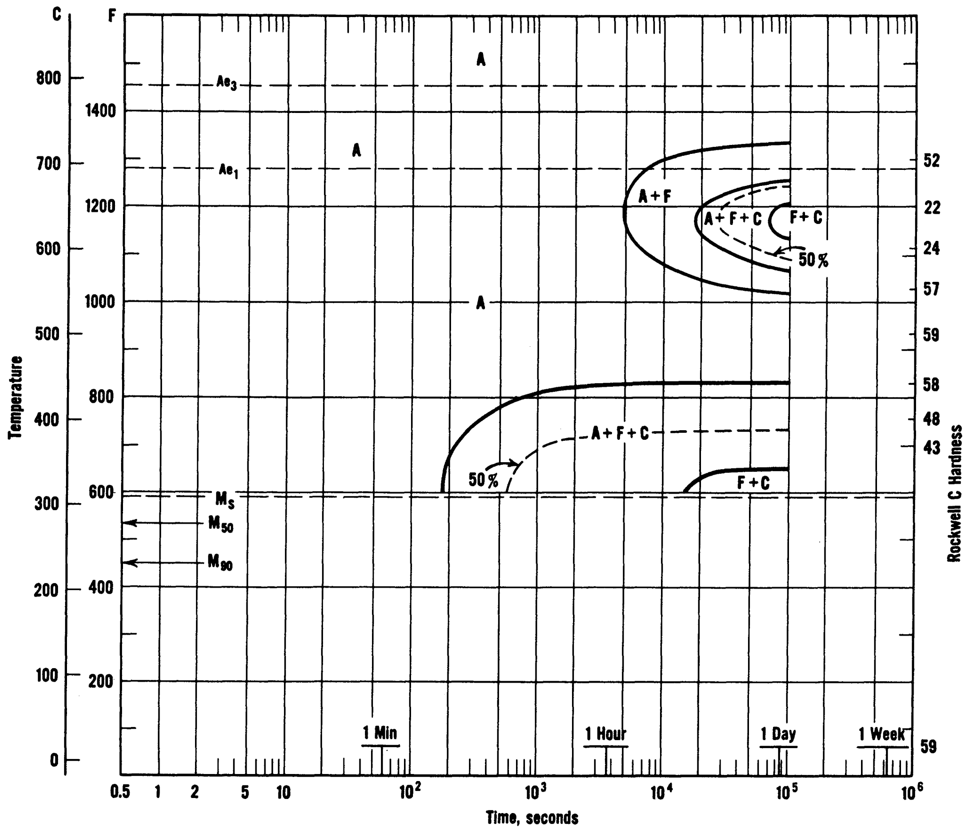
Austenitized at 1535 F
Grain Size: 9

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
International
Nickel Limited[5]

3 Ni-Cr-Mo-V



C-0.32 Mn-0.51
Ni-3.02 Cr-1.37
Mo-0.48 V-0.18

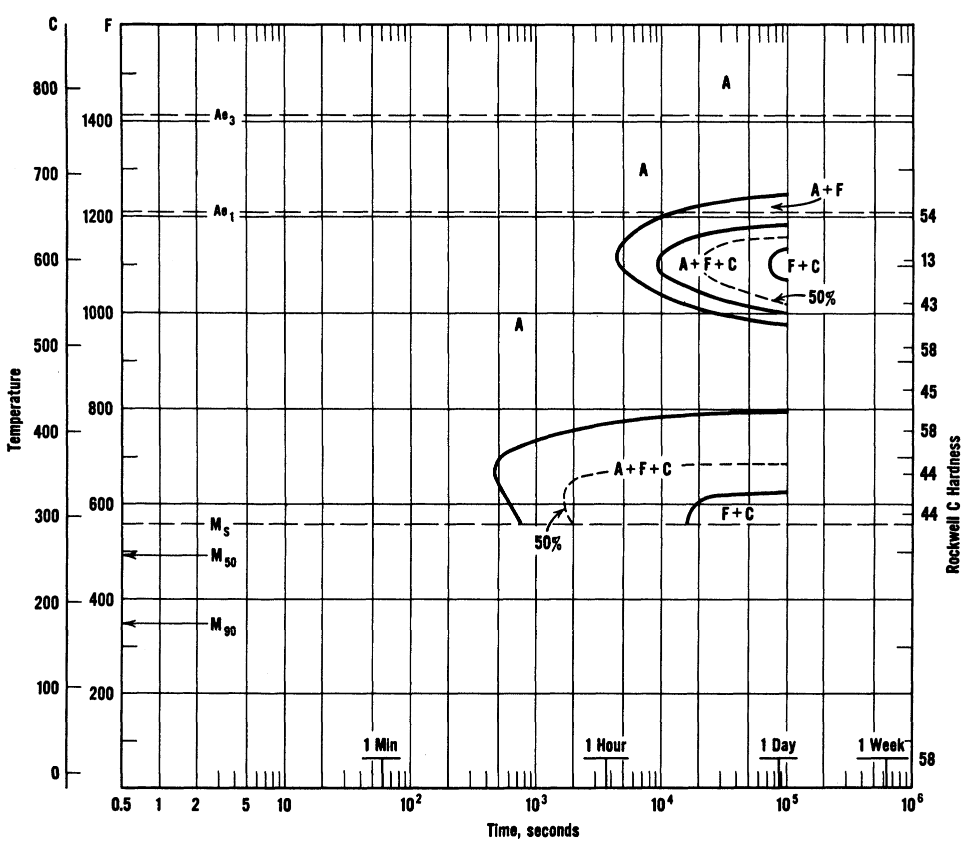
Austenitized at 1535 F
Grain Size: 9

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
International
Nickel Limited[5]

4¼ Ni-1½ Cr-1/10 Mo



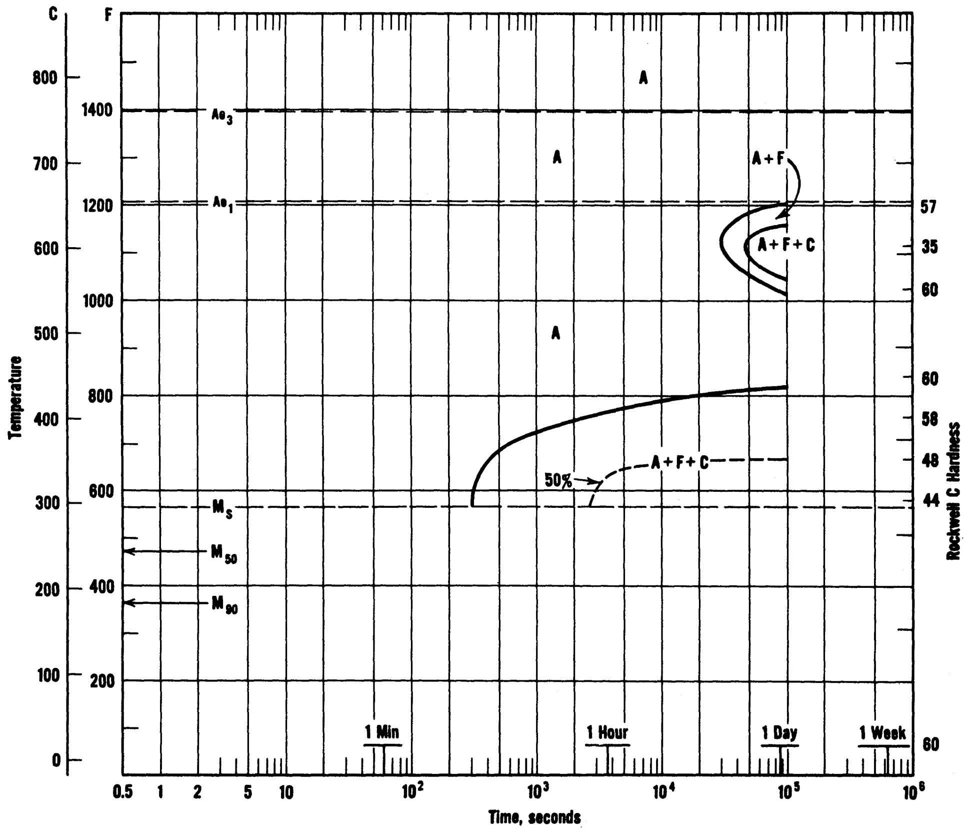
C-0.35 Mn-0.44
Ni-4.23 Cr-1.43
Mo-0.13

Austenitized at 1508 F
Grain Size: 9

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
International
Nickel Limited[5]



4¼ Ni-1½ Cr-⅓ Mo

C-0.33 Mn-0.51
Ni-4.16 Cr-1.44
Mo-0.31

Austenitized at 1508 F
Grain Size: 9

Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

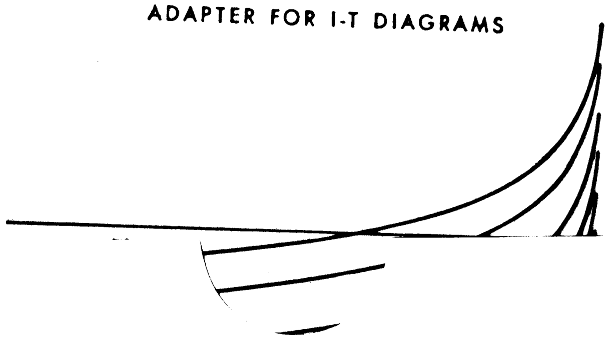
Data from International Nickel Limited[5]

REFERENCES

1. Grange, R. A. and Stewart, H. M., "The Temperature Range of Martensite Formation," Trans. Am. Inst. Mining and Metallurgical Engineers, *167,* 1946, p 467.
2. Steven, W. and Haynes, A. G., "The Temperature of Formation of Martensite and Bainite in Low-alloy Steels —Some Effects of Chemical Composition," Journal Iron and Steel Institute (London), *183,* 1956, p 349.
3. "Atlas of Isothermal Transformation Diagrams," United States Steel Corporation, Pittsburgh, Pa., 3rd ed., 1963, copyrighted.
4. "Supplement to the Atlas of Isothermal Transformation Diagrams," United States Steel Corporation, Pittsburgh, Pa., 1953, copyrighted.
5. "Transformation Characteristics of Direct-Hardening Nickel Alloy Steels," The Mond Nickel Company Limited (former name for International Nickel Limited), London, 3rd ed., 1958.
6. "Metals Handbook," Am. Soc. Metals, Metals Park, Ohio, 8th ed., Vol. 1, 1961, p 638.

NOTES

INTERNATIONAL NICKEL
ADAPTER FOR I-T DIAGRAMS



INCO COOLING CURVE ADAPTER

Purpose of the Adapter

This adapter provides a convenient means of determining from isothermal transformation (I-T) diagrams of steels the hardnesses and structures which will result from continuous cooling at different constant rates. It consists of cooling curves drawn to the same time-temperature scale as used in the I-T diagrams.

To Use the Adapter . . .

Superimpose the adapter on the I-T diagram so that the two vertical straight lines coincide with the vertical boundaries (left and right) of the diagram. Move adapter up or down until the horizontal reference line (near the top of the adapter) is located at the temperature at which controlled cooling is to begin (usually the Ae_1 temperature). The adapter curves will then indicate the type of structure and hardness which will result when the steel is cooled at any given constant rate.

• • •

Further instructions for the use of this device are given on page 4 of this bulletin.

INTERNATIONAL NICKEL INC.

Park 80 West—Plaza Two
Saddle Brook, N.J. 07662

A-389

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