Atlas of continuous cooling transformation diagrams for engineering steels

British Steel Corporation

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M Atkins BSc, B Met, FIM

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The CCT Atlas has been prepared by staff of British Steel Corporation, Swinden House, Sheffield Laboratories, Rotherham

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Contents

This publication presents information gathered by British Steel Corporation on the continuous cooling transformation behaviour of a wide range of engineering steels to assist people involved in the practical aspects of heat treatment and hot processing.

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Steel Type	Diagram No	Composition, weight % (see Note on page 8) C	Si	Mn	P	S	Cr	Mo	Ni	Others	As Quenched Austenite, Grain Size (ASTM)
Carbon											
'05' Carbon	1	0.05	—	0.25	—	—	—	—	—	—	—
'06' Carbon	2	0.06	—	0.30	—	—	—	—	—	—	—
'06' Carbon	3	,,	—	0.50	—	—	—	—	—	—	—
'10' Carbon	4	0.10	—	0.40	—	—	—	—	—	—	7
'10' Carbon	5	,,	—	0.60	—	—	—	—	—	—	9
'13' Carbon	6	0.13	—	,,	—	—	—	—	—	—	6/7
'16' Carbon	7	0.16	—	0.80	—	—	—	—	—	—	5/6
'18' Carbon	8	0.18	0.20	0.45	0.020	0.020	—	—	—	—	6/7
'25' Carbon	9	0.25	,,	0.70	,,	,,	—	—	—	—	,,
'30' Carbon	10	0.30	,,	,,	,,	,,	—	—	—	—	7/8
'38' Carbon	11	0.38	,,	,,	,,	,,	—	—	—	—	8/10
'40' Carbon	12	0.40	,,	,,	,,	,,	—	—	—	—	8
'44' Carbon	13	0.44	0.28	0.81	0.035	0.037	—	—	—	—	6/8
'51' Carbon	14	0.51	0.30	0.75	0.020	0.020	—	—	—	—	8
'52' Carbon	15	0.52	0.20	0.70	,,	,,	—	—	—	—	,,
'56' Carbon	16	0.56	0.30	0.75	,,	,,	—	—	—	—	,,
'60' Carbon	17	0.60	0.20	0.72	0.024	0.033	—	—	—	—	7
'61' Carbon	18	0.61	0.30	0.75	0.020	0.020	—	—	—	—	,,
'68' Carbon	19	0.68	—	0.70	—	—	—	—	—	—	6
'75' Carbon	20	0.75	0.33	,,	0.017	0.016	—	—	—	—	5/6
'86' Carbon	21	0.86	0.20	0.60	0.020	0.020	—	—	—	—	5/7
'96' Carbon	22	0.96	,,	,,	,,	,,	—	—	—	—	,,
'115' Carbon	23	1.15	0.17	0.55	0.015	0.015	—	—	—	—	8
Carbon Manganese											
1¼Mn	24	0.19	0.20	1.20	0.020	0.020	—	—	—	—	8/9
1¼Mn	25	0.28	,,	,,	,,	,,	—	—	—	—	7/8
1¼Mn	26	0.36	,,	,,	,,	,,	—	—	—	—	8/9
1½MnNb	27	0.15	0.25	1.40	,,	,,	—	—	—	Nb 0.08	8
1½Mn	28	0.19	0.20	1.50	,,	,,	—	—	—	—	9
1½Mn	29	0.28	,,	,,	,,	,,	—	—	—	—	8
1½Mn	30	0.36	,,	,,	,,	,,	—	—	—	—	7/8
1¾Mn	31	0.30	0.15	1.80	,,	,,	—	—	—	—	7
1¾Mn	32	0.38	0.25	,,	0.025	,,	—	—	—	—	7
1¾Mn	33	0.46	,,	,,	0.020	0.015	—	—	—	—	6/7
Carbon Manganese Free Cutting											
1Mn	34	0.10	0.20	1.10	0.020	0.250	—	—	—	—	—
1Mn	35	0.42	,,	1.15	,,	0.160	—	—	—	—	—
1½Mn	36	0.44	,,	1.50	,,	0.250	—	—	—	—	—
Manganese Molybdenum											
1½MnMo	37	0.27	0.20	1.55	0.025	0.025	—	0.28	—	—	7/9
1½MnMo	38	0.30	,,	,,	,,	,,	—	,,	—	—	7
1½MnMo	39	0.32	0.18	1.50	0.020	0.020	—	0.27	—	—	7/8
1½MnMo	40	0.35	0.20	1.55	0.025	0.025	—	0.28	—	—	,,
1½MnMo	41	0.37	0.18	1.50	0.020	0.020	—	0.27	—	—	8
1½MnMo	42	0.38	0.25	,,	,,	,,	—	0.45	—	—	,,

Steel Type	Diagram No	Composition, weight % (see Note on page 8) C	Si	Mn	P	S	Cr	Mo	Ni	Others	As Quenched Austenite, Grain Size (ASTM)
Manganese Chromium											
1$\frac{1}{4}$MnCr	43	0.22	0.21	1.10	0.015	0.020	0.60	0.02	0.18	—	Fine
1$\frac{1}{4}$MnCr	44	0.16	0.25	1.15	0.020	,,	0.95	—	—	—	,,
1$\frac{1}{4}$MnCr	45	0.20	,,	1.25	0.025	0.015	1.15	0.02	0.15	—	,,
Manganese Nickel Molybdenum											
1$\frac{1}{2}$MnNiMo	46	0.19	0.20	1.60	0.020	0.020	—	0.25	0.55	—	9
Manganese Nickel Chromium Molybdenum											
1$\frac{1}{2}$MnNiCrMo	47	0.27	0.24	1.35	0.025	0.025	0.45	0.20	0.75	—	7
1$\frac{1}{2}$MnNiCrMo	48	0.33	,,	,,	,,	,,	,,	,,	,,	—	,,
1$\frac{1}{2}$MnNiCrMo	49	0.37	,,	,,	,,	,,	,,	,,	,,	—	,,
1$\frac{1}{2}$MnNiCrMo	50	0.38	0.25	1.40	0.030	0.030	0.50	,,	,,	—	7/8
1$\frac{1}{2}$MnNiCrMo	51	0.43	0.24	1.35	0.025	0.025	0.45	,,	,,	—	6/7
Silicon Manganese											
1$\frac{3}{4}$SiMn	52	0.40	1.75	0.85	0.030	0.030	—	—	—	—	8/10
2SiMn	53	0.54	1.90	,,	,,	,,	—	—	—	—	7/8
2SiMn	54	0.59	,,	,,	,,	,,	—	—	—	—	7
2SiMn	55	0.62	,,	,,	,,	,,	—	—	—	—	7/9
Silicon Chromium											
1$\frac{1}{2}$SiCr	56	0.55	1.50	0.75	0.020	0.020	0.70	—	—	—	Fine
3$\frac{1}{2}$SiCr	57	0.45	3.40	0.60	0.015	0.010	8.50	—	—	—	,,
Silicon Chromium Molybdenum											
2SiCrMo	58	0.60	1.90	0.85	0.025	0.025	0.30	0.25	—	—	Fine
Molybdenum											
$\frac{1}{4}$Mo	59	0.17	0.25	0.60	0.020	0.020	—	0.30	—	—	Fine
$\frac{1}{4}$Mo	60	0.24	0.30	0.90	,,	,,	—	0.23	—	—	,,
$\frac{1}{4}$Mo	61	0.32	,,	0.80	0.025	,,	—	0.26	—	—	,,
$\frac{1}{4}$Mo	62	0.40	,,	,,	,,	,,	—	,,	—	—	,,
$\frac{1}{4}$Mo	63	0.48	0.25	,,	,,	,,	—	,,	—	—	,,
$\frac{1}{2}$Mo	64	0.22	,,	0.60	0.020	,,	—	0.50	—	—	,,
$\frac{1}{2}$Mo	65	0.38	0.30	0.80	0.025	0.021	—	0.53	—	—	,,
Nickel											
$\frac{1}{2}$Ni	66	0.55	0.20	0.65	0.025	0.025	—	—	0.65	—	Fine
1Ni	67	0.36	,,	0.80	0.020	0.020	—	—	0.85	—	7/8
1Ni	68	0.43	,,	,,	,,	,,	—	—	,,	—	,,
1$\frac{1}{2}$Ni	69	0.16	0.25	0.60	,,	0.015	0.20	0.05	1.50	—	8
3Ni	70	0.30	0.32	0.51	0.011	0.007	0.07	—	3.03	—	7/8
3$\frac{1}{2}$Ni	71	0.10	0.26	0.53	0.007	0.005	0.05	—	3.65	—	8
3$\frac{1}{2}$Ni	72	0.33	0.23	0.74	0.031	0.027	0.07	0.11	3.47	—	,,
3$\frac{1}{2}$Ni	73	0.40	0.26	0.62	0.007	0.005	0.23	0.10	3.45	—	8/9
5Ni	74	0.10	0.20	0.40	0.020	0.020	—	-	4.80	—	,,
9Ni	75	0.09	0.25	0.45	0.010	0.012	0.10	0.04	9.00	—	9

Steel Type	Diagram No	Composition, weight % (see Note on page 8) C	Si	Mn	P	S	Cr	Mo	Ni	Others	As Quenched Austenite, Grain Size (ASTM)
Nickel Manganese											
1½NiMn	76	0.16	0.25	1.40	0.020	0.015	0.20	0.05	1.50	—	7/9
Nickel Molybdenum											
1¾NiMo	77	0.17	0.20	0.55	0.020	0.020	0.20	0.25	1.80	—	8
1¾NiMo	78	0.24	,,	,,	,,	,,	,,	,,	,,	—	7/8
1¾NiMo	79	0.40	0.15	0.48	0.016	0.040	0.15	,,	1.75	—	6/7
3½NiMo	80	0.18	0.27	0.47	0.009	0.010	0.18	0.23	3.33	—	8/9
5NiMo	81	0.10	0.20	0.40	0.020	0.020	—	0.20	5.00	—	9/10
Nickel Chromium											
¾NiCr	82	0.15	0.20	0.80	0.020	0.020	0.63	0.05	0.85	—	6
1NiCr	83	0.16	,,	,,	,,	,,	0.85	,,	1.15	—	6/7
1¼NiCr	84	0.35	0.23	0.75	,,	,,	0.65	—	1.30	—	7/9
1¼NiCr	85	0.40	,,	,,	,,	,,	,,	—	,,	—	7/8
1½NiCr	86	0.14	0.25	0.50	,,	,,	1.55	—	1.55	—	8
1½NiCr	87	0.15	,,	0.75	,,	,,	0.95	—	1.45	—	,,
2NiCr	88	0.16	0.31	0.50	0.013	0.014	1.95	0.03	2.02	—	,,
3NiCr	89	0.32	0.20	0.57	0.020	0.020	1.15	—	3.00	—	8/9
3¼NiCr	90	0.12	,,	0.50	,,	,,	0.90	—	3.25	—	,,
4NiCr	91	0.15	0.15	0.40	,,	,,	1.15	—	4.10	—	8
4NiCr	92	0.30	0.20	0.50	,,	,,	1.25	—	,,	—	8
Nickel Chromium Molybdenum											
½NiCrMo	93	0.15	0.20	0.80	0.020	0.020	0.50	0.20	0.55	—	8/9
½NiCrMo	94	0.24	,,	,,	,,	,,	,,	,,	,,	—	,,
½NiCrMo	95	0.30	0.25	,,	,,	,,	,,	,,	,,	—	6/7
½NiCrMo	96	0.41	,,	0.85	,,	,,	,,	,,	,,	—	8/9
½NiCrMo	97	0.48	0.34	0.75	,,	0.010	0.58	,,	0.60	—	,,
½NiCrMo	98	0.60	0.25	0.85	0.025	0.025	0.50	,,	0.55	—	,,
¾NiCrMo	99	0.40	,,	0.65	0.020	,,	0.75	0.25	0.85	—	9/10
1NiCrMo	100	0.36	,,	,,	,,	0.020	1.05	0.22	1.05	—	7
1½NiCrMo	101	0.16	0.20	0.80	,,	,,	,,	0.15	1.40	—	8/9
1½NiCrMo	102	,,	0.25	0.50	,,	,,	1.65	0.30	1.55	—	8
1½NiCrMo	103	0.36	,,	0.70	,,	,,	1.50	0.25	1.50	—	7/8
1½NiCrMo	104	0.40	,,	0.60	,,	,,	1.20	0.15	,,	—	,,
1½NiCrMo	105	,,	,,	,,	,,	,,	,,	0.30	,,	—	,,
1¾NiCrMo	106	0.16	0.20	0.80	,,	,,	1.05	0.15	1.80	—	8
1¾NiCrMo	107	0.41	0.25	0.70	,,	,,	0.80	0.25	,,	—	7
2NiCrMo	108	0.17	0.20	0.60	,,	,,	1.55	0.20	2.00	—	8/9
2NiCrMo	109	0.30	0.25	0.48	,,	,,	2.00	0.40	,,	—	,,
2½NiCrMo	110	0.31	,,	0.60	,,	,,	0.65	0.55	2.55	—	7/8
2½NiCrMo	111	0.40	,,	,,	,,	,,	,,	,,	,,	—	,,
3NiCrMo	112	0.31	,,	0.55	,,	,,	1.05	0.28	3.00	—	7/9
3¼NiCrMo	113	0.12	0.28	0.53	,,	0.010	0.58	0.20	3.20	—	12/13
3½NiCrMo	114	0.13	0.20	0.50	,,	0.020	0.85	0.18	3.40	—	8/9
4NiCrMo	115	0.15	0.25	0.40	,,	0.018	1.15	0.20	4.10	—	8
4NiCrMo	116	0.30	,,	0.60	,,	0.020	1.25	0.30	,,	—	7
4NiCrMo	117	0.34	0.20	0.50	,,	,,	1.80	0.35	4.00	—	9

Steel Type	Diagram No	Composition, weight % (see Note on page 8) C	Si	Mn	P	S	Cr	Mo	Ni	Others	As Quenched Austenite, Grain Size (ASTM)
Chromium											
½Cr	118	0.15	0.20	0.40	0.020	0.020	0.40	—	—	—	7/8
½Cr	119	0.38	0.25	0.70	,,	,,	0.50	—	—	—	8
½Cr	120	0.46	,,	,,	,,	,,	,,	—	—	—	,,
½Cr	121	0.59	,,	0.60	0.025	0.025	0.65	—	—	—	,,
¾Cr	122	0.20	0.20	0.80	0.020	0.020	0.80	—	—	—	7/8
¾Cr	123	0.60	0.25	0.85	0.025	0.025	0.75	—	—	—	7/9
1Cr	124	0.20	0.30	0.75	0.020	0.020	0.95	—	—	—	,,
1Cr	125	0.30	0.20	0.70	,,	,,	1.05	—	—	—	9/10
1Cr	126	0.39	,,	,,	,,	,,	,,	—	—	—	7/9
1Cr	127	0.50	0.35	0.75	0.025	,,	1.20	—	—	—	6/8
13Cr	128	0.07	0.40	0.50	0.020	0.010	13.0	—	0.20	—	9/10
13Cr	129	0.12	,,	,,	,,	,,	12.5	—	,,	—	8
13Cr	130	0.17	0.38	0.40	,,	,,	,,	—	,,	—	,,
13Cr	131	0.24	0.37	0.27	0.021	,,	13.3	0.06	0.32	—	7
13Cr	132	0.32	0.30	0.30	0.020	,,	13.0	,,	0.20	—	10
High Chromium Nickel											
18CrNi	133	0.14	0.67	0.68	0.024	0.012	17.98	0.06	2.95	—	5/6
High Chromium Molybdenum Vanadium											
12CrMoV	134	0.20	0.25	0.70	0.030	0.020	12.00	1.00	0.65	V 0.30	7/9
Chromium Molybdenum											
½CrMo	135	0.14	0.25	0.55	0.020	0.020	0.60	0.55	—	—	7
½CrMo	136	0.20	,,	0.75	,,	,,	0.40	0.45	—	—	,,
¾CrMo	137	0.12	0.30	0.45	0.015	0.015	0.85	0.60	0.16	—	,,
¾CrMo	138	0.27	0.13	0.60	0.030	0.022	0.74	0.55	0.19	—	6/7
¾CrMo	139	0.60	0.25	0.85	0.020	0.020	0.80	0.30	—	—	10
1CrMo	140	0.18	,,	0.75	,,	,,	1.00	0.20	—	—	8/9
1CrMo	141	0.26	,,	0.70	,,	,,	1.05	0.22	—	—	7/9
1CrMo	142	0.30	,,	0.50	,,	,,	1.00	0.20	—	—	8
1CrMo	143	0.34	,,	0.65	,,	,,	1.05	0.25	—	—	9
1CrMo	144	0.36	,,	0.80	,,	,,	1.00	0.20	—	—	8/9
1CrMo	145	0.40	0.20	0.85	,,	,,	1.05	0.30	—	—	,,
1CrMo	146	0.46	0.25	,,	,,	,,	1.00	0.20	—	—	,,
1CrMo	147	0.50	,,	,,	,,	,,	,,	0.22	—	—	7/9
1¼CrMo	148	0.15	0.30	0.60	0.030	0.030	1.25	0.50	—	—	6/7
1¼CrMo	149	0.35	0.27	0.55	0.031	0.022	1.23	0.51	0.14	—	7/8
1¼CrMo	150	0.37	0.25	0.85	0.020	0.020	1.15	0.20	—	—	,,
1¼CrMo	151	0.42	,,	,,	,,	,,	,,	,,	—	—	6
2¼CrMo	152	0.14	0.23	0.46	0.010	0.010	2.28	1.05	0.21	—	7
3CrMo	153	0.20	0.25	0.50	0.020	0.020	3.10	0.52	—	—	7/8
3CrMo	154	0.28	,,	,,	,,	,,	,,	,,	—	—	7/9
3CrMo	155	0.32	,,	0.55	,,	,,	3.05	0.40	0.30	—	,,
3¼CrMo	156	0.17	0.14	0.60	,,	,,	3.25	0.55	—	—	7/8
3¼CrMo	157	0.26	,,	,,	,,	,,	,,	,,	—	—	,,
5CrMo	158	0.14	0.26	0.45	0.016	0.025	4.66	0.56	0.13	—	8/9
5CrMo	159	0.28	0.25	0.50	0.020	0.020	5.00	0.55	—	—	6
9CrMo	160	0.12	0.30	0.70	0.025	,,	9.00	1.00	—	—	7/8

Steel Type	Diagram No	Composition, weight % (See Note at foot of page) C	Si	Mn	P	S	Cr	Mo	Ni	Others	As Quenched Austenite, Grain Size (ASTM)
Chromium Molybdenum Vanadium											
½CrMoV	161	0.12	0.25	0.55	0.020	0.020	0.40	0.60	0.15	V 0.25	5/6
1CrMoV	162	0.22	0.30	0.60	,,	,,	1.15	,,	0.13	V 0.22	6/7
1¼CrMoV	163	0.37	0.29	0.62	0.032	0.026	1.19	0.59	,,	,,	7/9
2½CrMoV	164	0.30	0.25	0.60	0.010	0.015	2.50	0.20	0.30	V 0.18	9/10
3¼CrMoV	165	0.39	0.15	,,	0.020	0.020	3.25	0.95	—	V 0.20	,,
Chromium Vanadium											
1CrV	166	0.50	0.25	0.75	0.025	0.025	0.95	0.05	0.15	V 0.20	7
Chromium Aluminium Molybdenum											
1CrAlMo	167	0.33	0.30	0.65	0.020	0.020	1.15	0.20	—	Al 1.00	Fine
1½CrAlMo	168	0.31	,,	0.55	,,	,,	1.60	,,	—	Al 1.10	,,
1½CrAlMo	169	0.39	,,	,,	,,	,,	,,	,,	—	,,	,,
1½CrAlMo	170	0.42	,,	0.65	,,	,,	1.65	0.33	—	Al 1.00	,,
Carbon Chromium											
1CCr	171	1.01	0.22	0.40	0.039	0.021	1.36	—	0.21	—	7/8
1CCr	172	1.08	0.25	0.53	0.022	0.015	1.46	0.06	0.33	—	7/9

NOTE: Where possible, exact compositions are quoted. Minor or residual elements are shown when available. Nominal analyses refer to diagrams generally based upon two or more within an analysis range. Such diagrams are taken as representing mid-range compositions.
Refer to the above index for grain sizes.

Part 1

The use of continuous cooling transformation diagrams

Introduction

The steels included in this publication are predominantly those used by the engineering industry. In the United Kingdom, it has been common practice to specify and supply steels on the basis of composition and mechanical properties. It is also usual to state the maximum diameter of round bar in which these properties can just be obtained at the centre, referred to as the 'limiting ruling section'. In the case of rectangular sections, the equivalent round bar diameter has been tabulated. The application to more complicated shapes, or machined components with varied sections, depends on individual judgment as to the equivalent bar diameter in different locations.

The established guide to transformation behaviour is the isothermal transformation diagram. A steel is first heated to a high temperature to produce austenite and cooled rapidly to a lower temperature where it undergoes transformation, the amount depending upon the time held at temperature. The different kinds of structure produced by transformation, namely ferrite, pearlite, bainite or martensite, are then indicated on the diagram, together with the holding times required for transformation to start and finish. The result is a family of curves representing the various stages of transformation as a function of temperature and time.

Few heat treatment processes involve the step-wise cooling used to construct these diagrams. Instead, most of the structures are produced in continuous cooling operations. If the rates of cooling are slow, the structures correspond more closely to those indicated in the upper regions of the isothermal diagram. Faster rates of cooling will modify considerably the starting temperature and progress of transformation. It follows that some kind of continuous cooling transformation diagram is needed. Whilst it is possible to superimpose actual cooling curves on to a time/temperature transformation diagram, this has not been done in the present volume. Instead, a modified transformation diagram has been adopted, with individual bar diameters represented on the abscissa instead of transformation times. These diagrams are thus directly applicable to materials heat treated under works conditions and indicate the structures which can be produced at the centres of bars of the stated diameters.

Continuous cooling transformation diagrams

The Continuous Cooling Transformation (CCT) diagrams presented here illustrate typical patterns of transformation response of the various steels when cooled in air, oil or water.

Cooling curves are not shown because the diagrams are presented in terms of bar diameters as stated above. Different cooling curves would apply at the centre and surface of a bar, and correspondingly at intermediate positions. The CCT diagram refers only to the centre of a bar, but the structures at other positions can be inferred. For example, the structure produced upon cooling at some mid-radial position in a large diameter bar will correspond to that produced at the centre of a bar of smaller, so-called equivalent diameter, similar structures being produced at similar cooling rates.

A major difficulty in constructing CCT diagrams is the interpretation of transformation behaviour. Martensite and bainite are each affected by changes in composition of the parent austenite which may have resulted from any prior ferrite formation or carbide precipitation at higher temperatures. Undercooling and recalescence (due to sudden liberation of latent heat) can, in some cases, result in a reaction being completed at a temperature higher than that at which it began. The effects of such complicated behaviour are however included in the computation of these diagrams. The diagrams show the approximate proportions of the major phases and also the hardness of the microstructure obtained by continuous cooling. The effect of tempering on these hardness levels is shown in many instances.

The hardenability of the steel can be assessed at a glance from the CCT diagram. Low hardenability steels show early transformation, mainly in the upper left hand side of the diagram, to ferrite and pearlite or bainite. High hardenability steels exhibit curves in the lower right hand side of the diagram, austenite changing predominantly to martensite over a wide range of bar diameters and quenching rates.

Air cooling has been used as the main criterion for developing the diagrams, with supplementary bar diameter scales provided for oil and water quenching. Although air and water are relatively standard fluids, oils can vary widely in their physical characteristics and hence their quenching ability. 'Oil' has been taken as a standard medium-fast quenching oil. Brine quenching has not been considered for the steels in this series.

Using the CCT diagram

The structures which can be expected in as-cooled bars, whether air-cooled or oil or water quenched, are indicated in each CCT diagram. For example, in the diagram for a '38' C steel (060A37), Fig 1/1, transformation at temperatures above 660°C will produce ferrite and pearlite, whereas between this temperature and the M_s temperature, bainite will start to be formed. Below the M_s temperature, the structure will be fully martensitic.

It is also apparent that with increasing bar diameter, the resulting structures change from martensite, through bainite to ferrite and pearlite. More specifically, in Fig 1/1, for the

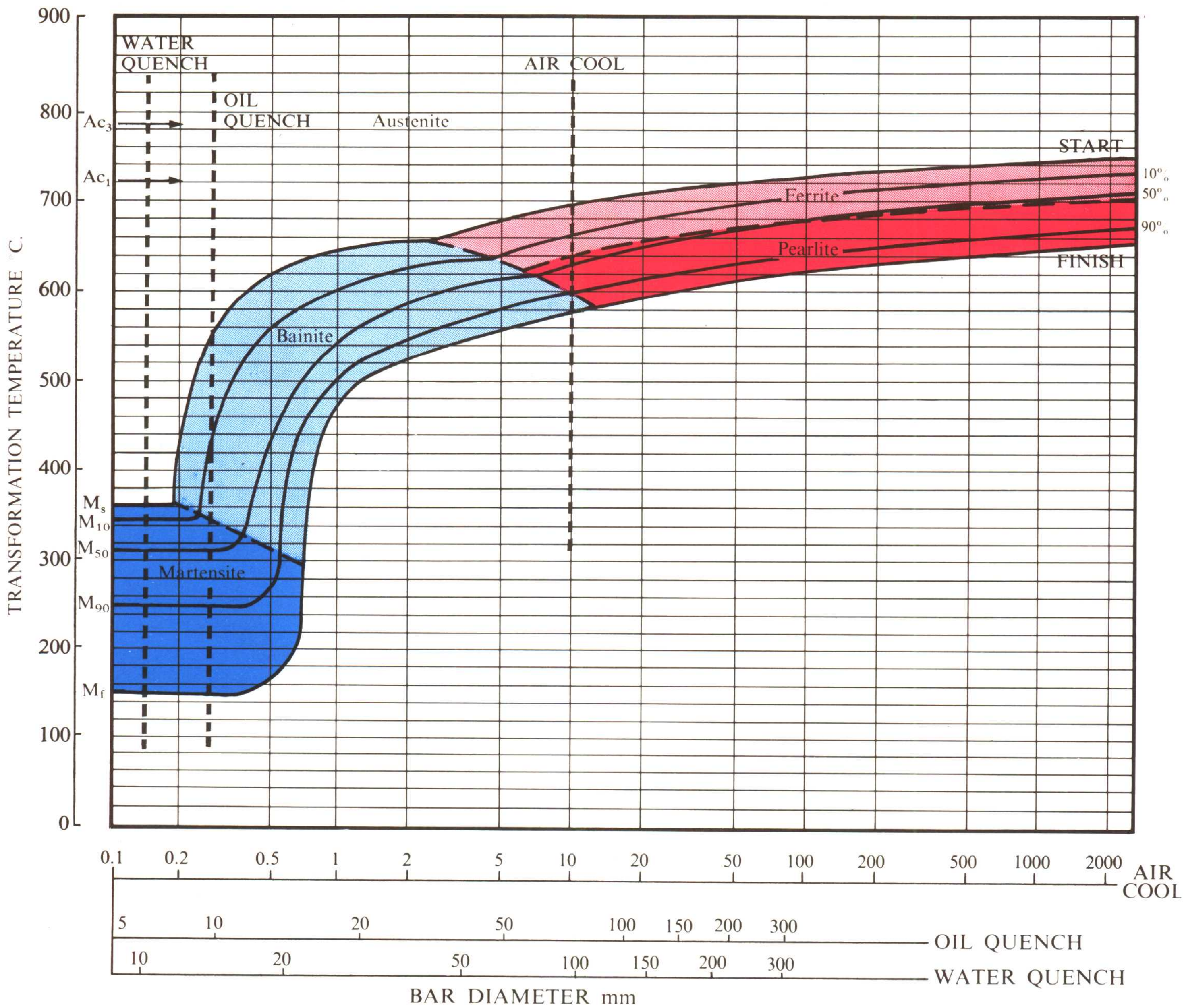


Fig 1/1 CCT diagram for '38' C steel (060A37) chosen to illustrate transformation behaviour under different cooling rates (Based on CCT Diagram No. 11.)

case of air cooling, martensite is formed in bars smaller than 0·18 mm, bainite at diameters up to about 2 mm, whilst increasing amounts of ferrite and pearlite are formed, with progressively less bainite, at diameters above 2 mm. Similarly, microstructures arising from oil and water quenching can be deduced.

Behaviour on cooling

Referring again to Fig 1/1, the cooling of a 10 mm bar in air will be considered. The 10 mm position is located on the scale for air cooled bars and the vertical line through this point is followed down from the austenitising temperature. Transformation starts at 700°C with the formation of ferrite, continuing to nearly 50% transformation at 640°C when pearlite begins to form. At 580°C, a trace of bainite is indicated before transformation is complete. If oil quenching of a 10 mm bar is now considered, the 10 mm position should be located on the oil quenched bar diameter scale. Again, following the vertical line down, it is seen that in this case bainite is the first phase to form from austenite at 580°C. At 330°C, after about 40% transformation, the remaining austenite transforms to martensite until the reaction is completed at 150°C.

Similarly, when water quenched, a 10 mm diameter bar will transform to martensite starting at 360°C and finishing at 150°C.

Examination of the left hand side of the diagram shows that martensite will form on air cooling with bars up to 0·18 mm diameter, on oil quenching up to 8 mm diameter and on water quenching up to 13 mm diameter.

Equivalent diameters

The 'equivalent diameter' refers to that size of round bar in which the axial temperature falls through a specified range in the same time as the temperature at the slowest cooling position in an irregular shaped body. A method of calculating equivalent diameters is summarised in British Standard 5046:1974, an outline of which is given in Part 3.

The equivalent diameter therefore enables the CCT diagram to be used to predict the heat treatment behaviour of complex shapes.

Ruling sections

CCT data for direct hardening steels will normally be used to indicate the structure of the steel prior to tempering. The heat treatment details for these materials are specified in BS 970 and related standards, where the required tensile and impact toughness properties are given together with the limiting ruling sections.

In Fig. 1/2, the CCT diagram for 1½ MnMo steel (605M36) is shown with the limiting ruling sections from BS 970 superimposed. In addition, the specified minimum levels of tensile strength are indicated. It will be seen that bars of 19 mm diameter would be fully hardened by oil quenching. Therefore, after tempering, a satisfactory tensile strength could be assured. Slightly larger bars, for example 30 mm diameter, containing a proportion of bainite, could be tempered to a lower strength level. However, with the larger limiting ruling sections, where the proportion of bainite has increased, tempering to even lower strength levels would be necessary to secure satisfactory impact resistance. Thus, Fig. 1/2 indicates the as-quenched structures to be expected at the various limiting ruling sections. An assessment of the mechanical properties likely to be achieved in practice can be made by reference to the appropriate specification.

Specifications

To use these diagrams for any particular steel specifications, the diagram for a steel of the same, or very similar, chemical composition should be chosen. The diagrams have been arranged in alloy groups and in ascending carbon and alloy content to aid interpretation of the effects of composition variations on the shape and position of the main transformation ranges.

The chemical compositions of 172 steels are listed in the Index (page 4). The relationship between these and many national and international specifications is given in Part 4.

Sensitivity of the diagrams to changes in composition

The CCT diagrams usually refer to an average composition within a given specification. It is found, however, that variations in composition within a specification range can sometimes lead to considerable differences in structure and properties. Moreover, there are critical ranges of bar diameter where slightly slower or faster cooling rates produce a rapid change in the predominating microstructure. In Fig 1/1, for example, a very small decrease in bar diameter could change the structure from bainite, commencing to form at say 580°C, to martensite starting at 360°C. In the critical regions, where the slope of the bainite boundary is steep, a steel bar can be undergoing transformation to a succession of structures over a wide range of temperature. It can be seen from Fig 1/1 that, for this particular steel, the most pronounced changes occur when the bar diameters lie within the approximate ranges:

0·2 to 0·7 mm for air cooling
9 to 15 mm for oil quenching
14 to 24 mm for water quenching

An examination of the effects of composition variables for steels in this and neighbouring specifications shows that all these diameters are increased by about 60% if the carbon content is increased by 0·05% within the specification. A change in manganese content of the same

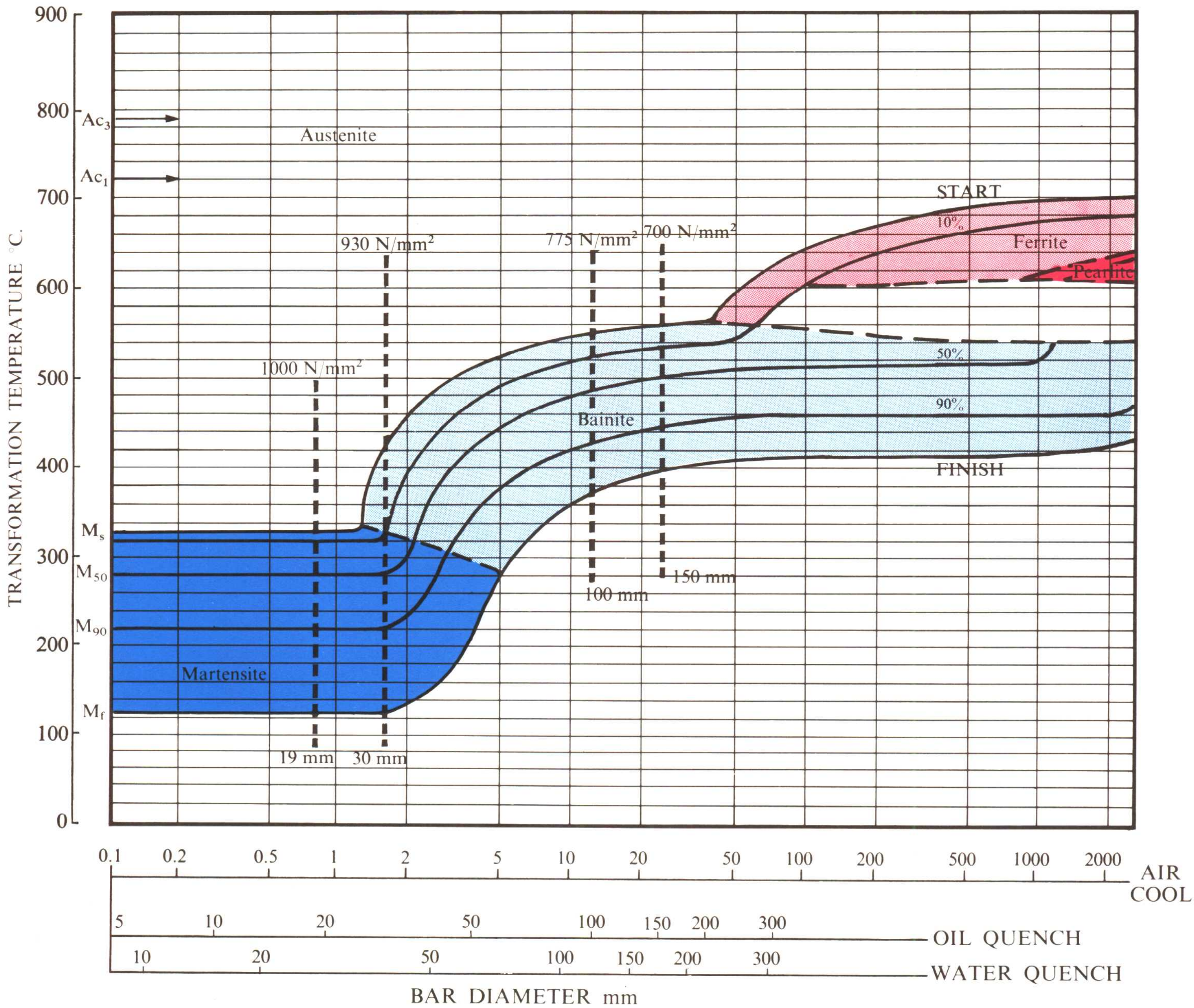


Fig 1/2 CCT diagram for $1\frac{1}{2}$MnMo alloy steel (605M36) chosen to illustrate the microstructures to be expected after oil quenching at the various limiting ruling sections. Also indicated are the tensile strength levels after hardening and tempering taken from BS 970 Part 2 1970 (Based on CCT Diagram No. 40).

amount would produce about one quarter of this effect.

Hardenability

The hardenability of a steel is usually determined by the Jominy end-quench test, in which a suitably heated round bar is quenched at one end only, and hardness measurements made along its length. The structure and hardness variations at different points along the bar are a result of the different rates of cooling at these points.

A correlation between Jominy hardenability and bar diameter has been produced by the American Society of Automotive Engineers (SAE). The part relating the centre position of an oil quenched bar to the position on a Jominy specimen is shown in Fig 1/3.

This allows the Jominy hardenability band for a specification, or the curve for a particular sample, to be superimposed on the hardness curve accompanying each CCT diagram. The bands have been included so that the interrelation of the Jominy curve and the hardness of as-cooled sections can be indicated.

Thus, by replotting the Jominy end quench test results in terms of hardness versus equivalent bar diameter, it is possible to assess its position in relation to the CCT diagram. It must be appreciated that this comparison is only approximate and is only valid at the left hand side of the diagram. In cases where the steel composition falls on the edge, or outside the range, of one diagram, reference should be made to a neighbouring specification.

Additional applications

The diagrams can be used to investigate continuous heat treatment cycles for thin sections, such as wire or strip, where particular microstructures are required to facilitate working or heat treatment. They are also suitable for the planning of safe heat treatment cycles for sections which need retarded cooling after hot working, to avoid low temperature transformation products.

Prediction of machinability from expected microstructures and hardness levels is possible. For example, from Fig 1/1, an air cooled bar of '38' C steel of over 10 mm diameter or equivalent section, will transform to over 90% ferrite and pearlite. This should give adequate machinability for all but the most demanding machining operations. On the other hand, Fig. 1/4 shows that nearly all sizes of 1½% NiCrMo steel (817M40) will require a more complex softening treatment for ease of machining since all diameters up to 1000 mm give structures harder than 250 HV.

The diagrams can also be used to study the effect of mass and to help in the calculation of critical quenching rates for complicated shapes and varied sections, where an estimate of a predominant equivalent diameter is possible. The prime objective in any hardening process is to choose the minimum rate of quenching which will produce through hardening and thereby eliminate excessive distortion or cracking. Fig 1/4 shows that 817M40 steel will easily produce martensite by oil quenching in all sections up to 100 mm and that no benefit can be gained by faster cooling.

It should be remembered that the microstructure indicated by the diagram is that expected at the axis of the section. In practice, the surface of a quenched bar will cool more rapidly than its centre and may contain smaller proportions of ferrite and pearlite. This aspect is examined in greater detail in Part 3, Section 3.2.

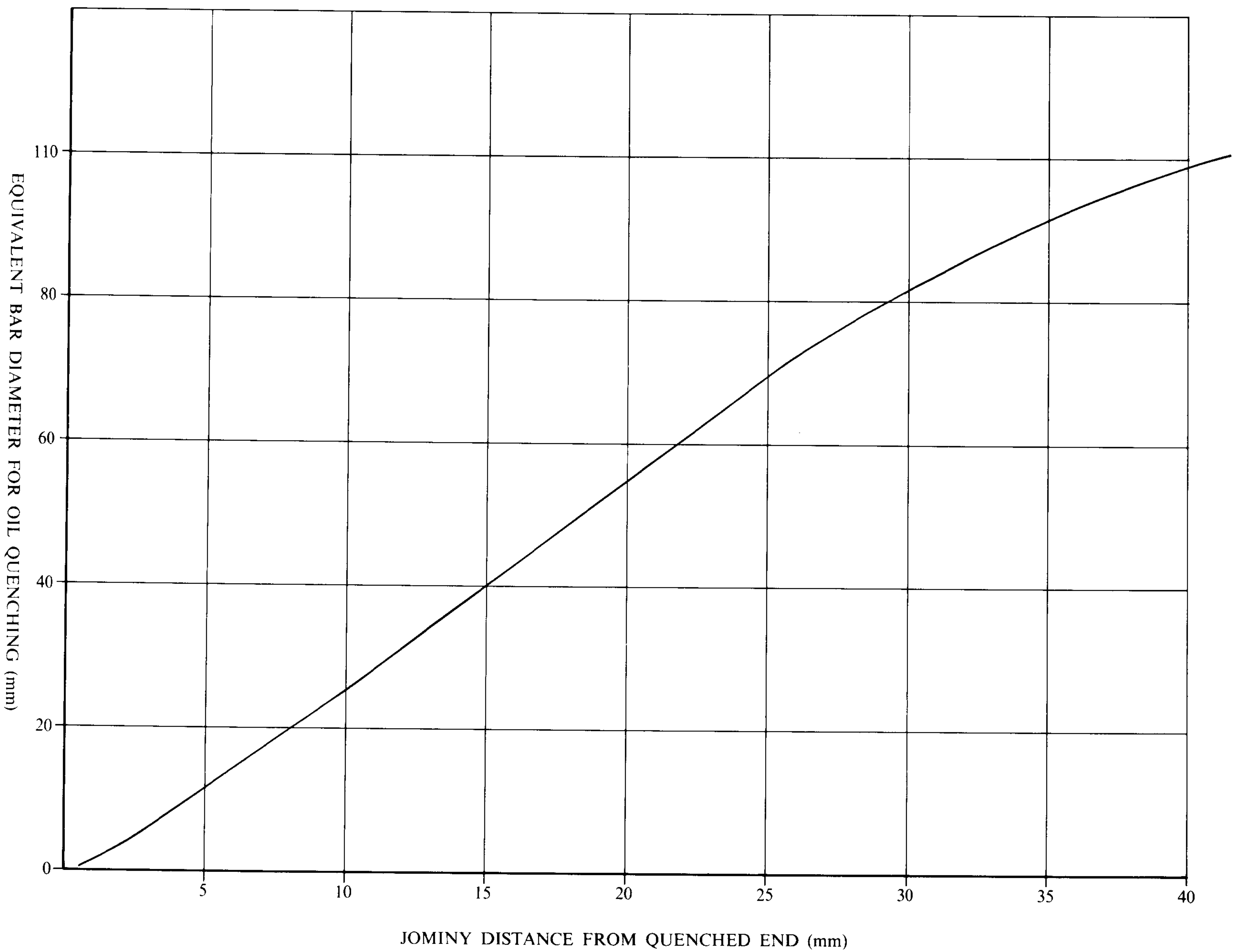
Limitations of the diagram

Continuous cooling transformation is affected by the treatment the steel has received before austenitising. The austenitising temperature and soaking time each affect the grain size of the austenite, hence modifying the subsequent transformation characteristics on cooling. The austenitising temperature also affects the composition of the austenite if the steel contains strong carbide-forming elements and consequently undissolved carbides may be present. Care should be taken, therefore, when adapting the diagrams for austenitising conditions different from those indicated. For this reason, the diagrams are not readily adapted to surface hardening by induction or flame heating, since rapid heating and short thermal cycle times have a drastic effect on the condition of the austenite.

The diagrams are not suitable for use in welding situations where heat affected zones can reach temperatures of the order of 1300–1350°C for very short times. After such treatment, the shape of the diagram would be expected to be modified drastically at the faster cooling rates which are relevant to this situation. The actual modification of the transformations, however, depends on heat input, preheat/postheat, etc. Hence, the use of the CCT diagrams in welding situations is limited to the approximate positioning of the M_s temperature of the weld heat affected zone for preheat calculations.

Another major factor, which cannot be illustrated in the diagram, is the effect of agitation in the quenching medium, whether it be air, oil or water. Agitation is obviously dependent on such practical features as bath size and component size and shape. These effects can only be examined experimentally. If, however, actual cooling curves can be obtained for a particular combination of operating conditions, they can then be converted into the corresponding bar diameters, using the tables described in Part 3, Section 3.2.

Fig 1/3 The correlation between Jominy hardenability and bar diameter



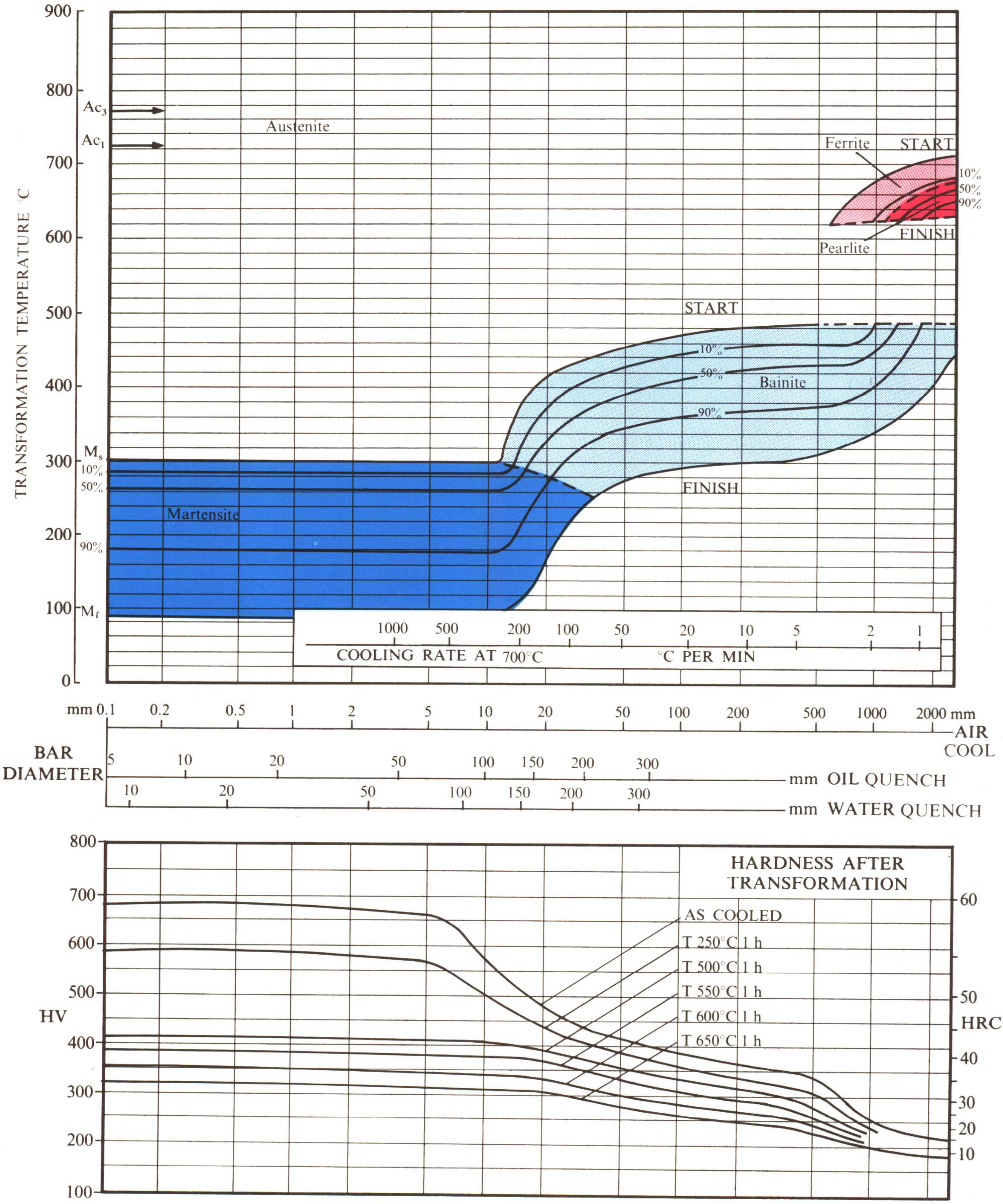


Fig 1/4 CCT diagram for $1\frac{1}{2}$NiCrMo alloy steel (817M40) chosen to illustrate the minimum rate of quenching to produce through hardening. Also included are the hardness levels after transformation which can be used to predict machining performance. (Based on CCT Diagram No. 105).