

Metallographer's Guide

Practices and Procedures for Irons and Steels

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Micrographs on cover:

Top, left: Annealed AISI/SAE 1005 steel showing equiaxed ferrite grains photographed using dark field illumination. Marshall's etch. 200×

Top, right: Annealing twins in AISI 347H austenitic stainless steel photographed using differential interference contrast (Nomarski). Electrolytically etched in 60% nitric acid in water. 5 volts, stainless steel cathode. 500×

Bottom, left: Partially spheroidized AISI/SAE 1060 steel photographed using bright field illumination. 4% picral etch. 500×

Bottom, right: Lath martensite in austenitized and quenched AISI/SAE 1040 steel photographed using bright field illumination. Etched in 2% nital. 500×

To Joan and Sandy for their enduring patience and encouragement.

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Preface

This guide was prepared not only for the beginning metallographer but also for the experienced metallographer who may be looking for alternatives and new approaches to metallographic practice. For the beginning metallographer, little or no knowledge of steels and cast irons is necessary since the first three chapters provide the basic information needed to understand the various types of steels and cast irons available in the commercial world. These chapters also provide examples of the multitude of microstructures that the metallographer will encounter, how these microstructures are created, and how they can be altered by heat treatment and other means. Some metallographers may be working in a small laboratory where no metallurgical support is available. The authors feel very strongly that to be effective, the metallographer must understand as much as possible about the metallurgy of the material he or she is preparing. Without this knowledge, the metallographer can offer little interpretation of the microstructure he or she develops even after applying the best metallographic practices. Also, without a proper background in recognizing metallographic constituents, he or she may produce an artifact through improper specimen preparation that will lead to a totally inappropriate result. Thus, it is important that the metallographer read the first three chapters to obtain a basic understanding of steel microstructures before proceeding to the metallographic techniques chapters.

As part of this guide, the authors felt that a metallographer should know some of the history of metallography. In this new century, we have come a long way from the early days of Sorby and Widmanstätten who pioneered what we now know as metallography of steels and cast irons a century and a half ago. Chapter 4 gives a brief history of these early metallographers and defines the identity of a metallographer by comparing the vast amount of information gained from a metallographic analysis to that produced from a chemical analysis. The chapter also describes the types of things that a metallographer will encounter in a typical workday in a large metallographic laboratory in the research department of a large steel company and a small metallography laboratory associated with an iron foundry. Actual metallographic tasks in both situations are described in detail. Chapter 6 discusses some of the tools that are available beyond the typical metallographic laboratory. In today's world, there has been an explosion in technology to aid the metallographer. Not only can one reveal the microstructural constituents in a steel or cast iron, but also one can determine the chemical analysis of each constituent even on a nanometer scale. To be effective, the metallographer must be familiar with the capabilities of these modern-day instruments.

Since this guide concentrates on light (optical) metallography, Chapter 5 has been added to describe in detail how a metallurgical microscope works. This is the instrument located in all metallographic laboratories. The metallographer must have an intimate knowledge of the microscope to use it properly. An understanding of the different types of oculars (eyepieces) and objectives is important so that the microstructure can be revealed in its truest form. Knowledge of the various types of illumination (bright field, dark field, interference contrast, etc.) is important to enhance the image of the microstructural features. The metallographer also must know how to maintain and clean the microscope to keep it in the best condition possible.

Specimen preparation procedures were saved for Chapters 7 and 8. The procedures presented in this guide have proven to work effectively to prepare the specimen. However, the authors recognize that other procedures also can work as effectively. This book guides the metallographer through the specimen preparation procedures in a step-by-step manner. Various options are offered, and preferred methods are described in detail. The authors provide a basic understanding of how and why the methods work. As the metallographer becomes more experienced, he or she may develop his or her own adaptations of the procedures presented here. This guide will get the metallographer started with a sound procedure that works.

A unique feature of this guide is a separate and complete index of the various steels and cast irons used as examples throughout the book. The index makes the hundreds of micrographs essentially an Atlas of Microstructures, and it precedes Chapter 1.

Although this book is for the novice metallographer, an experienced metallographer may find it useful in that dozens of special metallographic tips are scattered through the chapters on specimen preparation and the art of revealing microstructure. This guide could be used as a university or technical school text to accompany the teaching of a laboratory course in metallography.

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Atlas of Microstructures

Steels/irons	Fig. No.	Page No.	Steels/irons	Fig. No.	Page No.
Carbon steels			Carbon steels (continued)		
AISI/SAE 1005	Cover	ii	AISI/SAE 1080	6.9	153
AISI/SAE 1008	7.1	170		6.11	153
AISI/SAE 1010	1.2(a)	4		7.3	171
	3.10	55		7.8	174
	4.20	100		7.41	206
	4.21	100		8.2	218
	7.39	205		8.21	228
AISI/SAE 1015	3.41	73		8.38	236
AISI/SAE 1018	8.31	233	AISI/SAE 1095	1.2(c)	4
	8.32	233		2.26	36
	8.52	243		3.48	75
	8.53	243	AISI/SAE 1117	3.31	67
AISI/SAE 1020	2.42	42		3.32	68, 69
	3.5	53	AISI/SAE 1144	7.6	173
	3.42	74	AISI/SAE 11L44	8.5	219
	3.51	77	AISI/SAE 1213	1.3	5
	3.52	78		8.34	234
	5.35	128, 129	AISI/SAE 1524	2.43	42
	6.2	150	Steel, screw	7.22	188
	6.3	150	Steel, shot (S-230)	4.14	97
	7.4	172			
	7.7	174	Low-alloy steels		
	7.45	210	AISI/SAE 1335	6.27	161
	8.9	222	AISI/SAE 4327	7.15	182
	8.33	233	AISI/SAE 4340	3.21	63
AISI/SAE 1025	2.14	33		4.15	97
	7.14	180, 181		5.41	132
AISI/SAE 1035	3.39	73	AISI 52100	4.11	96
	3.40	73	AISI/SAE 8630	3.6	53
AISI 10B36	8.37	235		3.7	53
AISI/SAE 1040	Cover	ii		3.8	54
	1.2(b)	4		3.17	60
	2.6	28		3.19	61
	2.23	35		3.20	62
	3.1	50	AISI/SAE 8720	2.33	39
	3.3	51		2.34	39
	3.4	52, 53	AISI/SAE 8860	8.35	235
	3.15	58	AISI/SAE 9425	8.7	221
	5.64	146	AISI/SAE 52100	4.11	96
	5.65	147	Low-alloy	8.17	226
AISI/SAE 1045	3.29	66	0.7%C-3%Cr	3.33	69
	3.30	67		3.34	69
	6.18	156		3.35	70
AISI/SAE 1060	Cover	ii		3.36	70
	2.15	33		3.37	70
	2.16	33		3.38	73
	2.22	35	E660	6.37	167
	2.41	41	3%Cr	3.45	75
AISI/SAE 1070	4.8	94	0.2%C-1%Mn-5%Ni	2.30	37
	4.9	95	Ni-Cr-Mo	2.31	38
AISI/SAE 1080	2.1	23, 24		2.32	38
	2.19	34		2.39	41
	2.20	34		3.57	82
	2.21	35	0.23%C-3.4%Ni-1.7%Cr-0.5%Mo	8.26	231
	3.28	66	0.5%Mo-B	8.28	232
	3.47	75	2.5%Ni-0.4 Nb	7.46	211
	3.55	80		7.47	212
	3.56	81	0.75%C-3.25% Cr	5.32	126
	3.58	83	Cr-Mo	8.30	232
	3.59	83	Ni-Cu-Cr-Mo	2.39	41
	3.60	84			
	4.5	91	Tool steels		
	4.6	92	AISI/SAE A2	8.12	224
	5.24	122	AISI/SAE A8	5.67	147

Atlas of Microstructures

Steels/irons	Fig. No.	Page No.	Steels/irons	Fig. No.	Page No.
Tool steels (continued)			Iron alloys (continued)		
AISI/SAE D2	5.46	135	Iron-1.0%C	7.17	184
	8.27	231	Iron-1.2%C	3.49	76
AISI/SAE M2	1.19	15		3.50	77
AISI/SAE W1	8.22	229	Iron-1.4%C	2.7	28
				2.18	34
Stainless steels				3.46	75
AISI/SAE 301	8.45	240	Iron-1.75%C	5.42	133
AISI/SAE 303	4.17	98	Iron-1.86%C	2.27	137
	4.18	99	Wrought iron	8.4	218
	4.19	99	Lancashire iron	8.3	218
AISI/SAE 304	3.12	57	Meteorite	4.4	88
AISI/SAE 309	8.6	220			
AISI/SAE 316	1.11	11	High-strength steels		
	2.36	40	X65 linepipe	1.7	8
	3.43	74	HSLA	3.13	57
	3.44	74		6.10	153
	3.53	79		6.16	156
	3.54	79		6.28	161
	5.47	136		7.42	207
	5.60	141	Dual-phase	1.8	9
	8.44	239		2.38	40
	8.46	240		3.9	55
	8.47	241		7.12	179
AISI/SAE 316L	7.33	197		8.18	226
AISI/SAE 347H	Cover	ii		8.36	235
AISI/SAE 410	1.15	14	1/2Mo-B	8.28	232
	2.28	37	Comp F (MIL-S-23194)	8.29	232
AISI/SAE 430F	1.13	12			
Custom 630	1.17	14	Alloy steels		
	8.42	238	Maraging	1.21	15
	8.43	239		8.41	238
Duplex 7Mo Plus	1.16	14	Invar	1.22	15
Duplex 2205	8.40	237	A286 superalloy	1.18	14
	8.48	241	1%C-14%Cr	7.26	192
			0.93%C-1.45%Mn	2.37	40
Very-low carbon steels			0.93%C-14.5%Ni	8.11	224
Interstitial-free	3.16	59	25%Cr-12%Ni	5.36	129, 130
	8.20	227	19%Cr-9%Ni	5.63	145
Enameling	8.55	244	Grinding ball	7.10	176, 177
	8.56	244			
Motor lamination	1.23	16	Coated steels		
	8.39	236	Galvalume	6.5	151
Very-low carbon	5.44	134		6.6	151
	7.5	173		8.49	242
Low-carbon	7.18	184		8.50	242
	7.21	186		8.51	242
	8.8	222	Aluminized Type 1	4.7	93
	8.13	224	Aluminized Type 2	4.7	93
	8.14	225	Nickel plate	7.1	170
	8.23	229		7.18	184
	8.24	229		7.29	195
Low-carbon (0.02%)	2.13	32	Enamel	8.55	244
Low-carbon (0.04%)	2.17	33		8.56	244
Low-carbon cold-rolled	3.11	56			
	8.15	225	ASTM steels		
	8.16	226	ASTM A1 rail	1.4	6
				3.55	80
Iron alloys				3.56	81
Pure iron	8.19	226		4.5	91
Iron-0.2%C	2.24	36		4.6	92
	8.10	223		4.16	98
Iron-0.4%C	8.1	216	ASTM A 36 structural	1.5	6
	8.10	223		7.11	178
Iron-0.6%C	8.10	223		7.40	206

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Steels/irons	Fig. No.	Page No.	Microstructures	Fig. No.	Page No.
ASTM steels (continued)			Microstructures		
ASTM A 128 Hadfield	1.20	15	Acicular ferrite	2.16	33
ASTM A 247	1.25	17	Alloy carbides	1.19	15
	4.22	101, 102		5.46	135
ASTM A 470 rotor	1.9	9		7.10	176, 177
ASTM A 514	2.25	36		7.26	192
ASTM A 516	3.61	84		8.12	224
ASTM A 710	6.10	153		8.22	229
				8.27	231
ASME steels			Alloy layer	4.7	93
ASME SA 210 tubing	3.62	85	Annealing twins	1.11	11
ASME SA 213 T22 tubing	1.6	7		1.18	14
	8.25	230		1.22	15
				2.36	40
Other steels				8.44	239
Ancient steel	7.9	175	Austenite	1.11	11
Blister steel	4.2	88		1.18	14
				1.20	15
Cast irons				1.22	15
Gray iron	1.24	16		2.36	40
	1.25	17		3.12	57
	2.48	44		3.43	74
	2.56	47		3.44	74
	3.63	85		3.53	79
	5.13	115		3.54	79
	5.14	115		5.47	136
White iron	1.26	18		8.44	239
	2.45	43		8.46	240
	2.46	44	Austenite/ferrite	5.60	141
	2.49	45		8.47	241
	2.54	47	Bainite	2.1(b)	23
	2.55	47		2.31	38
	3.22	64		2.32	38
	5.17	117, 118		6.15	155
Malleable iron	1.28	18		7.46	211
	2.53	46		7.47	212
	3.23	64		8.7	221
	3.24	65	Bainite/ferrite	3.21(a)	63
	3.25	65		7.15(d)	182
Ductile (nodular) iron	1.30	20	Bainite/graphite	1.31	20
	2.51	45	Bainite (granular)	2.35	39
	2.52	46	Bainite (lower)	2.34	39
	3.26	65	Bainite (upper)	1.9	9
	3.27	65		2.33	39
	4.23	103		6.33	165
	4.24	103	Bainite transformation	1.3	5
Mottled iron	1.27	18	Banding	2.43	42
	2.50	45		3.1	50
Austempered ductile iron	1.31	20		3.13	57
				3.15	58
				3.19	61
				3.61	84
				6.27	161
				7.4	172
				8.34	234
				8.40	237
			Bull's-eye structure	3.26	65
				4.23(a)	103
			Carburized surface	3.31	67
				3.32	68, 69
			Cementite platelets	2.7	28
				2.18	34
				5.17	117, 118
			Central bursts in wire	4.8	94
			Cold work	3.11	56

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Microstructures	Fig. No.	Page No.	Microstructures	Fig. No.	Page No.	
Microstructures (continued)			Microstructures (continued)			
Cold work	3.16	59	Ferrite/austenite	8.40	237	
	5.47	136	Ferrite/bainite	3.21(a)	63	
	6.36	167	Ferrite/carbides	2.17	33	
	6.37	167		3.17	60	
	7.5	173		3.19	61	
	7.11(a)	178		8.1	216, 217	
	8.15	225		8.13	224	
	8.16	226		8.14	225	
	8.32	233		8.23	229	
	8.45	240	Ferrite/graphite	1.28	18	
	8.52	243		1.30	20	
	Copper precipitates	6.10	153		3.23	64
	Copper penetration	3.40	73		3.48	75
	Creep voids	3.57	82		3.49	76
	Decarburized surface	3.28	66		4.23	103
	3.29	66		4.24	103	
	3.30	67	Ferrite/pearlite	1.2(a)	4	
Deformation bands	3.12	57		1.2(b)	4	
	3.53	79		1.3	5	
	5.47	136		1.5	6	
Delta ferrite	4.19	99		1.7	8	
	5.60	141		2.6	28	
	8.47	241		2.14	33	
	8.48	241		2.23	35	
Dendritic structure	2.42	42		2.42	42	
	7.10	176		2.43	42	
	8.50	242		3.1	50	
	8.51	242		3.3	51	
	8.6	220		3.4	52, 53	
Dimpled fracture surface	6.19	156		3.5	53	
Enamel coating	8.55	244		3.6	53	
	8.56	244		3.7	53	
Epitaxial ferrite	3.10	55		3.13	57	
	3.32(e)	69		3.15	58	
	3.32(f)	69		3.19	61	
	5.44	134		3.52(c)	78	
	8.18	226		3.61	84	
	8.36	235		3.62	85	
Equiaxed ferrite	1.2(a)	4		4.20	100	
	1.23	16		4.21	100	
	2.13	32		6.2	150	
	8.8	222		6.27	161	
	8.13	224		7.3	171	
	8.20	227		7.4	172	
Eutectic carbides	8.27	231		7.9	175	
Exaggerated grain growth	3.4	52, 53		7.11	178	
Fayalite	6.18	156		7.14(d)	181	
Ferrite	1.13	12		7.29	195	
	1.23	16		7.40	206	
	2.13	32		8.31	233	
	3.11	56		8.32	233	
	3.16	59		8.34	234	
	5.44	134		8.52	243	
	7.5	173		8.53	243	
	7.21	186	Ferrite/martensite	1.6	7	
	8.8	222		1.8	9	
	8.15	225		2.16	33	
	8.16	226		2.38	40	
	8.18	226		3.9	55	
	8.20	227		3.10	55	
	8.39	236		3.32(e)	69	
	8.55	244		3.32(f)	69	
Ferrite/austenite	1.16	14		3.52(b)	78	
	4.19	99		7.12	179	

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Microstructures	Fig No.	Page No.	Microstructures	Fig. No.	Page No.
Microstructures (continued)			Microstructures (continued)		
Ferrite/martensite	8.36	235	Lath martensite	2.25	36
Ferrite/martensite/bainite/ pearlite	8.37	235		2.28	37
Flow lines	4.15	97		3.8	54
Fractured weld	4.10	95		3.20	62
	7.45	210		3.32(c)	68
	8.6	220		3.32(d)	68
Grain boundary carbides	2.17	33		3.52(a)	78
	5.36	129, 130		5.35	128, 129
	8.8	222		8.9	222
	8.13	224		8.10	223
	8.14	225		8.17	226
	8.25	230		8.33	233
Grain boundary segregation	3.36	70		8.41	238
	3.38	73		8.42	238
Graphite flakes	1.24	16		8.43	239
	2.48	44	Ledeburite	1.26	18
	3.63	85		1.27	18
	5.13	115		2.45	43
	5.14	115		2.46	44
Graphite nodules	2.52	46		2.49	45
	3.26	65		3.22	64
	3.27	65	Martensite	1.15	14
	4.22	101, 102		1.17	14
	4.23	103		1.21	15
	4.24	103		2.1(c)	24
Graphitic corrosion	3.63	85		3.17(a)	60
Graphitization	3.48	75		4.9	95
	3.49	76		7.14(c)	181
	3.50	77	Martensite/austenite	2.37	40
Heat-affected zone	4.10	95		2.39	41
Hot cracking (weld)	8.6	220		2.54	47
Hot shortness	3.39	73		2.55	47
	3.40	73		3.32(a)	68
Hydrogen flakes	3.58	83		3.32(b)	68
	3.59	83		3.46	75
	3.60	84		8.11	224
	3.61	84	Martensite/carbides	7.10	176, 177
	3.62	85		7.26	192
Inclusions (CaS)	6.25	160		8.27	231
Inclusions (FeS)	3.41	73	Martensite/pearlite	2.22	35
Inclusions (lead)	8.5	219		3.33	69
Inclusions (MnS)	1.3	5		5.32	126
	1.13	12	Meteorite	4.4	88
	3.33	69	Microcracks	3.46	75
	3.34	69		3.47	75
	3.35	70		7.17	184
	3.42	74	Oxide layer	7.22	188
	6.19	156	Oxide penetration	8.26	231
	7.6	173	Oxidized surface	6.18	156
	7.39	205		8.26	231
	8.2	218	Pearlite	1.4	6
	8.34	234		2.1(a)	23
Inclusions (oxide)	6.25	160		2.19	34
	6.26	160		2.20	34
	7.7	174		2.21	35
	8.3	218		3.56(d)	81
	8.34	234		3.58	83
Inclusions (slag)	8.4	218		4.5	91
	8.54	243		4.6	92
Inclusions (TiN)	5.67	147		5.24	122
	7.8	174		6.9	153
Internal oxidation	3.30	67		6.11	153
Lath martensite	2.24	36		7.3	171
				7.8	174

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Microstructures	Fig No.	Page No.	Microstructures	Fig. No.	Page No.
Microstructures (continued)			Microstructures (continued)		
Pearlite	8.21	228	Prior austenite grain boundaries	8.28	232
	8.38	236		8.29	232
Pearlite/bainite	3.21(b)	63		8.30	232
Pearlite/bainite/martensite	2.1(d)	24	Proeutectoid cementite	1.2(c)	4
Pearlite/cementite	1.26	18		2.7	28
	1.27	18		2.18	34
	2.7	28	Proeutectoid ferrite	2.15	33
	2.45	43		2.41	41
	2.46	44		7.41	206
	2.49	45	Recrystallized grains	3.16	59
	3.22	64		8.15	225
	5.17	117	Retained austenite	2.37	40
	8.22	229		2.38	40
Pearlite colonies	2.21	35		2.39	41
	8.21	228		3.10	55
Pearlite/ferrite	2.15	33		3.32(b)	68
	2.41	41		7.12	179
	7.3	171		8.11	224
Pearlite/graphite	1.24	16	Rusted surface	7.46	211
	2.48	44		7.47	212
	2.50	45	Sensitized stainless steel	3.43	74
	2.51	45		3.44	74
	2.53	46		3.54	79
	2.56	47		8.25	230
	3.24	65		8.44	239
	3.25	65	Silicon carbide particles	7.1	170
	3.26	65	Spangle dendrites	8.50	242
	3.63	85		8.51	242
	4.23	103	Spheroidized carbides	3.17(b)	60
	4.24	103		3.19(b)	61
	5.13	115		3.48	75
	5.14	115		8.1	216, 217
Pearlite lamella	2.19	34	Steadite	2.56	47
	2.20	34		5.14	115
	4.5	91	Stress-corrosion cracking	4.18	99
	4.6	92		4.19	99
	5.13	115	Sulfur segregation	4.16	98
	5.14	115	Surface carbides	8.33	233
	5.24	122	Surface damage (abrasive wheel)	7.9	175
	6.9	153		7.10	176
	6.11	153	Surface damage (EDM)	7.15	182
Pearlite/martensite	5.32	126	Surface damage (polishing)	7.41	206
Pearlite nodules	2.22	35		7.42	207
Phosphorus segregation	3.36	70	Surface damage (shearing)	7.11	178
Plate martensite	2.26	36		7.12	179
	2.27	37	Surface damage (torch-cut)	3.51	77
	3.32(a)	68		3.52	78
	3.32(b)	68		7.14	180
	2.37	40	Surface damage (wheel burn on rail)	3.55	80
	3.46	75	Temper carbon	1.28	18
	3.47	75		2.53	46
	3.56(b),(c)	81		3.23	64
	5.42	133		3.24	65
	7.17	184		3.25	65
	8.10	223		8.33	233
	8.11	224	Temper carbides	3.45	75
Prior austenite grain boundaries	3.33	69	Temper embrittlement	1.19	15
	3.36	70		2.30	37
	3.38	73	Tempered martensite	3.20	62
	3.57	82		3.21(c)	63
	5.41	132		3.56(b)	81
	8.17	226		4.11	96
	8.18	226		8.25	230
	8.25	230			

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Microstructures	Fig No.	Page No.	Microstructures	Fig. No.	Page No.
Microstructures (continued)			Microstructures (continued)		
Tempered martensite	8.33	233	Voids	3.36	70
	8.35	235		3.37	70
Tempered martensite/alloy carbides	1.19	15		3.57	82
	7.10	176	White surface layer	3.55	80
Titanium-molybdenum carbides	6.16	156		3.56	81
	6.28	161	Widmanstatten ferrite	2.14	33
Veining	8.19	226	Widmanstatten structure	4.4	88
Vermicular graphite	4.24	103	Wustite	6.18	156



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