## Contents

## Part I

2	Thermodynamic conditions for the Mn–O	
	system in sintering of manganese steels	5
2.1.	Manganese in steelmaking	5
2.2.	Basic thermodynamic characteristics of protective	
	atmospheres for sintering steels alloyed with manganese and other elements	8
2.3.	Influence of protective atmospheres on proper sintering of carbon containing steels	19
3	Alloying and sintering of manganese steels in	
	terms of high manganese vapour pressure	22
3.1.	Vapour pressure of elements	22
3.1.1.	Basic formulas characterising the sublimation of manganese	
	from solid manganese	23
3.1.2.	Effect of manganese vapour in laboratory sintering of	
2.1.2	Fe-Mn-C samples	26
3.1.3.	Manganese sublimation and condensation in free space	31
3.2.	Reaction of manganese vapour with porcelain	36
3.3.	Summary	37
4	Alloying and sintering of manganese steels by	
	manganese vapour	39
4.1.	Microstructure formation	39
4.1.1.	Conventional radiation sintering	39
4.1.2.	Induction sintering	49
4.2.	Nucleation of new grains in base iron powders in	
	Fe–Mn materials	50
4.3.	Sintering and alloying of manganese steels analysed by	
	the dilatometric tests	53
4.3.1.	Effect of base materials and processing variables	54

1

Contents
----------

4.3.2.	Effect of manganese on isothermal sintering and cooling	
	process according to the dilatometric graphs	67
4.3.2.1.	Enhancing effect of manganese in solid-state sintering	67
4.3.2.3.	Effect of cooling rate on the transformation of austenite in	
	sintered steels as indicated by dilatometric graphs	70
5	Effect of base materials and of various processing	
	methods on mechanical and some special properties	5
	of manganese steels	72
5.1.	Electrolytic manganese and ferromanganese grades -	
	physical-metallurgical and technical characteristics	72
5.1.2.	Ferromanganese grades	74
5.1.3.	As milled characteristics of manganese carriers	79
5.2	Low-carbon low-alloy sintered steel	83
5.2.1	Mechanical properties	85
5.2.2.	Microstructure and fracture	86
5.3.	Properties of induction sintered and upset-forged	
	manganese steels	88
5.3.1.	Mechanical properties of induction sintered Fe-4.5Mn-0.33C	
	steel	89
5.3.2	Microstructure	90
5.3.3.	Mechanical properties of induction sintered and upset-forged Fe-4.5Mn-0.33C steel prepared on the basis of both iron	
	powder grades	92
5.4.	Effect of various material and processing conditions on	
	mechanical and some specific properties of manganese	
	steels	93
5.4.1.	Effect of iron powder grades of markedly different structural	
	activity and manganese addition on properties of sintered	0.4
5 4 0	manganese steel	94
5.4.2.	Effect of various hot forming processes on mechanical properties of manganese steels	99
5.4.4.	Effect of manganese addition and of iron powder grade on	99
5.4.4.	friction properties	118
5.4.4.1	Friction and mechanical properties of sintered steels of	110
0.1.1.1	various composition	118
5.4.5.	Industrially sintered prototype structural parts prepared from	
	manganese steel	126
6	Effect of additional elements on the properties of	
	manganese steels	130
6.1.	Effect of molybdenum	130
6.1.1.	Properties of Fe-Mn-C steels with molybdenum addition	131

vi

6.1.2. 6.1.3.	Manganizing of powder steels combined with sintering Sintering of Fe–Mn–C and Fe–Mn–Mo–C steels in $\alpha$ -region	135
6.1.4.	and at 1120°C Effect of sintering temperature on properties of Fe–Mn–C,	136
	Fe-Cr-C and Fe-Mo-C steels	140
6.2.	Effect of liquid phase forming elements on properties of	
	Fe–Mn–C steels	141
6.2.1.	Effect of copper	141
6.2.2.	Effect of tin	145
6.2.3	Effect of phosphorus	146
6.3.	Effect of boron	150
6.3.1. 6.3.2.	Effect of boron addition on properties of Fe–Mn–C steel Effect of boron addition on tribological properties of	151
	Fe–Mn–C steels	154
6.3.3.	Effect of boron addition on mixed low-alloyed Fe-Mn-Cr-Mo-C steels	158
6.3.4.	Effect of boron addition on properties of Fe–Cr–Mo–V–(Mn)	
	sintered steels	160
6.3.5.	Manganese-assisted pack boriding of sintered steels	163
6.3.6.	Sintering and pack boriding – two-stage process	163
7	Properties of sintered and powder forged steels	
	I I 8	
	based on prealloyed powders	176
7.1.	<b>based on prealloyed powders</b> Properties of sintered and powder forged steels based on	176
7.1.	<b>based on prealloyed powders</b> Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high	
	<b>based on prealloyed powders</b> Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content	176
7.1.1.	<b>based on prealloyed powders</b> Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content Mechanical properties	
	<b>based on prealloyed powders</b> Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content Mechanical properties Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of	176
7.1.1. 7.1.2.	<b>based on prealloyed powders</b> Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content Mechanical properties Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content	176 178
7.1.1.	<b>based on prealloyed powders</b> Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content Mechanical properties Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content Properties of powder forged steels based on commercial	176 178 180
7.1.1. 7.1.2.	<b>based on prealloyed powders</b> Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content Mechanical properties Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content Properties of powder forged steels based on commercial prealloyed Fe–Cr–Mn–Mo–V powders	176 178
7.1.1. 7.1.2. 7.2.	based on prealloyed powders Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content Mechanical properties Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content Properties of powder forged steels based on commercial prealloyed Fe–Cr–Mn–Mo–V powders Density and mechanical properties	176 178 180 182
<ul> <li>7.1.1.</li> <li>7.1.2.</li> <li>7.2.</li> <li>7.2.1.</li> <li>7.2.1.1.</li> </ul>	based on prealloyed powders Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content Mechanical properties Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content Properties of powder forged steels based on commercial prealloyed Fe–Cr–Mn–Mo–V powders Density and mechanical properties <i>Density</i>	176 178 180 182 182
<ul><li>7.1.1.</li><li>7.1.2.</li><li>7.2.</li><li>7.2.1.</li></ul>	<ul> <li>based on prealloyed powders</li> <li>Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content</li> <li>Mechanical properties</li> <li>Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content</li> <li>Properties of powder forged steels based on commercial prealloyed Fe–Cr–Mn–Mo–V powders</li> <li>Density and mechanical properties</li> <li>Density</li> <li>Development and manufacturing of rolling bearing rings</li> <li>by powder forging of steels based on prealloyed Fe–Ni–Mo</li> </ul>	176 178 180 182 182 182
<ul> <li>7.1.1.</li> <li>7.1.2.</li> <li>7.2.</li> <li>7.2.1.</li> <li>7.3.</li> </ul>	<ul> <li>based on prealloyed powders</li> <li>Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content</li> <li>Mechanical properties</li> <li>Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content</li> <li>Properties of powder forged steels based on commercial prealloyed Fe–Cr–Mn–Mo–V powders</li> <li>Density and mechanical properties</li> <li>Density</li> <li>Development and manufacturing of rolling bearing rings by powder forging of steels based on prealloyed Fe–Ni–Mo and Fe–Cr–Mn–Mo powders</li> </ul>	176 178 180 182 182
<ul> <li>7.1.1.</li> <li>7.1.2.</li> <li>7.2.</li> <li>7.2.1.</li> <li>7.2.1.1.</li> </ul>	<ul> <li>based on prealloyed powders</li> <li>Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content <ul> <li>Mechanical properties</li> <li>Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content</li> </ul> </li> <li>Properties of powder forged steels based on commercial prealloyed Fe–Cr–Mn–Mo–V powders <ul> <li>Density and mechanical properties</li> <li>Density</li> </ul> </li> <li>Development and manufacturing of rolling bearing rings by powder forging of steels based on prealloyed Fe–Ni–Mo and Fe–Cr–Mn–Mo powders</li> <li>Mechanical properties of powder forged steels based on</li> </ul>	176 178 180 182 182 182 182
<ul> <li>7.1.1.</li> <li>7.1.2.</li> <li>7.2.</li> <li>7.2.1.</li> <li>7.2.1.1.</li> <li>7.3.</li> <li>7.3.1.</li> </ul>	<ul> <li>based on prealloyed powders</li> <li>Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content <ul> <li>Mechanical properties</li> <li>Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content</li> </ul> </li> <li>Properties of powder forged steels based on commercial prealloyed Fe–Cr–Mn–Mo–V powders <ul> <li>Density and mechanical properties</li> <li>Density</li> </ul> </li> <li>Development and manufacturing of rolling bearing rings by powder forging of steels based on prealloyed Fe–Ni–Mo and Fe–Cr–Mn–Mo powders</li> <li>Mechanical properties of powder forged steels based on prealloyed Fe–Ni–Mo and Fe–Cr–Mn–Mo powders</li> </ul>	176 178 180 182 182 182 182 185
<ul> <li>7.1.1.</li> <li>7.1.2.</li> <li>7.2.</li> <li>7.2.1.</li> <li>7.3.</li> </ul>	<ul> <li>based on prealloyed powders</li> <li>Properties of sintered and powder forged steels based on prealloyed Fe–Cr–Mn–Mo–(V) powders with high oxygen content <ul> <li>Mechanical properties</li> <li>Properties of powder forged steels based on idustrially produced chromium- and manganese-prealloyed powders of high oxygen content</li> </ul> </li> <li>Properties of powder forged steels based on commercial prealloyed Fe–Cr–Mn–Mo–V powders <ul> <li>Density and mechanical properties</li> <li>Density</li> </ul> </li> <li>Development and manufacturing of rolling bearing rings by powder forging of steels based on prealloyed Fe–Ni–Mo and Fe–Cr–Mn–Mo powders</li> <li>Mechanical properties of powder forged steels based on</li> </ul>	176 178 180 182 182 182 182

7.3.4. 7.3.5.	forged rolling bearing rings and their properties Examination of powder forged bearing rings properties Experimental equipment for atomisation of prealloyed	198 200
1.5.5.	Fe-Cr-Mn-Mo powders with low oxygen content	205
8	Processing and properties of hybrid Fe–(Cr)–xMn–	
	(Mo)–(V) steels	209
8.1.	Properties of hybrid steels based on prealloyed	
	Fe-Cr-Mo-V powders	209
8.1.1.	Mechanical and toughness properties and microstructure	210
8.1.2.1.	Fractures of Fe-Cr-Mo-V-Mn-V steels	214
8.2.	Processing and properties of hybrid Fe-Cr-Mo-xMn-	
	C steels	219
8.2.1	Properties of Fe-3Cr-0.5Mo steel with manganese addition	219
8.3.	Effect of manganese carrier on properties of hybrid	
	Fe-Cr-Mo-xMn steels	224
8.3.1.	Mechanical properties	225
8.3.1.1.	Sintering at 1180°C	225
8.4.	Sintered and sinter hardened hybrid steels	228
8.4.1.	As sintered properties	230
8.4.1.1.	Basic characteristics	230
8.4.2.	As sinter hardened properties	234
8.5.	Properties of hybrid Fe–Cr–0.5Mo–xMn–C steels sintered	
	under industrial conditions	237
8.5.1.	Basic characteristics	237
8.5.2.	Mechanical properties	238
8.5.3.	Microstructure and fracture	239
8.5.3.1.	Microstructure	239
8.5.4.	Effect of industrial sintering conditions on properties and	
	microstructures of hybrid Fe-3Cr-0.5Mo-Mn-C steels	242
8.6.	Properties of hybrid Fe–(0.85, 1.5)Mo–Mn–C steels	249
8.6.1.	Properties of Fe-0.85Mo-xMn-0.3C steels	249
8.6.2.	Properties of Fe-0.85Mo-Mn-0.5C steel	252
8.6.2.2.	Mechanical properties after sintering at 1150°C	253
8.6.3.	Properties of Fe–0.85Mo–xMn–0.6C steel	256
8.6.4.	Properties of industrially sintered mixed and hybrid	
	Fe–0.85Mo–xMn–C steels	257
8.6.5.	Properties of sintered hybrid Fe-(1.5, 0.85)Mo-Mn-0.5C steels	259

## Part II

9	<b>Basic characteristics of manganese steels from</b>	
	the year 1948	264
0 1	Thermodynamic and physical characteristics of chromium	

viii

	and manganese as alloying elements in powder	• • •
	metallurgy	264
9.2.	Properties of sintered manganese steels studied in the	
	initial stage	267
9.2.1.	Starting knowledge about sintered manganese steels with	
	high manganese and carbon contents	267
9.3.	Processing conditions and properties of sintered	
	austenitic manganese steels	270
9.3.1.	High-alloyed sintered manganese steels	274
9.4.	Alloying of manganese steels with master alloys	276
9.4.1.	Alloying of manganese steels by master alloys in carbide form	
	composed from elements with high oxygen affinity	276
9.4.2.	Alloying of manganese steels by Fe-Mn-Si-C master alloy	281
9.4.3.	Alloying of manganese steels by master alloys containing	
	Cr and Mn	283
9.5.	Liquid phase sintering of Fe–Mn steels	294
9.5.1.	Liquid phase sintering of Fe–Mn steels through low-melting	
	alloys	294
9.5.2.	Alloying of manganese steels with atomised Mn-Cu and	
	Mn–Ni master alloys	296
10	Effect of variable processing conditions and	
	materials on properties of sintered Mn–C steels	297
10.1.	Alloying with low-melting elements and sintering in	
10.1.	high-purity atmospheres	297
10.1.1.	Alloying with low-melting elements	297
10.1.1.	Sintering of Fe–Mn–C steels in high-purity atmospheres	303
10.2.	Effect of processing conditions on properties of	505
10.5.		205
10.2.1	manganese steels	305
10.3.1.	Effect of iron powder and ferromanganese grades	305 309
10.3.2.	Effect of sintering conditions	310
10.3.3. 10.3.4.	Effect of base powder grades Effect of some processing conditions and of different materials	314
10.3.4.	Effect of cooling rate	320
10.3.6.	Effect of sintering conditions	323
10.3.0.	Hardenability study	326
10.4.1.	Effect of manganese on hardenability of prealloyed powders	326
10.4.1.	Effect of tempering temperature	330
10.4.2.		332
10.5.	Sintering in semi-closed containers Effect of manganese on microstructure formation	336
10.5.1.	-	339
	Dimensional changes of Fe–Mn–C steels	559
10.6.	Effect of different processing variables on properties of Fe–Mn–C steels	340

10.7.	Processing conditions and properties of sintered	
	manganese steel for structural parts	348
10.7.1.	Preparation of gear steel	348
10.7.2.	Innovative processing of manganese steel gears	349
10.7.3.	Mechanical properties of sintered manganese steel gears	351
10.8.	Effect of Mn addition on strain micromechanism in as	
	sintered 316L steel	354
11	Effect of processing conditions and materials on	
	properties of sintered Fe, Cr, Mo, C steels	
	containing manganese	358
11.1.1.	Effect of different addition mode of molybdenum on properties	
	of manganese steel	358
11.1.2.	Effect of cooling rates on properties of Fe–Mn–Mo–C steels	366
11.1.3.	Dimensional changes of the compacts based on plain iron	
	powders with addition of prealloyed molybdenum powders	200
11 1 4	and of manganese tested by dilatometry	369 373
11.1.4. 11.1.5.	Properties of diffusion-alloyed steels affected by manganese Properties of industrially sintered Fe–Mn–Mo–C steels	373 379
11.1.3.	Processing and properties of sintered Mn–Cr–Mo–C steels	382
11.2.1.	Sinterability and hardenability of Mn–Cr–Mo steels	382
11.2.1.	Processing and properties of hybrid sintered	562
11.J.	Mn–Cr–Mo–C steels	391
11.3.1.	Properties of sintered 3Cr–0.5Mo steel promoted by manganese	391
11.3.1.	in form of liquid phase	391
11.4.2.	Properties of hybrid Mn–Cr–Mo steels coated with	571
11.7.2.	hydrocarbons	393
11.5.	Properties of sintered steels based on prealloyed	595
11.0.	Cr–Mo–Mn powders	402
11.5.1.	Properties of high temperature sintered steels based on	402
11.2.1.	prealloyed Cr–Mo–Mn powders	402
11.5.2.	Influence of sintering temperature on the properties of	102
	prealloyed PM steel containing Cr, Mo and Mn	411
11.5.3.	Properties of manganese steels based on CrL and CrM	
	prealloyed powders	414
11.5.4.	Properties of sintered steels based on Cr and Cr–Mn prealloyed	
	powders with various Cr and Mn content	419

## Part III

12	Sintering of manganese steels in low- and	
	high-purity atmospheres: Results and evaluation	425
12.1.	Basic thermodynamic and physical characteristics of	

х

Index		475
Referen	ces	458
	corresponding conditions	453
	values of manganese-containing steels attained under	
12.5.2.	Highest tensile (UTS) and transverse rupture strength (TRS)	
12.5.1.	Materials and processing conditions	452
	manganese-alloyed steels with the highest strength properties	452
12.5.	Overview of materials and processes for preparation of	
12.4.	Crucial results	451
10.4	oxygen	445
12.3.	occurring in atmospheres with different partial pressure of	
12.3.	manganese steel Explanation of the sintering processes of manganese steels	441
12.2.2.	Industrially sintered prototype structural parts prepared from	4.4.1
12.2.3.	Sintering of manganese steels in atmospheres with different ratios of H and N with dew points up to $-60^{\circ}$ C	437
	steels sintered in H/N atmospheres with different dew points	432
12.2.	Chemistry and mechanical properties of manganese contain	ning
	steels	426
	manganese in term of its use for alloying of sintered	
Contents		xi