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## MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Cr-Mn STRUCTURAL PM STEELS

### MIKROSTRUKTURA I WŁASNOŚCI MECHANICZNE SPIEKANYCH, KONSTRUKCYJNYCH STALI CHROMOWO-MANGANOWYCH

The effects of chemical composition, sintering atmosphere and cooling rate on density, microstructure and mechanical properties of Fe-3%Mn-(Cr)-(Mo)-0.3%C PM steels are described. Pre-alloyed Astaloy CrM and Astaloy CrL, ferromanganese and graphite powders were used as the starting materials. After pressing in rigid dies the compacts were sintered at 1120 and 1250°C for 60 minutes atmospheres with different H<sub>2</sub>/N<sub>2</sub> ratios and cooled either at 1.4°Cmin<sup>-1</sup> (with the furnace) or 65°Cmin<sup>-1</sup> (convective cooling). The convective cooled specimens were subsequently tempered at 200°C for 60 and 240 minutes. All specimens were tested for tensile strength (UTS), elongation (A), offset yield strength (R<sub>0.2</sub>), TRS, impact toughness and apparent surface hardness (HV 30). After mechanical tests the microstructure of the Fe-Mn-Cr-Mo-C PM steels was studied by optical microscopy. It has been found that by sintering in inexpensive and safe nitrogen-rich atmospheres it is possible to achieve properties similar to those shown by specimens sintered in a hydrogen-rich atmosphere.

*Keywords:* PM Cr-Mn steels, mechanical properties, sintering atmosphere, cooling rate, sinter-hardening

W pracy przedstawiono wpływ składu chemicznego mieszanki proszków, a także rodzaju atmosfery oraz szybkości chłodzenia na gęstość, mikrostrukturę oraz własności mechaniczne spiekanych stali konstrukcyjnych Fe-3%Mn-(Cr)-(Mo)-0.3%C. Do badań wykorzystane zostały wstępnie stopowane, komercyjne proszki żelaza Astaloy CrL i Astaloy CrM, produkcji szwedzkiej firmy Höganäs oraz niskowęglowy proszek żelazomanganu i proszek grafitu. Prasowanie mieszanek proszków o żądanym składzie chemicznym realizowano w stalowych matrycach, wykonując wypraski prostopadłościennie o wymiarach 5×10×55 mm oraz wytrzymałościowe (zgodne z PN-EN ISO 2740). Spiekanie kształtek odbywało się w temperaturze 1120 i 1250°C w czasie 60 minut, w atmosferze o różnej zawartości wodoru i azotu. Chłodzenie spieków prowadzono z szybkością 1,4°C/min (z piecem) lub 65°C/min (konwekcyjnie w chłodnicy pieca). Spieki chłodzone z szybkością 65°C/min poddane zostały odpuszczaniu w temperaturze 200°C w czasie 60 i 240 minut. Spieczone kształtki poddano statycznej próbie rozciągania oraz próbie trójpunktowego zginania; przeprowadzone również zostały badania udarności oraz pomiary twardości. Badania mikrostruktury spiekanych stali prowadzono z wykorzystaniem mikroskopii świetlnej. W toku prowadzonych badań wykazano, że spiekanie kształtek w taniej i bezpiecznej atmosferze azotu (lub w atmosferach bogatych w azot) pozwala uzyskać zadowalające własności mechaniczne spieków, porównywalne z własnościami tych stali, wytwarzanych poprzez spiekanie w atmosferze wodoru.

## 1. Introduction

The potential of Mn and Cr as alloying elements, reflected in their widespread use in wrought medium-to-high strength steels, is to be realised in powder metallurgy. An interesting development in the processing of PM steels is the addition of Mn to Fe-Cr-0.5%C steels sintered at above 1250°C [1]. The mechanical properties of these steels were largely determined by the microstructure, so it is important to know how alloying elements affect hardenability and microstructural features. Obviously the effect of Mn on Cr

steel strength is due to the combination of Mn, Cr, N and C present in the sintering atmosphere [2]. For Astaloy CrL and Astaloy CrM containing 1.5 and 3% Cr endogas is too wet for their processing. This group of steels has to be specially treated during sintering because of high affinity of Mn and Cr for oxygen. Manganese intensifies the detrimental effect of oxygen on mechanical properties of PM Cr steels. Cracked ammonia, traditionally used as a sintering atmosphere for low-alloy steel components, is being substituted by N<sub>2</sub>/H<sub>2</sub> mixtures containing up to 10% H<sub>2</sub>. To process Astaloy CrM industrially, however, methane is injected into the N<sub>2</sub>/H<sub>2</sub> atmosphere.

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It is known that chromium causes a large increase in the solubility of nitrogen in steel.

Hardened microstructures resulting in an optimum combination of strength and ductility can be formed during the sinter-hardening cycle by using furnaces which allow higher cooling rates and subsequent tempering at  $\sim 200^\circ\text{C}$ . As a result, higher amounts of bainitic/martensitic structures can be expected. This was illustrated for Fe-3%Mn-(Mo)-0.6%C alloys [2-4]. Very slow furnace cooling ( $1.4^\circ\text{Cmin}^{-1}$ ) was found to favour plasticity [5]. Significant improvements in the properties were observed in specimens cooled at  $65^\circ\text{Cmin}^{-1}$  and subsequently tempered at  $200^\circ\text{C}$ . The as-sintered specimens showed low impact toughness but tempering at  $200^\circ\text{C}$  resulted in precipitation of the  $\epsilon$ -carbide in low-carbon martensite, which lowers internal stresses [6]. Some PM steels are used in the fully bainitic/martensitic condition [7]. However, some thermal treatments, including rapid cooling from the sintering temperature, often result in embrittlement. Cias et al [8] have demonstrated that the problems of successful PM exploitation of steels containing  $\sim 3\%$  Mn are associated with elimination of oxide networks present in such alloys by sintering in reducing atmospheres having dew points of  $-55^\circ\text{C}$  or  $-40^\circ\text{C}$  at  $1120^\circ\text{C}$  and  $1200^\circ\text{C}$ , respectively. It has also been shown [9-10], that for successful processing of Mn containing steels it is essential that the dew point of the furnace  $\text{N}_2/\text{H}_2$  atmosphere must be strictly controlled and as low as possible.

Only control of the "local microclimate" ensured by use of semi-closed container, or getter, minimised interactions with the flowing atmosphere. CO generated

within a PM component should prove to be a more efficient reducing agent than pure dry hydrogen at above  $900^\circ\text{C}$  and high temperature carbothermic sintering at  $1250\text{-}1280^\circ\text{C}$  has been found important to produce the best combination of strength and ductility [11].

The aim of the present study was to establish an economical route of producing low-alloy nitrogen-free structural steels, and second, to substitute Ni, classified as class 3 carcinogen and allergic element [12], with Mn.

## 2. Experimental methods, materials and procedures

Pre-alloyed Höganäs Astaloy CrL and Höganäs Astaloy CrM were used as the base powders. 3% of manganese, in the form of low-carbon (1.3% C) ferromanganese (77% Mn) powder, and 0.3% ultra fine graphite powder were added to the base powders in order to prepare two mixtures Fe-3%Mn-1.5%Cr-0.2%Mo-0.3%C or Fe-3%Mn-3%Cr-0.5%Mo-0.3%C (based on pre-alloyed Astaloy CrL and Astaloy CrM, respectively) by intermingling the components in a Turbula mixer for 30 minutes. The mixed powders were then compacted in steel dies with zinc stearate lubricated walls. Two types of compacts with approximately the same density were prepared:  $5\times 10\times 55$  mm TRS specimens and ISO 2740 dog-bone tensile test bars. The green ( $d_1$ ) and as-sintered ( $d_2$ ) densities of the compacts are summarised in Table 1. Isothermal sintering was carried out in dry (30 ppm moisture) atmospheres with different  $\text{H}_2$  to  $\text{N}_2$  ratio (Table 2) in a laboratory horizontal tube furnace at  $1120$  and  $1250^\circ\text{C}$  for 60 minutes, employing slow ( $1.4^\circ\text{Cmin}^{-1}$ ) and convective ( $65^\circ\text{Cmin}^{-1}$ ) cooling.

TABLE 1

Green and as-sintered densities of Fe-Mn-Cr-Mo-C PM steels (mean values)

Chemical composition	Green density	As-sintered density		Green density	As-sintered density	
		ISO 2740 bars			rectangular $5\times 10\times 55$ mm bars	
	$d_1, \text{g/cm}^3$	$1120^\circ\text{C}$	$1250^\circ\text{C}$	$d_1, \text{g/cm}^3$	$1120^\circ\text{C}$	$1250^\circ\text{C}$
Fe+1.5%Cr+0.2%Mo+3%Mn+0.3%C	6.92	6.91	6.91	7.14	7.08	7.18
Fe+3%Cr+0.5%Mo+3%Mn+0.3%C	6.86	6.84	6.88	7.06	7.00	7.09

TABLE 2

Sintering atmospheres

Designation of atmosphere	Chemical compositions
A0	100% $\text{H}_2$
A1	75% $\text{H}_2$ -25% $\text{N}_2$
A2	25% $\text{H}_2$ -75% $\text{N}_2$
A3	5% $\text{H}_2$ -95% $\text{N}_2$
A4	100% $\text{N}_2$

For each chemical composition of steels, 5 batches of specimens were sintered in each (A0-A4) atmosphere and tempered at 200°C for 60 and 240 min. To improve the local dew point of microatmosphere and to minimise the loss of manganese due to volatilisation, sintering was carried out in a semi-closed stainless steel container. The mechanical properties of investigated steels are given in Tables 3-5.

### 3. Results

The physical and mechanical properties of Fe-Mn-Mo-Cr-C PM steels are summarised in Tables 1,3 and 4. Green and as-sintered densities were calculated using geometrical method. The results were then verified using Archimedes' method (Table 1).

As was presented in Table 3, for higher Cr and Mo concentration, high temperature sintering in nitrogen has to be employed to improve strength properties. Recorded values for UTS, elongation and TRS after sin-

tering at 1250°C were higher than that after low temperature process. These values correspond well to the bainitic/martensitic structure of PM steels. What is more, there is no evident percentage differences between sintering in H<sub>2</sub>-rich and pure N<sub>2</sub> atmosphere. For lower Cr and Mo concentration, slightly better properties were recorded after sintering in hydrogen-rich than in nitrogen atmosphere, irrespective to the sintering temperature. Young's modulus evaluated by the supersonic method along the sample was in the range of 144-151 GPa. When we look at plasticity and hardness of Mn-Cr-Mo PM steels (Table 3), the same tendency as in strength properties can be observed. It can be also pointed out relatively high elongation – up to 2.5%, which corresponds well with the impact toughness. The microstructure of slow (1.4°Cmin<sup>-1</sup>) cooled, not tempered PM steels are shown in Figs 1-4. In Table 4 and 5 the mechanical properties of the investigated steels after tempering at 200°C for 0, 60 and 240 minutes were summarised. The microstructure of convective (65°Cmin<sup>-1</sup>) cooled and tempered PM steels are shown in Figs 5-10.

TABLE 3

As-sintered properties of Fe-Mn-Cr-Mo-C PM steels cooled at 1.4°C/min (mean values)

Chemical composition	Sintering temperature, °C, and atmosphere	UTS, MPa	R <sub>0.2</sub> , MPa	A, %	TRS, MPa	Toughness, Jcm <sup>-2</sup>	HV30	
Fe+1.5%Cr+0.2%Mo +3%Mn+0.3%C	1120	A0	662	408	1.8	1460	5.61	231
		A1	512	455	1.3	872	4.1	190
		A2	438	361	0.9	1024	2.7	207
		A3	400	342	0.8	814	2.8	247
		A4	374	285	0.7	909	2.6	229
	1250	A0	629	453	1.5	1514	11.2	222
		A1	602	440	1.6	1226	5.7	260
		A2	510	462	1.1	1214	5.8	249
		A3	456	484	0.8	1208	3.9	235
		A4	466	440	1.2	970	3.9	225
Fe+3%Cr+0.5%Mo+ 3%Mn+0.3%C	1120	A0	598	541	0.9	1104	5.1	322
		A1	584	498	1.1	969	4.0	255
		A2	532	451	1.1	1048	3.9	302
		A3	515	386	1.0	972	3.5	341
		A4	495	479	1.0	975	3.9	353
	1250	A0	774	546	1.8	1425	7.7	254
		A1	816	587	2.5	1469	7.2	326
		A2	672	569	1.5	1145	4.7	345
		A3	572	526	1.1	1026	4.8	351
		A4	670	-	2.0	1056	3.7	362

It was found that the steel microstructure strongly depends on the cooling rate after sintering. Bainitic or bainitic/martensitic structure was formed during cooling at  $30^{\circ}\text{Cmin}^{-1}$  and  $20^{\circ}\text{Cmin}^{-1}$  after sintering at  $1120^{\circ}\text{C}$  and  $1250^{\circ}\text{C}$ , respectively. In general, the bainitic structure is relatively acicular and much finer than the pearlitic one. This accounts for the improved bending and tensile properties. In investigated steels bainite consists of an aggregate of acicular ferrite and carbides. Its morphology changes progressively with the transformation temperature, i.e. the grain size and acicularity of the structure increases as the temperature decreases. The upper bainite comprises larger ferrite plates bounded by  $\text{Fe}_3\text{C}$  precipitates that form directly from the austenite.

It has been shown [1, 10, 13, 14] that the structures form in situations that didn't correspond to the accepted classical definition. These structures consisted of fine bainite and Mn-rich retained austenite zones, partly transformed into martensite, that do not necessarily contain carbides. When long austenitic-martensitic plates extend across the grains, the impact strength sharply decreases. Finally, a spectacular strength increase along with a marked decrease in impact strength is observed in most specimens when a certain amount of acicular martensite is formed inside the acicular-bainitic regions at the end of the bainitic transformation. Continuous cooling results in a mixture of upper and lower bainitic structures unless the transformation is substantially suppressed by the prior occurrence of the equilibrium, pearlitic transformation.

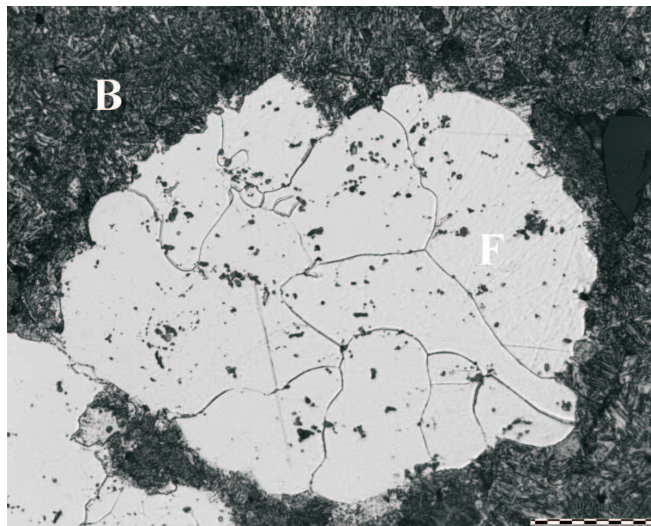


Fig. 1. Micrograph of Astaloy CrL-based PM steel sintered at  $1120^{\circ}\text{C}$  in  $\text{H}_2$ ; ferrite island (F) in bainite (B) matrix, mag. 500x

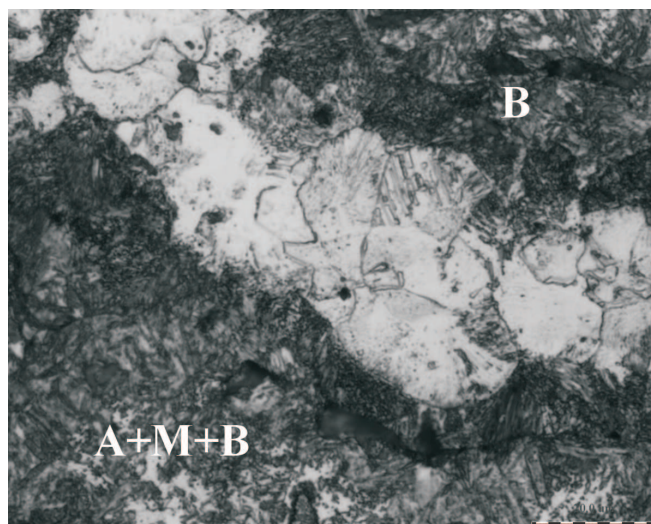


Fig. 2. Micrograph of Astaloy CrL-based PM steel sintered at  $1120^{\circ}\text{C}$  in  $\text{N}_2$ ; austenite (A) / martensite (M) / bainite (B) (A+M+B), mostly bainite (B); mag. 500x

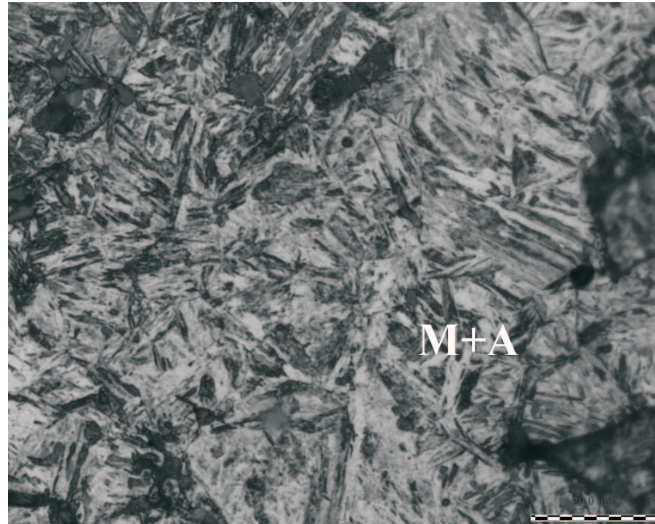


Fig. 3. Micrograph of Astaloy CrM-based PM steel sintered at 1120°C in H<sub>2</sub>; martensite (M) in austenite (A) matrix; mag. 500x

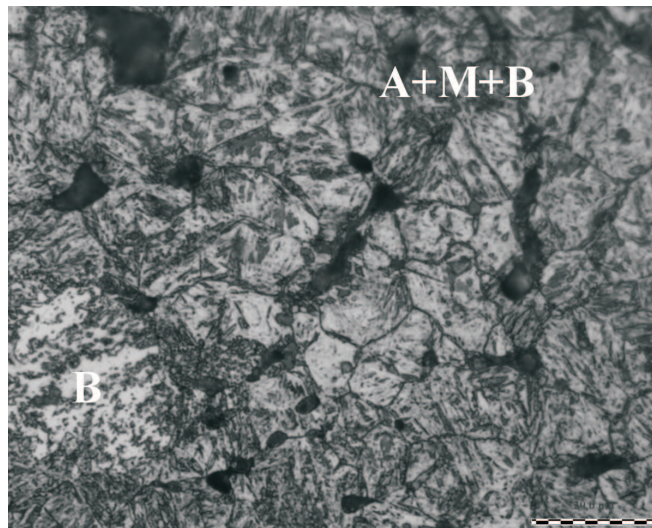


Fig. 4. Micrograph of Astaloy CrM-based PM steel sintered at 1120°C in N<sub>2</sub>; austenite (A) / martensite (M) / bainite (B) (A+M+B), bainitic (B) islands; mag. 500x

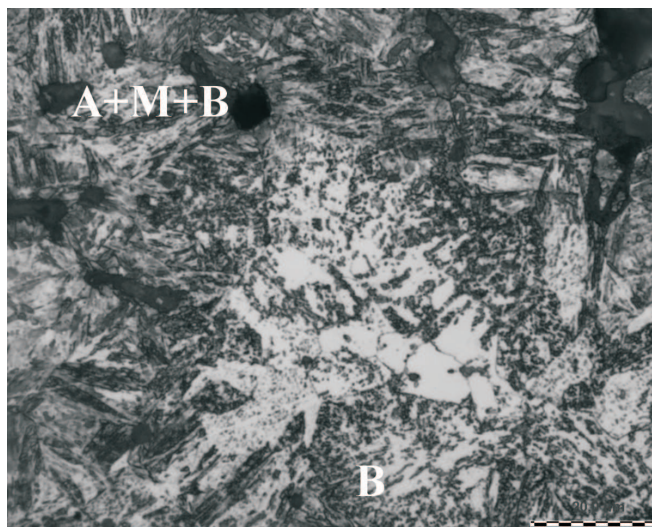


Fig. 5. Micrograph of Astaloy CrL-based PM steel sintered at 1120°C in H<sub>2</sub>, not tempered; austenite (A) / martensite (M) / upper bainite (B) islands; mag. 500x

TABLE 4

Mechanical properties of Fe-Mn-Cr-Mo-C PM steels sintered at 1120°C, rapidly cooled at 65°Cmin<sup>-1</sup> and tempered at 200°C

Chemical composition / sintering atmosphere / tempering time, min		UTS, MPa	R <sub>0.2</sub> , MPa	A, %	TRS, MPa	Toughness, Jcm <sup>-2</sup>	HV30	
Fe-1.5%Cr+0.2%Mo+3%Mn+0.3%C	A0	0	545	–	1.0	1171	6.0	198
		60	554	481	0.8	1216	3.4	245
		240	625	553	0.6	1163	5.2	263
	A1	0	514	507	0.8	825	4.1	222
		60	439	–	0.6	1017	3.0	262
		240	662	457	1.1	1045	3.9	210
	A2	0	634	517	1.2	1003	4.1	342
		60	662	608	1.0	1049	3.6	318
		240	608	554	0.9	1018	7.0	280
	A3	0	654	498	1.1	805	4.8	317
		60	542	481	0.8	1020	3.0	284
		240	506	405	0.7	912	2.5	278
A4	0	495	450	0.8	765	4.3	315	
	60	541	481	0.8	1191	3.4	274	
	240	544	508	0.8	1082	3.4	298	
Fe+3%Cr+0.5%Mo+3%Mn+0.3%C	A0	0	–	–	–	1041	4.6	389
		60	439	357	0.6	1195	5.8	305
		240	687	635	1.2	1096	5.5	291
	A1	0	447	–	0.7	702	3.0	206
		60	563	–	0.8	1030	3.3	268
		240	535	474	0.8	1230	3.5	310
	A2	0	642	537	1.1	689	5.5	400
		60	645	560	1.1	1105	5.0	317
		240	575	517	0.9	1035	4.0	309
	A3	0	416	–	0.5	828	4.1	372
		60	648	537	1.7	982	3.3	323
		240	621	577	2.0	941	3.2	307
	A4	0	595	492	1.9	399	2.5	395
		60	706	535	2.5	855	4.1	320
		240	700	587	2.5	1131	4.1	319

TABLE 5  
 Mechanical properties of Fe-Mn-Cr-Mo-C PM steels sintered at 1250°C, rapidly cooled at 65°Cmin<sup>-1</sup> and tempered at 200°C

Chemical composition / sintering atmosphere / tempering time, min		UTS, MPa	R <sub>0.2</sub> , MPa	A, %	TRS, MPa	Toughness, Jcm <sup>-2</sup>	HV30	
Fe-1.5%Cr+0.2%Mo+3%Mn+0.3%C	A0	0	573	410	1.1	1354	14.0	252
		60	604	474	1.2	1613	15.2	222
		240	630	543	1.2	1412	14.1	239
	A1	0	594	447	1.3	1214	11.4	253
		60	682	475	1.5	1549	10.9	244
		240	638	506	1.4	1358	10.7	251
	A2	0	622	505	1.2	1530	7.7	220
		60	753	537	1.6	1348	6.5	278
		240	791	557	1.7	1530	9.2	282
	A3	0	799	472	1.8	1519	5.2	296
		60	785	535	1.7	1407	6.0	273
		240	669	565	1.2	1169	6.3	268
A4	0	822	554	2.2	1428	10.4	281	
	60	829	554	2.0	1469	5.8	272	
	240	813	596	1.7	1702	15.3	262	
Fe+3%Cr+0.5%Mo+3%Mn+0.3%C	A0	0	858	563	2.3	1349	7.9	314
		60	811	594	1.8	1543	6.6	302
		240	813	598	1.7	1463	5.8	282
	A1	0	781	521	1.6	1501	8.2	306
		60	752	632	1.3	1665	8.1	313
		240	808	601	1.7	1428	6.4	296
	A2	0	886	573	2.3	1610	7.9	331
		60	905	613	2.3	1695	6.9	304
		240	811	576	1.7	1598	10.1	329
	A3	0	901	604	2.2	1572	13.0	334
		60	872	615	2.2	1610	8.9	319
		240	925	595	2.8	1705	8.4	338
	A4	0	802	583	1.7	1675	14.1	328
		60	954	562	2.8	1658	10.7	315
		240	965	584	2.8	1527	8.0	327

Chemical analysis using Leco instruments was employed to check the carbon and oxygen content of the investigated steels. As shown in Table 6, decarburisation was observed. The higher carbon loss, of 0.11%, was recorded for CrM samples sintered at 1250°C in A3 atmosphere with H<sub>2</sub>/N<sub>2</sub> ratio 3:1.

As shown in Figs 1-10, specimens with lower Cr and Mo content, sintered at 1120°C, show a bainitic/martensitic structure, whereas in those containing more Cr and Mo, martensitic/austenitic structures are mainly observed. After sintering at 1250°C, the structure consists mainly of martensite and bainite regions with small amount of austenite.

TABLE 6

Oxygen and carbon content of PM Fe-Mn-Cr-Mo-C steels

Sintering temperature, °C and atmosphere		Fe+1.5%Cr+0.2%Mo+3%Mn+0.3%C		Fe+3%Cr+0.5%Mo+3%Mn+0.3%C	
		C, wt.-%	O <sub>2</sub> , wt.-%	C, wt.-%	O <sub>2</sub> , wt.-%
1120	A0	0.287	0.587	0.303	0.507
	A1	0.266	0.331	0.277	0.310
	A3	0.289	0.460	0.304	0.390
	A4	0.274	0.338	0.276	0.333
1250	A0	0.221	0.252	0.218	0.343
	A1	0.208	0.140	0.221	0.161
	A3	0.190	0.157	0.228	0.290
	A4	0.191	0.165	0.214	0.280

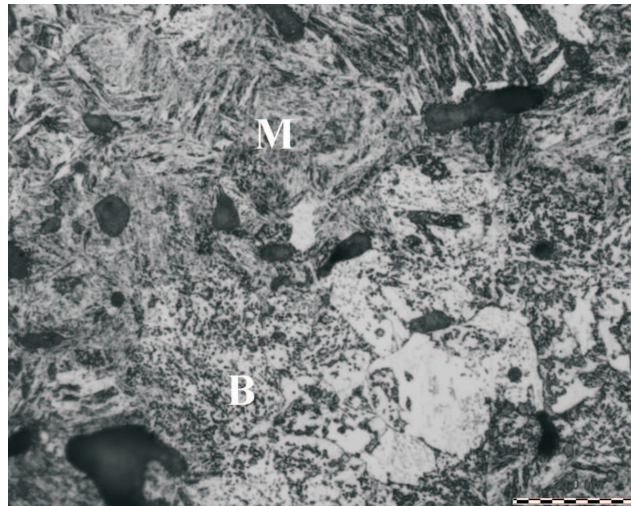


Fig. 6. Micrograph of Astaloy CrL-based PM steel sintered at 1120°C in H<sub>2</sub>, tempered at 200°C for 60 min; bainite (B) in martensite (M) matrix; mag. 500x

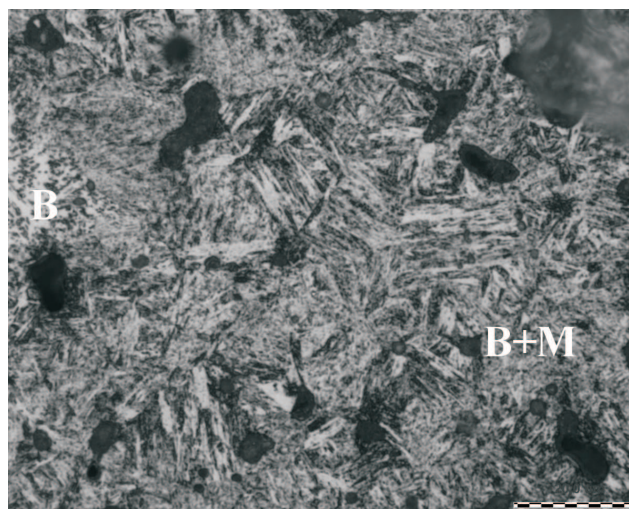


Fig. 7. Micrograph of Astaloy CrL-based PM steel sintered at 1120°C in H<sub>2</sub>, tempered at 200°C for 240 min; bainite (B) / martensite (M) (B+M); mag. 500x



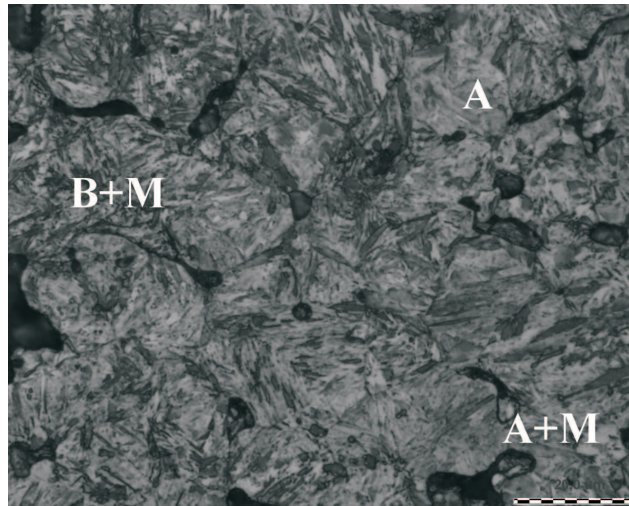


Fig. 8. Micrograph of Astaloy CrM-based PM steel sintered at 1120°C in N<sub>2</sub>, not tempered; martensite (M), austenite (A) and acicular bainite (B); mag. 500x

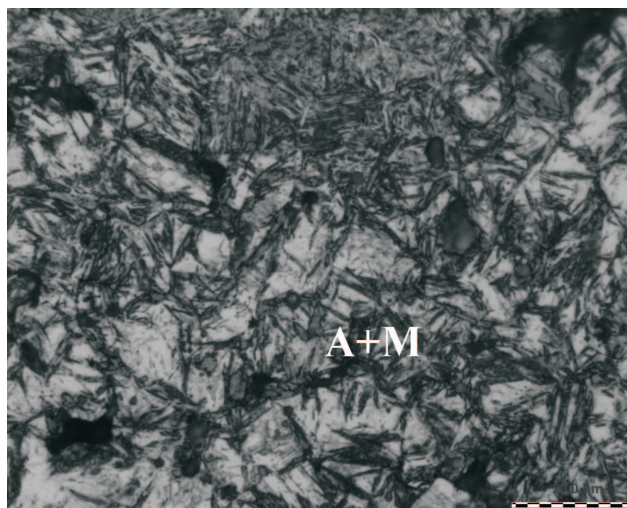


Fig. 9. Micrograph of Astaloy CrM-based PM steel sintered at 1120°C in N<sub>2</sub>, tempered at 200°C for 60 min; austenite (A) + martensite (M) (A+M); mag. 500x

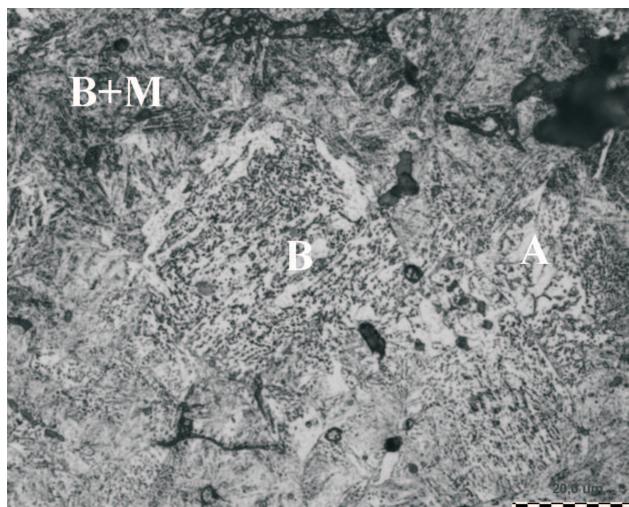


Fig. 10. Micrograph of Astaloy CrM-based PM steel sintered at 1120°C in N<sub>2</sub>, tempered at 200°C for 240 min; bainite (B), austenite (A), martensite (M); mag. 500x

#### 4. Discussion and conclusions

The investigated alloys belong to the group of low alloyed sinter-hardened medium-to-high strength steels, which are used for structural parts in ferrous powder metallurgy and with success substitute traditional, expensive PM steels. The tensile and yield strengths of investigated steels were in excess of 850 MPa and 550 MPa, respectively. The aim of the work was to develop, by single compaction processing, PM steels with properties typical of double pressed sintered steels.

Sinter-hardening steel is usually produced in a sintering furnace with a gas rapid cooling function. If the hardened structure can be obtained at a normal cooling rate ( $\sim 10^{\circ}\text{Cmin}^{-1}$ ), a sintering furnace with a conventional cooling zone can be used and larger economic benefit will be brought. In these investigations, by selecting and adding the optimum quantities of alloying elements that improve hardenability, a martensitic structure was obtained with relatively low cooling rate.

Economical aspect has been the foremost reason why ferromanganese powders have not become common practice in the PM industry. Cheap ferromanganese powders have long been attractive to the PM industry, however the cost associated with generating low dew point sintering atmosphere has prevented commercial use. For example, the attraction of cheaper ferromanganese powder relative to Ni powder is lost once dissociated ammonia atmosphere approaches dew point  $-55^{\circ}\text{C}$  (30 ppm moisture). However there are technological reasons as well preventing use of fine ferromanganese powders. The dimensional and mechanical behaviour of sintered steels in which the Mn alloying elements are admixed is influenced greatly by agglomeration and segregation before the pressing process. This result in localised lower or higher alloying contents (chemical inhomogeneities). Agglomerated ferromanganese powder result in unacceptably large Mn-rich or pure Mn areas in the sintered steels as well as areas lean in Mn content. Finer powders are difficult to blend without agglomeration using conventional mixing technology. Powder mixes may segregate during handling causing compositional variations and hence dimensional variation between compacts. Agglomeration and segregation not only negates the benefits of improved distribution and higher mechanical properties attributed to fine powders, but also lead to failure. This segregation can be minimised using organic binder. Bonding of ferromanganese to Fe powder by resin should result in no perceivable difference in handling to the end user. The use of manganese and chromium for PM applications will be possible by binder-treated premix technology of a highly compressible pre-alloyed low alloy base material (Astaloy CrL, Astaloy CrM etc.).

The mechanical properties of investigated PM steels appear comparable to other studies [2, 9, 10, 13]. The strength results showed strong dependence on the sintering atmosphere ( $\text{H}_2$ ,  $\text{N}_2$ ), especially for tempered steels. A comparison of the tensile strength, elongation and impact values found quite good agreement. The effect of using a higher sintering temperature than  $1120^{\circ}\text{C}$  on mechanical properties is evident from the presented results. The tensile and transverse rupture data showed a measurable effect of the sintering temperature and tempering time. Increasing Cr content from 1.5% to 3% and/or tempering time offered improvement in properties under conditions employed. The application of semi-closed container offers a means to increase the mechanical properties of single compacted manganese steels to those typical of double pressed and sintered steels. Most significantly, the properties of the sinter-hardened manganese and manganese-chromium-molybdenum steels produced by single compaction exceeded those of the double pressed, double sintered and heat-treated commercial PM steels.

The work carried out has described the advantages of adding ferromanganese powder to Fe-Cr-Mo-C sintered powder compacts. We are interested in the  $\text{N}_2$ -sintering route to reduce  $\text{H}_2$  levels in furnace gases to level less than that which is explosive in the air in the range 4-74.5%. It was therefore felt necessary to study the influence of type of sintering atmosphere on the utilisation of Mn and Cr additions to obtain better economical results and suitable safety precautions. The work was carried out using  $\text{N}_2/\text{H}_2$  atmosphere with a dew point of below  $-60^{\circ}\text{C}$ , so that it is not difficult to make a direct comparison with results obtained in industry, and with other published work, where different  $\text{N}_2/\text{H}_2$  atmospheres had been used. Dew point refers to the dryness of a  $\text{H}_2$  only atmosphere; if dilute (given water vapour content), the reducing potential is reduced, because the amount of  $\text{H}_2$  is reduced. In flowing  $\text{N}_2$  atmosphere, reduction of MnO oxides by solid carbon below  $1425^{\circ}\text{C}$  is impossible. Only control of the local microclimate in semi-closed container, i.e. CO/ $\text{CO}_2$  ratio, ensures optimum conditions for thermocarbonic oxide reduction and efficient sintering [2]. Regarding microstructures of the investigated steels,  $\text{N}_2$  with a dew point of  $-60^{\circ}\text{C}$  proved as successful a furnace atmosphere as equally dry  $\text{H}_2$ . It is therefore concluded that, provided sintering of Fe-3%Mn-(Cr)-(Mo)-0.3%C steels is carried out in a semi-closed container (with availability of carbon and manganese therein, in our case within the green compact), furnace atmosphere of dry  $\text{N}_2$  is as effective in preventing formation of deleterious oxide networks as of dry  $\text{H}_2$ , or of  $\text{H}_2$ - $\text{N}_2$  mixtures. Specimens sintered at  $1250^{\circ}\text{C}$  and possessed higher mechanical properties, irrespective of the  $\text{H}_2$ - $\text{N}_2$  ratio in the furnace atmosphere. For the investigated steels the

tensile and transverse rupture strength were approximately directly proportional to the  $H_2$  content in the sintering atmosphere. Chromium enhances, however, as compared with previous results [4], the detrimental effects of  $N_2$  on strength of the PM Mn steels. Nitrogen in solid solution improves hardness and produces little effect upon elongation and impact toughness. The effect of  $N_2$  on brittle fracture of these steels should be investigated further, especially in regard to the “clustering”  $N_2$  atoms about substitutional alloy atoms Cr and Mn. Quantitatively correlating properties with microstructure is a problem that exists even in the case of relatively simple structure such as those consisting of a finely dispersed phase inside inhomogeneous matrix. In case of the structures discussed herein, the problem was considerably complicated in specimens cooled with cooling rate  $65^\circ\text{Cmin}^{-1}$  because four constituents were present simultaneously: very fine pearlite (troostite), bainite, martensite and retained austenite. This is the reason why we restricted ourselves to some general remarks regarding a possible correlation between the cooling rates and the structure and mechanical properties of PM Fe-3%Mn-(Cr)-(Mo)-0.3%C steels. Many factors can be considered to explain the investigated steels strength: inherent strength of bainite, solid solution hardening of the ferrite, obstacles placed by the austenitic-martensitic island, presence within the structure of an appreciable percentage of martensite resulting from partial transformation of the stabilised austenite. However, the user is interested in the mechanical properties of bainitic structures, and it appears possible to relate the tensile strength, impact toughness and ductility to microscopic factors such as the bainitic grain size, and the size and distribution of carbides. In the various investigations conducted in connection with the morphology and mechanical properties of steels cooled at a cooling rate of  $65^\circ\text{Cmin}^{-1}$ , we observed numerous aspects of the so-called bainitic structures. In the investigated steels, a bainitic structure was obtained by the direct quenching of austenite. This structure exhibited not only a high tensile strength but also impact properties than approach those of tempered martensite. However, in the case of these self-hardening steels, it is practically impossible to obtain a bainite with a structure similar to that of tempered martensite by continuous cooling due to presence of acicular martensite. Self-hardening PM steels which produce the martensitic structure even if the cooling rate is quite low are susceptible to high residual stresses and cracking. With decreasing transformation temperature, there is a greater expansion during the bainitic transformation, and this leads to a higher level of internal stresses at the lower transformation temperatures. Bainitic structures require to be tempered at  $200^\circ\text{C}$  to achieve a combination of

optimum strength and ductility. With respect to the microstructures and mechanical properties of the investigated steels, we found that the investigated steels can be successfully sintering at  $1250^\circ\text{C}$ .

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