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COMPARISON OF MECHANICAL PROPERTIES AND MICROSTRUCTURE OF Cr-Mn-Mo STEELS BASED ON ASTALOY CrL AND ASTALOY CrM PRE-ALLOYED POWDERS

PORÓWNANIE WŁASNOŚCI MECHANICZNYCH ORAZ MIKROSTRUKTURY SPIEKANYCH STALI Cr-Mn-Mo WYKONANYCH NA BAZIE PROSZKÓW STOPOWYCH ASTALOY CrL I ASTALOY CrM

Low carbon ferromanganese and graphite powders were admixed to Höganäs water atomised pre-alloyed Astaloy CrL and Astaloy CrM powders - to produce six variants of Fe-Cr-Mn-Mo-C steels. These were pressed into tensile ISO 2740 and bend 5x10x55 mm specimens at 660 MPa, sintered in semi-closed containers for 1 hour in dry nitrogen or hydrogen at 1120°C or 1250°C and cooled at 65°C/min. Neither detectable densification nor swelling took place, whatever the powder and sintering conditions. The sintered specimens were subsequently tempered at 200°C for 60 and 240 minutes.

Green and sintered densities were expectedly highest for Astaloy CrL base at $\sim 7.1 \text{ gcm}^{-3}$, $> 0.1 \text{ gcm}^{-3}$ larger than for the Astaloy CrM alloy. Sintered samples (as-sintered density was in the range 6.81-7.02 gcm^{-3}) were characterised for microstructure, Vickers microhardness, three-point bending, tensile properties, as well as sintering behaviour in dilatometer.

Recorded mechanical properties were as follows: tensile strength was up to 968 MPa, tensile elongation – up to 4.56%, and impact energy does not exceeded 15.18 Jcm^{-2} . The TRS limit was up to 2034 MPa. Tensile strengths were higher for hydrogen sintering, generally by $\sim 5\%$. Bend tensile strengths were somewhat higher for nitrogen sintering.

The structure of investigated PM steels consisted of mainly bainite and martensite; also retained austenite and regularly arranged pores were observed during light microscopy examination. While properties were variable due to microstructure, results indicate that the material provides new possibilities. These findings, coupled with the superior hardenability of the alloy makes the material a candidate for a number of structural applications and warrants further and continued laboratory investigation.

Keywords: structure, mechanical properties, PM steels, dilatometry

Proszek niskowęglowego żelazomanganu oraz proszek grafitu zmieszano z rozpylanymi wodą proszkami stopowymi Astaloy CrL i Astaloy CrM w celu wykonania sześciu, różniących się składem chemicznym, mieszanek proszków, które następnie poddano prasowaniu pod ciśnieniem 660 MPa, w celu wykonania dwóch rodzajów wyprasek: prostopadłościennych, o wymiarach 5x10x55 mm oraz zgodnych z PN-EN ISO 2740. Sprasowane kształtki spiekano w atmosferze azotu i wodoru w temperaturze 1120°C oraz 1250°C przez okres 60 minut. Po spiekaniu nie uzyskano wzrostu gęstości oraz nie zaobserwowano pęcznienia spieków. Spieczone kształtki poddano następnie odpuszczaniu w temperaturze 200°C w powietrzu w czasie 60 minut.

Największymi gęstościami po prasowaniu i spiekaniu, wynoszącymi około 7,1 g/cm^3 , charakteryzowały się kształtki wykonane na bazie proszku stopowego Astaloy CrL. Wartości te były o około 0,1 g/cm^3 większe od gęstości wyprasek i spieków wykonanych na bazie proszku stopowego Astaloy CrM.

Spiekane stale poddane zostały badaniom metalograficznym oraz przeprowadzone zostały pomiary twardości (metodą Vickersa), wytrzymałości na zginanie trójpunktowe oraz wytrzymałości na rozciąganie. Sprasowane kształtki poddano również badaniom dylatometrycznym kinetyki procesu spiekania.

Uzyskano następujące własności mechaniczne: wytrzymałość na rozciąganie nie przekroczyła 968 MPa, wydłużenie – 4,56 %, a udarność dochodziła do 15,18 J/cm^2 . Maksymalna wartość wytrzymałości na zginanie wynosiła 2034 MPa. Zaobserwowano, że nieco lepszymi własnościami charakteryzowały się spieki wytwarzane w atmosferze azotu.

Badania metalograficzne wykazały, że struktura badanych stali składała się głównie z bainitu i martenzytu; zaobserwowano również austenit szczątkowy oraz pory o regularnych kształtach.

W wyniku prac stwierdzono, że uzyskane, zadowalające własności stali pozwalają na zastosowanie ich jako spiekane materiały konstrukcyjne.

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Abbreviations

A - austenite;	ND – not defined;
A_t – elongation at fracture, %;	NT – not tempered;
B – bainite;	ST – sintering temperature, °C;
d_0 – green density, gcm^{-3} ;	$R_{0.2}$ – 0.2% offset yield strength, MPa;
d_1 – as-sintered density, gcm^{-3} ;	TRS – transverse rupture strength, MPa;
HV ₃₀ surf. – apparent surface hardness;	TTS – ultimate tensile strength, MPa;
M – martensite;	

1. Introduction

The overall objective of this study was to develop nickel-free, high-hardenability “engineered” self-hardening steel that will decrease the operating cooling rate of the sintering furnaces in the range from 100 – 300 Kmin^{-1} (accelerated cooling) to 10 – 60 Kmin^{-1} (conventional cooling). The self-hardening PM steel becomes fully hardened, when they are cooled in sintered furnace from above its critical point and does not require rapid quenching by gas or oil. Such steels attain their martensitic/bainitic structure without going through the variable rate rapid cooling process. In powder metallurgy such steels are referred to as being sinter-hardenable in the conventional continuous belt furnace. Usually, a conventional sintering furnace has to process parts for which it was not chosen to obtain a higher percentage of martensite and bainite conversion, for example for parts having lower alloy content. On the other hand, conventional cooling is the best solution for several types of parts, especially highly alloyed slender high-performance parts, which require very close control during hardening.

An attendant benefit of conventional cooling is that parts do not distort to the extent they would in furnaces equipped with accelerated cooling sinter-hardening system with cooling rates of 300 Ks^{-1} , or the risk of distortion is greatly reduced. Additions of nickel, chromium, molybdenum and manganese are effective toward this end. However, nickel is recognised as a significant threat to both the environment and public health [1]. Pending legislation could result in the banning of nickel from a wide variety of products, including also PM steels. Therefore, the initial emphasis was on studying the properties and characteristics of Mn, Cr and Mo containing alloys because they are most likely to form the basis of self-hardening steels [2-10]. Alloying steel with 3%Mn, 1.5-3%Cr, 0.2-0.5%Mo and 0.3-0.8%C, that is hardened through conventional (slow) cooling to reduce possible deformation, is believed to be the reason for improved properties of parts processed in a conventional furnace with this feature compared with those observed in earlier commercial alloys.

2. Experimental procedure

Two Fe-Cr-Mo pre-alloyed Höganäs iron powders, Astaloy CrL and Astaloy CrM, have been used in the reported investigations. Table 1 summarises the mixes made for the six Mn-Cr-Mo steels. The manganese was added in the form of low-carbon ferromanganese powder produced by mechanical milling. Höganäs C-UF graphite was used as respective elemental carbon addition. The powders were mixed in Turbula mixer (30 min, 60 rpm). No lubricant was added to the powder before mixing. Two types of compacts were pressed: 55x10x5mm test bars and ISO 2740 “dogbone” standard tensile test specimens. Sintering was carried out in a horizontal laboratory furnace with water-jacketed rapid cooling zone for 60 minutes at 1120°C and 1250°C in pure hydrogen and nitrogen atmospheres (dew point -60°C). The average cooling rate 65 °Cmin⁻¹ over the range of 1250°C to 200°C was obtained. Specimens were tempered at 200°C for 60 and 240 minutes, where applicable.

Additional investigations were carried out on the investigated Mn-Cr-Mo steel and comprised dilatometric tests on sintered specimens held isothermally at various temperatures and subsequently cooled at 20 Kmin^{-1} . The sintered specimens were tested to determine dimensional behaviour, baseline mechanical properties, and microstructure. Dimensional changes in length, also tensile (UTS), yield ($R_{0.2}$), and transverse rupture strengths, as well as tensile elongation (A_t) were measured. Transverse rupture strength (TRS) were measured on ISO 2740 (TRS 1) and rectangular specimens (TRS 2). Table 1 presents green and as-sintered densities of the investigated materials.

TABLE 1

Green (d_0) and as-sintered (d_1) densities of the investigated compacts – mean values and standard deviation

Chemical composition	d_0, gcm^{-3}		d_1, gcm^{-3}	
	ISO	rectangular	ISO	rectangular
3Mn + Astaloy CrL + 0.3C	6,83±0.01	7.02±0.03	6.86±0.02	7.02±0.08
3Mn + Astaloy CrL + 0.6C	6.80±0.01	6.74±0.05	6.81±0.01	6.78±0.05
3Mn + Astaloy CrL + 0.8C	6.72±0.06	6.63±0.13	6.73±0.07	6.86±0.04
3Mn + Astaloy CrM + 0.3C	6.76±0.04	6.92±0.02	6.82±0.04	6.92±0.07
3Mn + Astaloy CrM + 0.6C	6.73±0.03	6.82±0.05	6.75±0.04	6.81±0.07
3Mn + Astaloy CrM + 0.8C	6.72±0.05	6.85±0.03	6.72±0.05	6.86±0.05

3. Results and discussion

3.1. Dilatometric tests

During the tests specimens were observed to expand below B_s and M_s as a result of transformation during cooling at 20 Kmin^{-1} . Uninterrupted cooling produced a mixture of bainite and martensite particles. Bainite transformation began at about $450^\circ\text{C} - 500^\circ\text{C}$ and con-

tinued during cooling, what was presented in Figure 1 and Table 1.

Martensitic transformation not always was complete at before interruption of the dilatometric test. If we had specimens sintered in dilatometer and cooled at 20 Kmin^{-1} , bainitic/martensitic transformation would be occurred during this cooling and given a structure like shown in Figures 2-5.

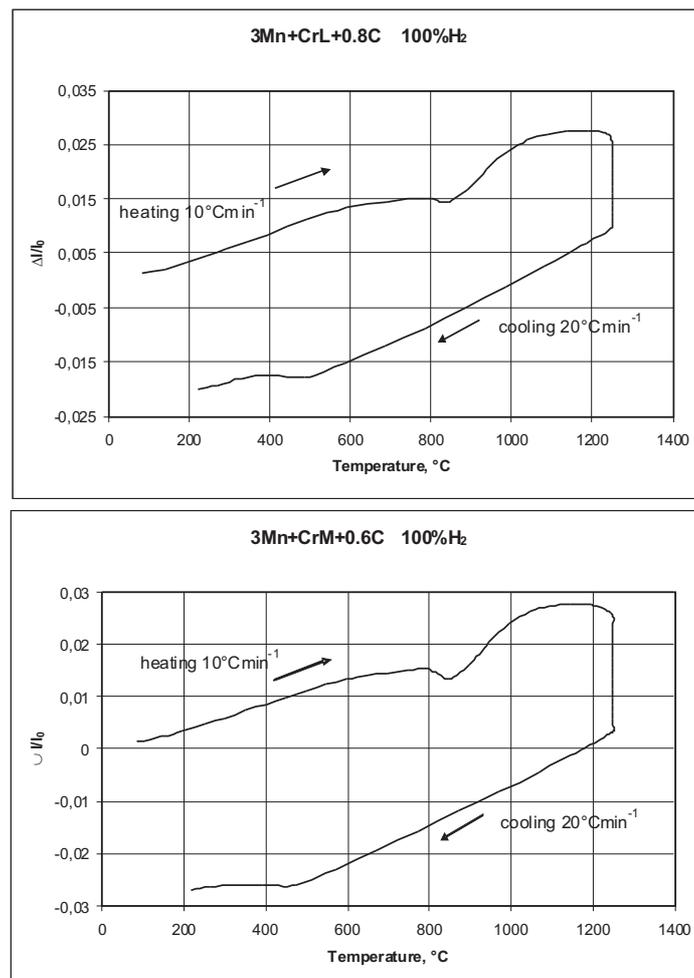


Fig. 1. Effects of heating, isothermal sintering at 1250°C and uninterrupted cooling on dilatometric curves

3.2. Mechanical properties

Transformation characteristics and mechanical properties of investigated steels are summarised in the Tables 2-4. The mechanical properties of six steels listed in Table 1 were determined systematically. The first three steels were of the CrL type, while the fourth, fifth and

sixth were the CrM type, both with 3%Mn additions. Compared with the data recorded for the 3%Mn+CrL specimens, the 3%Mn+CrM data showed slightly higher tensile and bend strengths. Also, the yield strength, determined for the 3%Mn+CrM steels, was higher than that of the 3%Mn+CrL alloys, reflecting higher chromium content values.

Continuous cooling transformation temperatures established by dilatometric analysis

TABLE 2

ST, °C	Carbon content, %	3%Mn + CrL	3%Mn + CrM
	F _s ; P _s ; B _s transformation temperature, °C		
1120	0.3	F _s ; P _s = 850; 650	B _s ~500
	0.6	B _s ~500	M _s <200
	0.8	B _s ~450	M _s <200
1250	0.3	F _s ; P _s = 800;700	B _s ~500
	0.6	B _s ~500	B _s ~500
	0.8	B _s ~450	B _s ~450

TRS showed higher values than UTS. It is well-recognised that the value of transverse rupture strength can exceed that of ultimate tensile strength of the same PM material, identically processed, by a factor up to ~2, although both these parameters relate to the tensile stress causing fracture. The analysis first takes account of the pre-failure plastic strain, which enables conversion of the nominal strengths, UTS and TRS, to true fracture stresses [8]. Note is then taken of the different volume and area and the stress distribution in a specimen undergoing bending, in contrast to the uniformly stressed tensile specimen gauge length. The TRS test was originally developed for use on PM high-speed steels, for which it provides very accurate measurements of tensile properties. This experiment established that the TRS test was also capable of determining tensile properties of PM structural steels with reasonable accuracy. The TRS test requires a flat surface for accurate measurements, so flat ISO 2740 specimens were used. Overall there was good agreement between the UTS and TRS data sets.

Tensile and three point bending testing was used to determine alloy strength and ductility properties of steel, but there is concern that testing of standard ISO 2740 specimens may not provide an accurate indication of actual sintered part performance. Part of the basis for this concern is that the thermal processing conditions experienced during laboratory experiments may not be accurately reproduced in industrially produced parts. This means that the mass transport conditions that occur in the laboratory specimens and that will influence their properties are unlikely to be reflected in industrial furnace. Impact strengths in the as-sintered and tempered

condition were more dependent upon the sintering temperature than are the tensile properties.

4. Microstructure and correlation between microstructure and mechanical properties

Images of the microstructures after cooling rate 65 °Cmin⁻¹, taken in an optical microscope, are shown in Figures 2-5. All the structures obtained are similar to those described previously for Mn steels [4]. In any case, all the steels present some analogies. Generally speaking, the various types of microstructure have been observed in various proportions in all the steels examined. The as-sintered structure consisted of bainite and austenitic/martensitic particles. Optical micrographs in Figs. 2-5 show also complex structures composed of bainite surrounding a large number of small, substantially unaligned austenitic/martensitic areas, which are partially decomposed to carbide and ferrite. Austenite grain boundaries are visible. The structure is coarser after sintering at 1250°C. In both cases, the austenite regions are typical when they are observed at very high magnification; the grains are relatively small.

The size of the bainite grains in specimens sintered at 1120°C is smaller than that obtained after sintering at 1250°C. The unrecompensed austenite particles are also smaller but more numerous and very irregular in shape. The difference between the structures obtained by cooling in the same rates after sintering at 1120°C and after sintering at 1250°C could account for the observed difference in mechanical properties. Alloying elements play an appreciable role in determining the mor-

phology of these structures. Thus, the high-manganese and the high-chromium regions in 3%Mn+CrM steel usually exhibit structures comprising long coarse plates with these transformed regions extending across prior austenite grains. On the other hand, the structure is less acicular in the 3%Mn+CrL steel and grows along the grain boundaries. This difference is far from negligible and some of its features have already been discussed. The structural morphology differs considerably in these alloys. As with structure of 3%Mn+CrL+0.8%C steel, the 3%Mn+CrM+0.8%C steel structure corresponded to a mixture of bainite, martensite, and pearlite with the appearance of the latter resembling troostite. However, some austenitic islands can be already observed. The CrL branch again corresponds to massive granular bainite. The formation of this structure is followed easily since it occurs over a wide range of cooling rates. At the lower end of the range, the structures consist of quasi-granular bainite where the austenitic/martensitic islands are often decomposed and give rise to carbide clusters. In principle, the mechanical properties of the investigated steels can be accounted for in terms of the structures observed under the microscope. The investigations, however, have shown that a complete solution of this correlation problem requires quantitative

data and describing the microstructures by parameters. In the steels considered in the present paper, however, the problem is complicated by the occurrence of certain bainitic structures consisting of ferrite and carbides and austenitic/martensitic areas.

The comparative study of mechanical properties as a function of microstructure has revealed the existence of a qualitative correlation in all the steels investigated. In view of the fact that numerous factors such as the intrinsic properties of each phase, their arrangement with respect to each other, the boundary effect etc. are involved, it appears difficult to evaluate at present time the relative importance of each of these factors.

The problem of quantitatively correlating properties with microstructure is complex even in the case of relatively simple structures such as those consisting of a finely dispersed phase inside a homogeneous matrix. In the case of inhomogeneous PM steel structures identified in the present work, the problem is considerably complicated by the fact that four constituents are often present simultaneously: bainite, cementite, martensite and austenite. This is the reason why we shall restrict ourselves in the present discussion to some general remarks regarding a possible correlation.

Mechanical properties of CrL-based sintered steels

3%Mn+CrL+0.3%C											
Sintering			Cooling °C min ⁻¹	Tempering		UTS, MPa	A _t , %	R _{0.2} , MPa	TRS 1, MPa	TRS 2, MPa	Impact, J cm ⁻²
°C	Atm.	min.		°C	min.						
1120	H ₂	60	65	0	0	569	1.02	ND	982	1171	6.04
				200	60	566	0.80	481	966	1216	3.37
					240	640	0.55	553	1045	1163	5.15
	N ₂			NT	0	513	0.78	450	911	765	4.26
				200	60	556	0.82	481	995	1191	3.40
					240	559	0.80	508	962	1082	3.39
1250	H ₂	60	65	NT	0	580	1.08	410	1351	1354	13.97
				200	60	608	1.16	474	1279	1613	15.18
					240	638	1.23	543	1301	1412	14.06
	N ₂			NT	0	827	2.19	554	1682	1428	10.35
				200	60	832	1.98	554	1325	1702	15.25
					240	817	1.68	596	1237	1469	5.78
3%Mn+CrL+0.6%C											
1120	H ₂	60	65	NT	0	468	1.50	420	1059	912	2.81
				200	60	514	1.51	473	738	1062	3.49
					240	576	1.56	484	1214	1057	3.30
	N ₂			NT	0	392	1.05	347	765	634	1.92
				200	60	544	1.50	539	1270	836	2.64
					240	476	1.19	442	909	754	2.99
1250	H ₂	60	65	NT	0	611	1.98	489	1292	1154	5.49
				200	60	729	2.68	547	1516	1380	7.26
					240	852	3.46	566	1579	1461	7.95
	N ₂			NT	0	607	1.83	476	1264	1490	7.24
				200	60	728	2.31	481	1503	1420	4.27
					240	679	1.89	497	1269	1119	3.72
3%Mn+CrL+0.8%C											
1120	H ₂	60	65	NT	0	318	0.65	ND	742	754	2.12
				200	60	474	1.53	440	989	1100	3.79
					240	473	1.29	ND	1080	1121	3.17
	N ₂			NT	0	434	1.20	ND	482	601	1.75
				200	60	431	1.18	474	950	924	3.34
					240	392	0.90	311	979	904	2.73
1250	H ₂	60	65	NT	0	647	2.73	552	1186	1231	6.76
				200	60	704	3.29	583	1435	1316	8.25
					240	600	2.33	546	1360	1177	7.62
	N ₂			NT	0	363	1.01	329	674	845	2.67
				200	60	684	2.58	432	1335	1178	5.24
					240	674	2.54	4347	1209	1145	3.67

TABLE 4

Mechanical properties of CrM-based sintered steels

3%Mn+CrM+0.3%C											
Sintering			Cooling °C min ⁻¹	Tempering		UTS, MPa	A _t , %	R _{0.2} , MPa	TRS 1, MPa	TRS 2, MPa	Impact, J cm ⁻²
°C	Atm.	min.		°C	min.						
1120	H ₂	60	65	NT	0	300	0.20	ND	1177	1041	4.59
					200	60	462	0.58	357	797	1195
				240		700	1.06	635	1076	1096	5.47
	N ₂			NT	0	604	1.93	492	1076	399	2.47
					200	60	716	2.53	535	1335	855
				240		715	2.49	587	1014	1131	4.07
1250	H ₂	60	65	NT	0	866	2.35	563	1851	1349	7.85
					200	60	818	1.80	594	1492	1543
				240		819	1.70	598	1629	1463	5.82
	N ₂			NT	0	806	1.70	583	1463	1675	14.07
					200	60	957	2.75	562	1932	1658
				240		971	2.84	584	2135	1527	7.98
3%Mn+CrM+0.6%C											
1120	H ₂	60	65	NT	0	446	1.27	422	689	464	2.23
					200	60	580	1.83	435	886	953
				240		576	1.69	471	1097	1104	5.26
	N ₂			NT	0	321	0.83	273	1366	609	2.28
					200	60	481	1.37	412	855	836
				240		415	1.05	385	1039	776	3.87
1250	H ₂	60	65	NT	0	550	1.73	458	1593	1023	6.92
					200	60	968	4.37	603	1734	1566
				240		818	2.95	613	1835	1498	7.89
	N ₂			NT	0	592	1.90	495	705	1284	4.57
					200	60	925	4.00	548	2034	1363
				240		801	2.83	604	1209	1270	6.52
3%Mn+CrM+0.8%C											
1120	H ₂	60	65	NT	0	302	0.89	ND	571	653	2.61
					200	60	431	1.36	405	956	791
				240		457	1.50	437	1033	871	4.32
	N ₂			NT	0	215	0.65	ND	502	633	2.81
					200	60	389	1.31	360	929	910
				240		384	1.30	341	848	895	5.72
1250	H ₂	60	65	NT	0	726	3.08	472	1372	1014	4.94
					200	60	887	4.56	536	1644	1305
				240		619	2.21	503	1113	1704	10.11
	N ₂			NT	0	324	0.82	ND	956	730	5.35
					200	60	671	2.58	517	1303	1274
				240		589	2.01	521	1155	1129	6.05

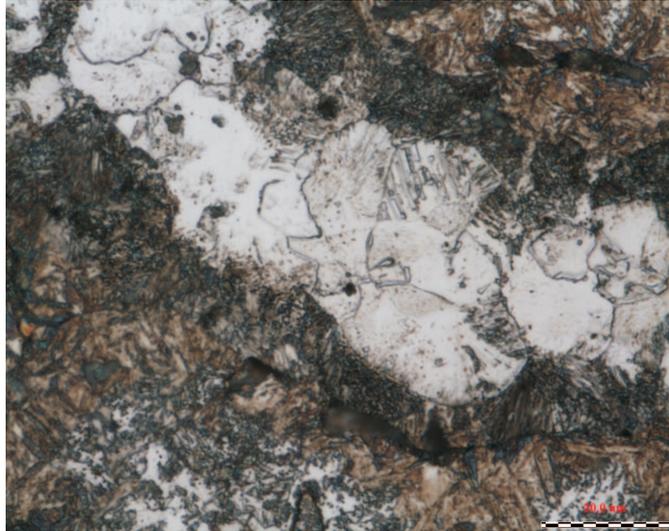


Fig. 2. Microstructure of 3%Mn+CrL+0.3%C steel; ST=1120°C, 100%N₂; A+B, island of retained austenite



Fig. 3. Microstructure of 3%Mn+CrL+0.3%C steel; ST=1250°C, 100%N₂; M, B, A

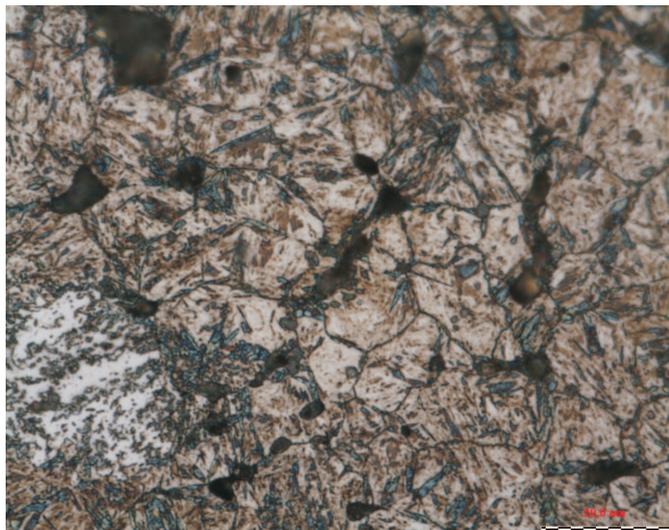


Fig. 4. Microstructure of 3%Mn+CrM+0.3%C steel; ST=1120°C, 100%N₂; A+M+B, mostly bainite



Fig. 5. Microstructure of 3%Mn+CrM+0.3%C steel; ST=1250°C, 100%N₂; B, M, pores

5. Summary

Selected mechanical properties of the Mn-Cr-Mo PM steels have been measured. Statistically significant variations in properties due to differences in starting materials have been observed in these measurements. These observations are largely explained by the microstructure of the alloys. The differences are attributable to segregation of carbide clusters.

Tempering can be used to enhance the mechanical properties of the investigated steels. The differences in mechanical properties between as-sinter and tempered specimens were assessed. It was found that for both Astaloy CrL and CrM powder based steels, tempering substantially improves the strength and slightly increases the elongation. For all the materials, the fracture strengths were found to be increasing with increasing tempering time. Results indicate that 0.3%C specimens exhibit greater fracture strength and impact strength than 0.6%C and 0.8%C specimens irrespective of sintering temperature and atmosphere. A comparison of mechanical properties with other carbon contents was beyond the scope of this paper and thus was made not here. Further improvements in the properties of the steels are obtained by increasing the sintering temperature. The results show enhanced mechanical properties at higher sintering temperature for all powder mixtures containing 0.3%, 0.6% and 0.8% by weight of carbon.

The laboratory experiments described above suggest that if a problem of brittle fracture exists, then low carbon content, when used with tempering, could improve the situation. Such a combination appears to offer the possibility of achieving higher strength. Conversely, any increase in carbon content above 0.3% may increase the occurrence of brittle fracture. An excellent

combination of strength and elongation was obtained in the 3%Mn+CrM+0.3%C steel sintered in nitrogen atmosphere.

This type of steel grade is a strong candidate for use in PM structural components due to a good balance between strength and ductility and good energy-absorption capacity.

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