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The Application of Sintered Steel Containing 2.5%Mn and 0.8%C

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Abstract
The study was an investigation whether sintered Fe-2.5%Mn-0.8%C steel is suitable for production of gears. Base powders, iron grade Höganäs NC 100. 24, low carbon ferromanganese (77%Mn, 23%Fe and 1.3%C) and graphite C-UF, were mixed in a Turbula TC2 mixer. Subsequently the mixture was sent to the Bulgarian company Sinter-M, Jambol, where a pilot set of gears was made in industrial conditions. Some green compacts were laboratory sintered at AGH, Krakow, at 1120°C and 1250°C for 60 minutes in the mixture of 95%N_2-5%H_2 (different from an industrial atmosphere) and sinterhardened (rapidly cooled from the sintering temperature with cooling rate~ 1K/s). A set was sintered in Jambol at 1150°C for 60 minutes in an industrial furnace in an atmosphere of 70%N_2-30%H_2. These are the gear sintering conditions for their currently used steel, Fe-1.75% Ni-1.50% Cu-0.50% Mo-0.6%C, from base powders Distaloy AB, iron powder ASC 100.29 and graphite. Measurements were made of density and tooth resistance to bending, and metallographic and fractographic observations made of gears, both sintered in Bulgaria and in Krakow. The highest tooth resistance to bending was for Mn steel gears, ~1260 MPa, laboratory sintered at 1250°C or industrially sintered at 1150°C, which was about 100MPa less when sintered at 1120°C, still ~100MPa above the performance of Fe-1.75% Ni-1.50% Cu-0.50% Mo-0.6%C.

Keywords: sintered gears, PM steels, manganese

1. Introduction

In recent years, to make material production process as economic and ecological as possible, an increase in the use of the powder metallurgy route has been observed [1]. In steels, nickel, copper and molybdenum are often used as alloying additions; elements which are expensive (especially nickel and molybdenum) [2, 3]. Furthermore, nickel is carcinogenic, especially in strongly dispersed form [4]. For this reason, there are ongoing attempts to substitute nickel with manganese. The properties of Mn PM steels are comparable to those of Ni steels; additionally, Mn is cheap and harmless to health. However, to date, sintered Mn steels are not used on large scale in industry. The main problem is associated with its high affinity for oxygen, causing the formation of oxides during sintering and resulting in deterioration of material properties. Previous studies have shown, however, that at a content of 2.5% Mn and 0.8% C it is possible to obtain sintered steel with both high strength and plastic properties (YS = 623MPa, UTS = 754MPa, TRS = 1187MPa, A = 3.44%) [5]. For comparison, sintered steels currently used together with their properties are presented in Table 1.

Table 1. Mechanical properties of Fe-2.5/3%Mn-0.8%C with those of the most demanding PM steels of MPIF Standard 35 [6]: FC-0208-60, FC-0508-60, FN-0408-55 and FLN-4205-55 with yield strengths above 400MPa

Steel designation/description		Chemical composition%, balance Fe					Mechanical properties						
		C	Ni	Cu	Mo	Mn	density, [g/cm^3]	0.2% offset yield stress [MPa]	UTS [MPa]	A [%]	TRS [MPa]	Hardness	Ref.
Fe-Cu	FC-0208-60	0.6÷0.9	-	1.5÷3.9	-	-	7.2	450	520	<1	1070	84 HRB	6
Fe-Cu	FC-0508-60	0.6÷0.9	-	4÷6	-	-	6.8	480	570	<1	1000	80 HRB	6
Fe-Ni	FN-0408-55	0.6÷0.9	3÷5	0÷2	-	-	7.2	410	550	1	1030	87 HRB	6
Hybrid	FLN-4205-55	0.4÷0.7	1.3÷2.5	-	0.49÷0.85	0.2÷0.4	7.3	430	600	2	1210	83 HRB	6
2Mn	Sinterhardened 1250°C	0.8	-	-	-	2	6.6	430	710	4.2	1200	429 HV	7
3Mn	Sinterhardened 1120°C	0.8	-	-	-	3	6.6	600	730	3.4	1234	345 HV	7
3Mn	Sinterhardened 1250°C	0.8	-	-	-	3	6.6	530	630	3.0	1110	390 HV	7
3Mn	Sintered 1120°C	0.8	-	-	-	3	6.9	410	500	1	1230	183 HV	8
3Mn	Sinterhardened 1120°C + tempered	0.8	-	-	-	3	7.0	410	740	2.3	1740	250 HV	8
3Mn	Sintered 1250°C	0.8	-	-	-	3	7.0	480	610	1.2	1310	189 HV	8
3Mn	Sintered 1250°C + tempered	0.6÷0.7	-	-	-	3	6.9	450	730	1.6	N/D	N/D	9
3Mn	Sinterhardened 1250°C	0.8	-	-	-	3	7.0	460	480	1.5	1060	210 HV	8
3Mn	Sinterhardened 1250°C + tempered	0.8	-	-	-	3	6.7	470	830	3.7	1480	247 HV	8
2.5Mn	Sinterhardened 1120°C	0.8	-	-	-	2.5	6.5	500	670	3.3	1000	287 HV	5
2.5Mn	Sinterhardened 1250°C	0.8	-	-	-	2.5	6.5	620	750	3.7	1190	270 HV	5

Table 2. Mechanical properties of sintered Fe-(1-3)%Mn-0.8%C steels – mean values and corrected standard deviations

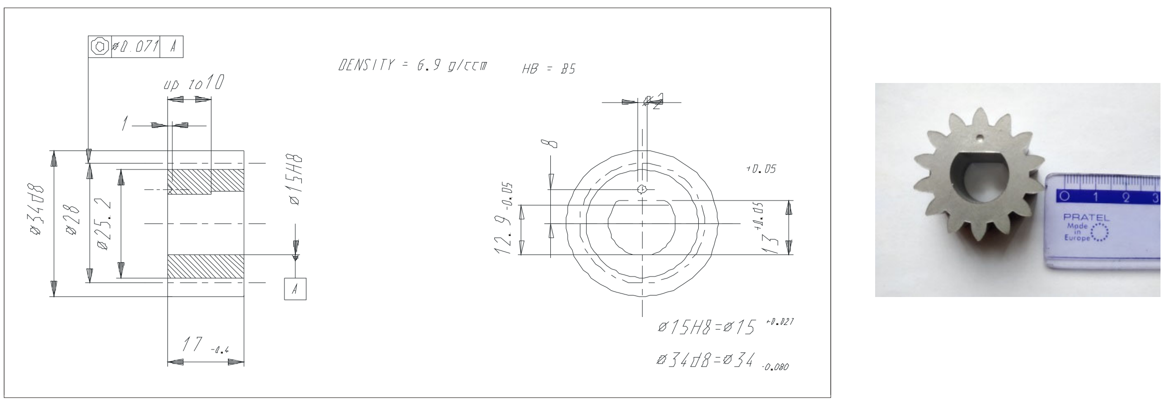
Chemical composition	Sintering variant*	0.2% offset yield stress [MPa]	UTS [MPa]	TRS [MPa]	A [%]	HV 0.05 (cross-section)
Fe-1%Mn-0.8%C[16]	1120°C/SH	285±23	511±22	888±85	4.36±0.5	240±54
	1250°C/SH	297±45	587±32	1070±95	5.80±0.54	241±43
Fe-1.5%Mn-0.8%C	1120°C/SH	371±43	580±55	1005±115	4.13±0.73	250±21
	1250°C/SH	370±25	632±39	1132±84	4.92±0.54	226±11
Fe-2%Mn-0.8%C[16]	1120°C/SH	367±22	611±22	997±85	3.73±0.54	310±66
	1250°C/SH	429±31	713±53	1200±88	4.23±0.60	429±55
Fe-2.5%Mn-0.8%C	1120°C/SH	501±44	671±31	997±120	3.34±0.33	287± 53
	1250°C/SH	623±75	754±61	1187±110	3.66±0.43	270± 36
Fe-3%Mn-0.8%C[16]	1120°C/SH	529±29	626±81	1112±108	2.95±0.30	390±131
	1250°C/SH	602±42	727±48	1234±130	3.35±0.35	343±87

*Batch size – 15 samples, SH – sinterhardened

2. Experiments

5 compositions: Fe-X%Mn-0.8%C (where X= 1, 1.5, 2, 2.5, 3). were mixed for 30min. in a Turbula TC2 mixer. Green compacts according to PN-EN ISO 2740 standard were pressed on a hydraulic press at 660 MPa using zinc stearate as a lubricant for punches. Sintering of compacts was carried out in the atmosphere of 95%N_2-5%H_2 for 60 minutes at 1120°C or 1250°C in a laboratory furnace. The specimens were sinterhardened by fast cooling with a cooling rate ~1K/sec from the sintering temperature. Then they were mechanically (tensile, bending, hardness), metalographically and fractographically tested. The results are presented in Table 2 [5], and on this basis the steel with the composition of Fe-2.5% Mn-0.8%C was selected for further tests.

The powder mix of Fe-2.5%Mn-0.8%C was sent to the Bulgarian Sinter-M Jambol company for pressing of a pilot set of gears under industrial conditions on a JOSHIZUKA hydraulic press at 700 MPa. The dimensions and photograph of the gear are presented in Fig. 1 and Table 3. Then, before sintering, the compacts were kept at 700°C in burning zinc stearate zone for 40 minutes. The next step was sintering at 1150°C for 60 minutes in an industrial furnace in an atmosphere of 70%N_2-30%H_2.



a) b)

Fig. 1. Ritzel gear; a) technical drawing, b) sintered gear

Table 3. Design parameters of the industrially produced gears

Item	Symbol	Ritzel gear
Outside diameter [mm]	d_k	34.0
Standard pitch diameter ($z \cdot m_n$) [mm]	d_0	28.0
Root diameter (d_0-2.5m_n) [mm]	d_r	25.0
Base diameter ($d_0 \cos\alpha_0$)	D_b	26.31
Teeth number	Z	14
Module [mm]	m_n	2
Standard pressure (profile angle) [°]	α_0	20
Addendum modification coefficient	x	+0.5
Addendum (1.00m_n) [mm]	h_a	2
Dedentum (1.25m_n) [mm]	h_d	2.5
Blank width [mm]	b	17.0

A set of the green gear compacts of gears was sent to AGH, Poland. These gears were sintered in a laboratory furnace at 1120°C or 1250°C, for 60 minutes in protective atmosphere containing 95%N_2-5%H_2. A further set to be tested for comparison purposes sent from the Sinter-M company were Fe-1.75%Ni-1.50%Cu-0.50%Mo-0.6%C sintered gears made of powder mixtures currently used there. The mix was based on pre-alloyed iron powder Distaloy AB, pure iron powder ASC 100.29 and graphite powder.
All the sets of sintered gears, with production data summarised in Table 4, were investigated at AGH-UST, Krakow, Poland for density (in all cases approx. 6.9 g/cm^3), tooth bending resistance, microstructure (by SEM and LM) and fractography. Tooth resistance to bending test was carried out on a WDW-Y300D machine (Zhongke Innovation Technology – China) equipped with a special holder for bending the teeth. Metallographic observations were carried out on 3% Nital-etched cross-sections on the lateral surface of the tooth.

Table 4. Conditions of production of the gears

Wheel description	Chemical composition	Sintering temperature	Sintering atmosphere
1120_I	Fe-2.5%Mn-0.8%C	1120°C	95%N_2-5%H_2
1120_II			
1250_I		1250°C	
1250_II			
1150_I		1150°C	70%N_2-30%H_2
1150_II			
BG_I	Fe-1.75%Ni-1.5%Cu-0.5%Mo-0.6%C	1150°C	
BG_II			

3. Results

Tooth bending strength was calculated from the formula (1) [9].

$$R_{gz} = \frac{Y_{FS} * K_n * \cos \propto * F}{m * a} \quad (1)$$

where: R_{gz} is maximal static tooth root stress (bending stress) at the critical tooth profile, Y_{FS} is the tooth profile factor, a is blank width (facewidth), in mm, and m is the normal (nominal) module of the gear, in mm. Two specimens were randomly chosen for testing from each batch of sintered gears. Because of the construction of the bending holder, 7 teeth were broken from each wheel. The results of tooth resistance to bending are presented in Table 5 and in Fig. 2.

Table 5. Tooth resistance to bending

Wheel description	Tooth 1 [MPa]	Tooth 2 [MPa]	Tooth 3 [MPa]	Tooth 4 [MPa]	Tooth 5 [MPa]	Tooth 6 [MPa]	Tooth 7 [MPa]	Average with standard deviation [MPa]
1120_I	1038	1140	1084	1102	1071	1210	-	1107±55
1120_II	1137	1137	1119	1117	1129	1139	1121	1128±9
1250_I	1216	1280	1195	1288	1144	1340	1355	1260±72
1250_II	999	1000	1012	1255	1307	1322	1273	1167±143
1150_I	1296	1276	1233	1216	1237	1213	1306	1255±33
1150_II	1267	1267	1350	1233	1253	1209	1223	1249±46
BG_I	992	1047	1006	1010	969	1060	1092	1033±43
BG_II	1054	1054	976	976	1023	1085	1127	1060±48

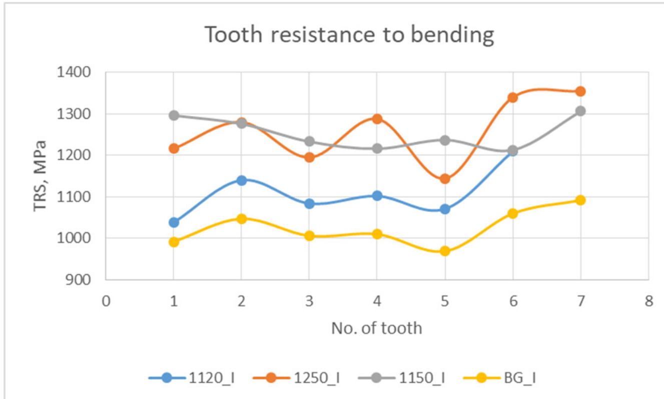


Fig. 2. Tooth resistance to bending

It appears that the lowest performance was for Fe-1.75%Ni-1.50%Cu-0.50%Mo-0.6%C gears industrially sintered at 1150°C, with the average bending strength even about 200MPa lower than for gears with composition of Fe-2.5%Mn-0.8%C, laboratory sintered at 1250°C (1260 MPa) or industrially sintered at 1150°C. Laboratory sintering at 1120°C resulted in intermediate performance.

Metallographic and fractographic observations are presented in Fig. 3. The microstructure of Fe-2.5%Mn-0.8%C gears, sintered at 1250°C in atmosphere 95%N_2-5%H_2 and at 1150°C in 70% N_2-30% H_2 was characterized by a majority of bainitic areas with some fine pearlite and martensite (in the case of sintering at 1250°C). In the case of sintering at 1120°C, the structure was more pearlitic-bainitic. Fe-1.75%Ni-1.5%Cu-0.5%Mo-0.6%C gears were characterized by a heterogeneous structure of pearlite, ferrite and bainite. Fractographic observations indicated the in the Mn steel ductile fracture was predominant, evidenced by the numerous clusters of plastically deformed pits, and there were also cleavage facets. In Fe-1.75%Ni-1.5%Cu-0.5%Mo-0.6%C gears fractography was characterized by poor bonding and shallow dimples, often contaminated inside.

4. Discussion

Higher strength properties in Fe-2.5%Mn-0.8%C gears are attributed to their bainitic-pearlite structure and the creation of stronger bonding in the material. It resulted usually in local ductile fracture (especially for gears sintered at 1120°C). There were also areas of brittle intergranular fracture, which is perhaps related to occurrence of martensite. It is important to note that the gears sintered at 1250°C in the atmosphere 95%N_2-5%H_2 were characterized by a similar microstructure and properties as gears sintered at a lower temperature – 1150°C, but in the atmosphere 70%N_2-30%H_2. From an economic point of view, this is a valuable consideration, because using a lower sintering temperature would result in reduction in production costs. Another economic aspect is the price of powders. In the case of powders, the material costs using pre-alloyed powders are about twice as large as could be when using a mixture with Fe-2.5% Mn-0.8% C.

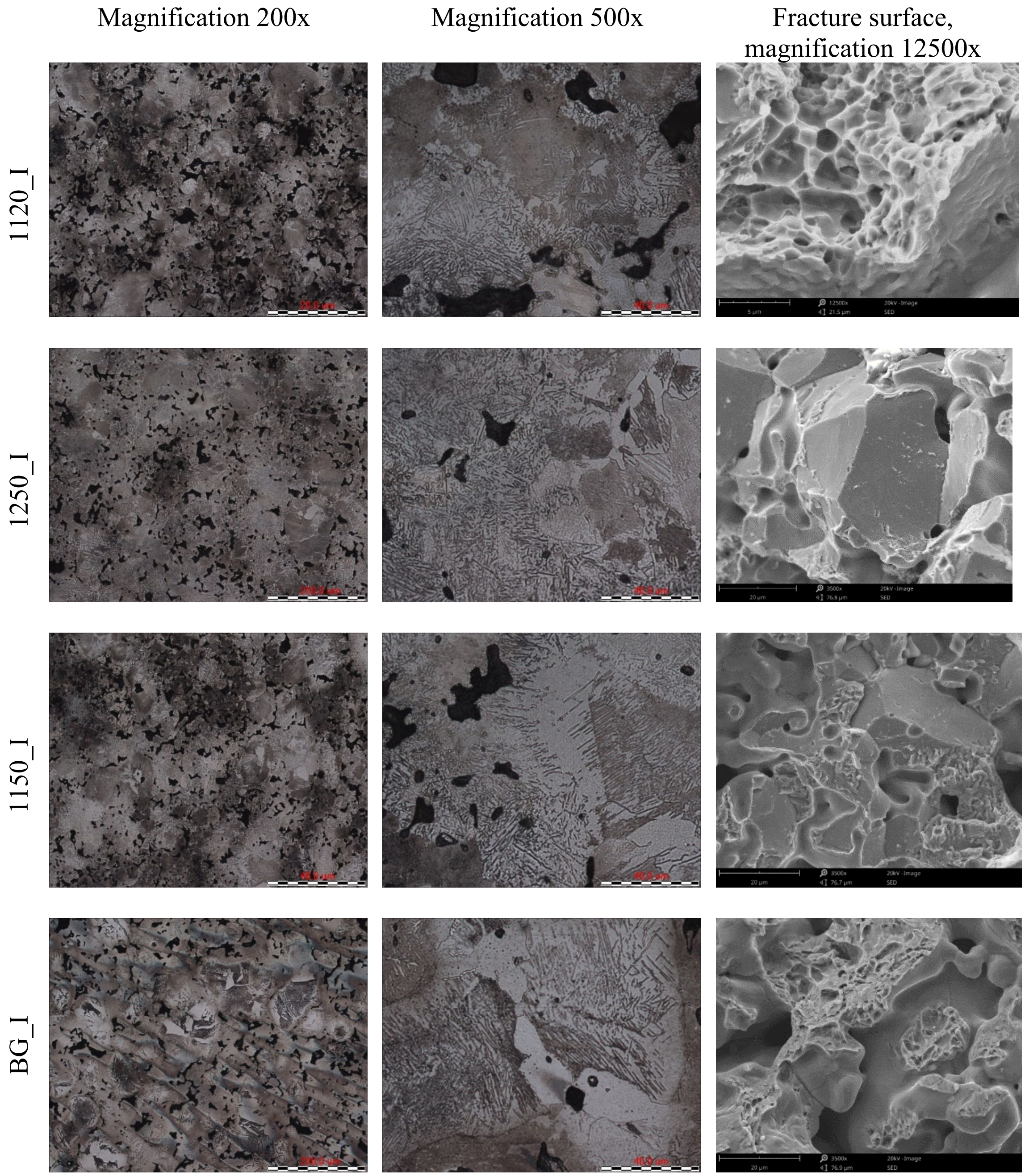


Fig. 3. Metallographic observations of sintered gears

5. Conclusions

- The preliminary results on gears now presented indicate that sintered steel Fe-2.5%Mn-0.8%C is a serious candidate for use in industry;
- Similar properties and bainitic-pearlitic microstructure were obtained after sintering at 1250°C in the atmosphere 95%N_2-5%H_2 and at 1150°C in an atmosphere 70%N_2-30%H_2. This has economic implications.

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