

THE INFLUENCE OF ADMIXED INORGANIC ADDITIVES ON PROPERTIES AND MACHINABILITY OF SINTERED PLAIN IRON AND STEELS

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Dedicated to Dr. Andrej Šalak at the occasion of his 80th birthday.

Abstract

For enhancing the machinability of sintered ferrous materials, the addition of fine particles, generally claimed to be solid lubricants, is a common measure. In this work, the effect of admixed inorganic additives to PM plain iron and steels on the properties and the machinability in turning was studied, taking in the quality of the turned surface as criterion. Various sulfides, as well as lead, hBN, and graphite were admixed as powders to standard PM iron powder grades, compacted, and sintered. It showed that most of the sulfides decompose during sintering, after cooling leaving a eutectic structure of iron sulfide $Fe_{1-x}S$ at the interparticle boundaries. MnS remains stable during sintering, as does BN, at least in a N_2 -containing atmosphere, decomposing in a N_2 -free environment at higher temperatures. The mechanical properties are not very much affected by the sulfides while graphite and hBN are rather detrimental. The same holds for the finish of the turned surface; surprisingly, the decomposed sulfides also resulted in satisfactory surface quality, in part even better than a MnS addition. This indicates that also the $Fe_{1-x}S$ enhances machinability, although it is not generally recognized as a solid lubricant. In any case, dry sliding tests of sintered specimens do not yield useful results for assessing the solid lubricity of machining aids.

Keywords: sintered steel, additives, machinability, turning, sulfides

INTRODUCTION

For powder metallurgy precision parts, net shape manufacturing is a primary advantage compared to e.g. machining from wrought steel stock. However, also for PM parts, machining is frequently necessary, since there are geometrical features that cannot – or at least not economically – be moulded by uniaxial die compaction [1-3]. This holds e.g. for undercuts, crossholes, threads, etc. Compared to machining of wrought steels, sintered steels are significantly more difficult to machine, this being attributed primarily to the inherent porosity, although also the microstructural heterogeneity of many sintered steels must be considered [4]. Furthermore, many PM steels are rather soft, or contain soft areas, thus tending to form built-up edges during cutting.

A common measure to improve machinability is the addition of machining aids, which are mostly claimed to be solid lubricants. For free-machining wrought steel grades, formerly Pb was used which formed small droplets in the steel matrix. Today, mostly sulfurized steels are employed that form MnS inclusions during solidification and cooling

[5]. Also for sintered steels, an addition of MnS is the most common measure, although also other lubricants have been tested and are, in part, also employed in practice [6,7]. It is generally assumed that the additives coat the cutting edges with a thin layer that prevents the formation of built-up edges, in addition to the chip-breaking capability [5]. Some solid-lubrication should therefore be afforded by the additives.

There is a large variety of solid materials with lubricating properties, this behaviour being mostly linked to a layered crystal structure. This can be found e.g. with graphite, MoS₂, and hBN, while MnS is not a solid lubricant according to these criteria. So far, addition of these compounds has been described in the literature. One basic problem however with the addition of lubricants to the starting powder is chemical reaction with the matrix during sintering, in part also with the atmosphere [8].

Within this work, the behaviour of admixed additives during sintering and their effect on dimensional and mechanical properties as well on the machinability in turning was studied for sintered plain iron and also in part for sintered carbon steel.

EXPERIMENTAL TECHNIQUE

Various additives available as sufficiently fine powders were employed. The powders were in part available as coarse (c) and fine (f) grades, respectively; their properties are listed in Table 1. From graphite, both natural (MFL) and artificial (KS) grades were tested.

Tab.1. Properties of the solid lubricant powders used.

Lubricant	Density [g.cm ⁻³]	d ₅₀ [μm]	Melting point [°C]	ΔG ₀ For sulfides: [kJ/g-atom S]
PbS	7.5	66	1114	-100
ZnS	4.1	80	1020	-192
MoS ₂ (c)	4.8	110	1185	-117
MoS ₂ (f)	4.8	94	1185	-117
Cu ₂ S (c)	5.6	57	1100	-79
Cu ₂ S (f)	5.6	<27	1100	-79
Sb ₂ S ₃	4.12	75-150	550	-58
MnS	3.99	12.6	1610	-178
BN (c)	2.34	<1	dec. ca. 3000	-254
BN (f)	2.34	50-180	dec. ca. 3000	-254
Pb (c)	11.34	20	327	-- (element)
Pb (f)	11.34	8-10	327	-- (element)
C MFL	2.26	200	>3500	-- (element)
C KS75	2.26	<75	>3500	-- (element)
C KS150	2.26	<200	>3500	-- (element)

The additives were admixed to plain water atomized iron powder (Höganäs AB, ASC 100.29), with an addition of 0.5 % EBS as a pressing lubricant. In part, 0.8 % natural graphite (Kropfmühl UF4) was also admixed. For some experiments, sponge iron powder (NC100.24) and Fe-Mo prealloy powder Astaloy Mo were also employed. The amount of additives was in part varied, in some cases up to levels that are definitely not technically feasible, but enabled us to identify possible trends.

The powders were blended in a tumbling mixer for 60 min to ensure sufficient homogeneity. Here, problems with segregation were encountered e.g. with the coarse graphites and hBN grades, respectively, the particles tending to segregate to the top of the

bulk powders. Then the mixes were compacted to impact test bars $55 \times 10 \times \text{approx. } 8 \text{ mm}^3$ and, for the machining tests, to bars $60 \times 7 \times 7 \text{ mm}^3$, pressing tools with floating dye being used. The compacting pressure was uniformly 600 MPa. The compacts thus produced were sintered in an electrically heated push-type furnace under flowing hydrogen. Sintering temperature was 1120°C , only for the compacts containing coarse graphite it was lowered to 1070°C to prevent excessive C dissolution. Sintering time was uniformly 60 min.

The sintered samples were tested according to standard procedures. Density was measured following the displacement method, and for assessing the mechanical strength, the impact energy was measured using unnotched bars, since this property is most sensitive to interparticle bonding, which might be adversely affected by the additives. The microstructure was studied on metallographic sections, usually both unetched, and after etching with 3 % nital.

For determining the machinability, the bars were first roughly turned on a laboratory lathe of high stiffness to cylinders of about 6.5 mm diameter at a length of about 15 mm, then the finish turning was done with a cutting depth of 0.1 mm. The tool was an indexable hardmetal insert P20, and the cutting speed was adjusted at the low level of 15 m/min, in order to enhance formation of built-up edges. Thus, the effect of the machining aids was expected to stand out more clearly. The as-turned surfaces were then investigated optically, and the roughness R_a was measured using a contacting profilometer Hommeltester T2000.

MECHANICAL PROPERTIES, MICROSTRUCTURE, AND MACHINABILITY

Sulfides

The properties of the specimens are listed in Table 2 for the plain Fe based materials and in Table 3 for the materials based on Fe-0.8 % C. From the list of properties it stands out clearly that most sulfides tend to affect the dimensional behaviour during sintering, in particular at higher contents, swelling being observed. This effect is most pronounced for Sb_2S_3 in which case $>1\%$ expansion has been measured; the resulting low density adversely affects the impact energy. Cu_2S , on the other hand, also results in swelling but the impact energy is nevertheless very satisfactory. It can be supposed that here the well known copper swelling has occurred; in the case of Sb, there is virtually no solubility in Fe but formation of intermetallic phases that are stable up to about 1020°C [9], while the additive Sb_2S_3 melts already at about 550°C .

Generally, higher levels of additives adversely affect the impact energy, which is well visible both for e.g. PbS and MnS. Comparing the effects of various additives at the same nominal content of 2 mass %, the relatively low strength of the MnS containing materials is discernible.

Metallographic sections showed that, as described also e.g. in [10, 11], most sulfides have decomposed during sintering. MnS has remained as a defined phase, still exhibiting the original admixed MnS particles (Fig.1a) while the other sulfides have decomposed to form a Fe-metal solid solution and a Fe-sulfide eutectic which, during solidification, resulted in the formation of a network of the sulfide Fe_{1-x}S . This reaction can be seen clearly from the microstructure which resembles that of heavy alloys and thus is typical for liquid phase sintered materials (Fig.1b). A similar effect could be expected from the addition of elemental sulphur; however, the high vapour pressure of S would result in considerable evaporation loss even before the eutectic melt has been generated. Therefore, an addition of S through decomposing sulfides might be a suitable way to "protect" sulphur from evaporation until the liquid phase is generated.

Tab.2. Properties of Fe-x% additive, compacted at 600 MPa, sintered 60 min at 1120°C in H₂.

Base powder	Lubricant	Green density [g.cm ⁻³]	Sintered density [g.cm ⁻³]	Δl/l [% lin]	KC [J.cm ⁻²]	Nominal S content [mass %]	Surface roughness Ra [μm]
Fe atomized	---	7.12	7.25	-0.24	>31	--	10.7
Fe atomized	0.5 % PbS	7.26	7.21	-0.10	>47.6	0.07	7.2
Fe atomized	2 % PbS	7.10	7.12	-0.04	>31	0.27	2.25
Fe atomized	5 % PbS	7.25	7.04	+0.11	23.2	0.67	2.2
Fe atomized	10 % PbS	7.18	6.89	+0.18	6.4	1.34	1.25
Fe atomized	2 % MoS ₂ (c)	7.04	7.06	+0.16	22.8	0.80	n.d.
Fe atomized	2 % MoS ₂ (f)	7.03	7.06	+0.11	18.0	0.80	n.d.
Fe sponge	2 % MoS ₂ (f)	6.99	6.92	-0.01	14.7	0.80	1.5
Fe sponge	5 % MoS ₂ (f)	6.90	6.77	-0.02	3.5	2.00	1.0
Astaloy Mo	2 % MoS ₂ (f)	7.05	6.99	+0.01	15.2	0.80	2.0
Fe atomized	2 % Cu ₂ S (c)	7.06	7.00	+0.28	>31	0.40	n.d.
Fe atomized	2 % Cu ₂ S (f)	7.09	7.02	+0.20	>31	0.40	n.d.
Fe atomized	2 % Sb ₂ S ₃	7.01	6.77	+1.25	9.2	0.57	n.d.
Fe atomized	2 % ZnS	6.97	6.89	+0.08	25.3	0.66	n.d.
Fe atomized	0.3 % MnS	7.17	7.22	-0.08	>27.6	0.11	5.3
Fe atomized	0.5 % MnS	7.16	7.21	-0.12	>26.8	0.18	2.2
Fe atomized	1.0 % MnS	7.14	7.18	-0.13	18.7	0.37	1.3
Fe atomized	2 % MnS	7.07	7.11	-0.17	11.6	0.74	0.8

Tab.3. Properties of Fe-0.8 % C-x % solid lubricant, compacted at 600 MPa, sintered 60 min at 1120°C in H₂.

Base powder	Lubricant	Green density [g.cm ⁻³]	Sintered density [g.cm ⁻³]	Δl/l [% lin]	KC [J.cm ⁻²]	Nominal S content [mass %]	Surface roughness Ra [μm]
Fe atomized	---	7.05	7.03	-0.01	11.7	--	8.3
Fe atomized	0.5 % PbS	7.18	7.06	+0.28	8.9		8.0
Fe atomized	2 % PbS	7.16	6.97	+0.49	13.9		3.6
Fe atomized	5 % PbS	7.13	6.80	+0.55	12.6		1.7
Fe atomized	10 % PbS	7.02	6.73	+0.62	6.5		1.3

The low stability of most sulfides in the Fe matrix agrees with the literature data for the respective ternary systems [9] and also with experimental results [10,11]. The only exception is MnS, which is very stable up to high sintering temperatures if a small amount of Mn is present in the Fe matrix which prevents the introduction of Fe into the MnS, FeS being much less stable than MnS. In all other sulfides, the lower stability, in part in connection with the high solubility of the metallic constituent in the iron matrix, enhances decomposition. This is particularly well visible with Cu₂S-containing materials: here, after sintering the eutectic network, it is discernible in the unetched section (Fig.1c), while after etching, the typical core-rim structure of sintered Fe-Cu is found (Fig.1d). ZnS is somewhat of an exception since its free energy of formation is even higher than that of MnS, but here it can be supposed that the high vapour pressure of Zn results in a shifting of the equilibrium towards decomposition, the Zn vapour generated being consistently removed by the flowing atmosphere.

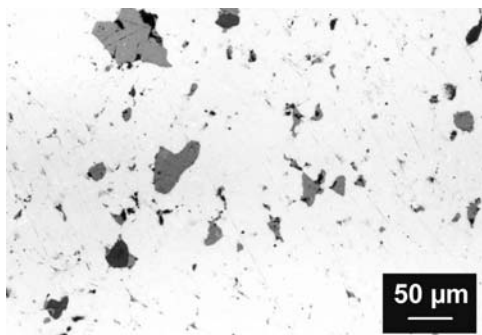
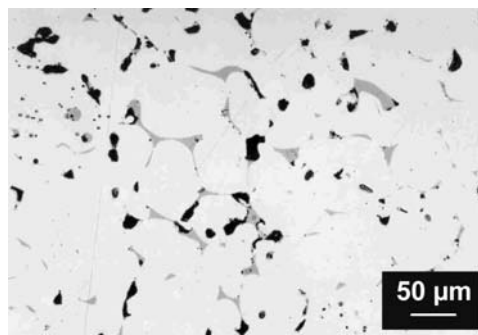
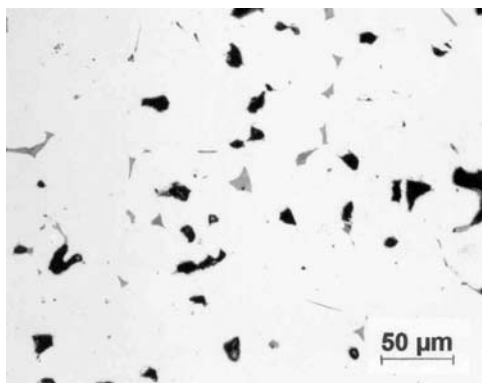
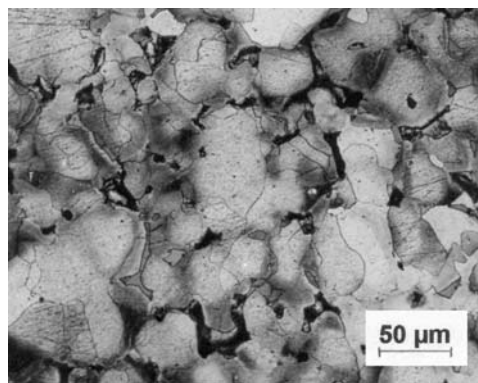


Fig.1a. Fe-2% MnS.

Fig.1b. Fe-2% MoS₂.Fig.1c. Fe-2% Cu₂S, as-polished.Fig.1d. Fe-2% Cu₂S, Nital etched.

Another special case is PbS, Pb being insoluble in Fe in contrast to Mo, Cu, Zn, and the other sulfide forming elements. Here it showed, nevertheless, that PbS also forms the “heavy alloy” microstructure with the sulfide “binder” phase. According to [9], both the sulfide eutectic and liquid Pb should be present at sintering temperature; also for Pb the feasibility of evaporation has to be considered (which in practice is critical due to the toxicity of Pb). Nevertheless, as will be shown below, in the case of Pb being added as elemental powder, the liquid Pb droplets formed during sintering seem to at least partly survive the sintering process, and after sintering it is found that Pb is present as fine (<10 µm), rounded inclusions. Therefore, when PbS is added, both Pb and Fe_{1-x}S might act as machining aids.

The fairly high impact energy of the materials containing sulfide networks, as compared to MnS, indicates that the sulfide network is not as detrimental as are carbide or oxidic ones. It is known that sulfides are fairly ductile and that sulfidic inclusions do not cause fatigue cracks as do carbide, nitridic or oxidic ones [12]; the results here also indicate that the strength of these sulfide contacts should not be underestimated.

The machinability tests were done for MnS, PbS, and MoS₂ only, the latter being regarded as a “model” for the decomposing sulfides; a Mo prealloy matrix was selected to level out possible effects of irregular Mo distribution. Here it showed that with regard to the sulphur content added, MnS yields the lowest roughness values and also MoS₂ is quite effective while PbS is less satisfactory. If the optical surface finish is taken (Fig.2), MoS₂ in the Astaloy Mo matrix was most effective, resulting in an extremely smooth surface finish.

For MnS, the minimum content seems to be 0.5 %; higher levels result in lower roughness but hardly any change in optical finish. With PbS, fairly high contents are necessary to result in a satisfactory finish; here the optical image and the roughness values are in good agreement. PbS in carbon containing materials enhances the machinability, although the effect is not too pronounced, and also here fairly high levels of PbS addition are necessary to obtain a reasonable surface finish (Fig.3). This can be taken as an indication that at the cutting parameters chosen here, not only built-up edges are responsible for the poor surface finish of the reference specimens.

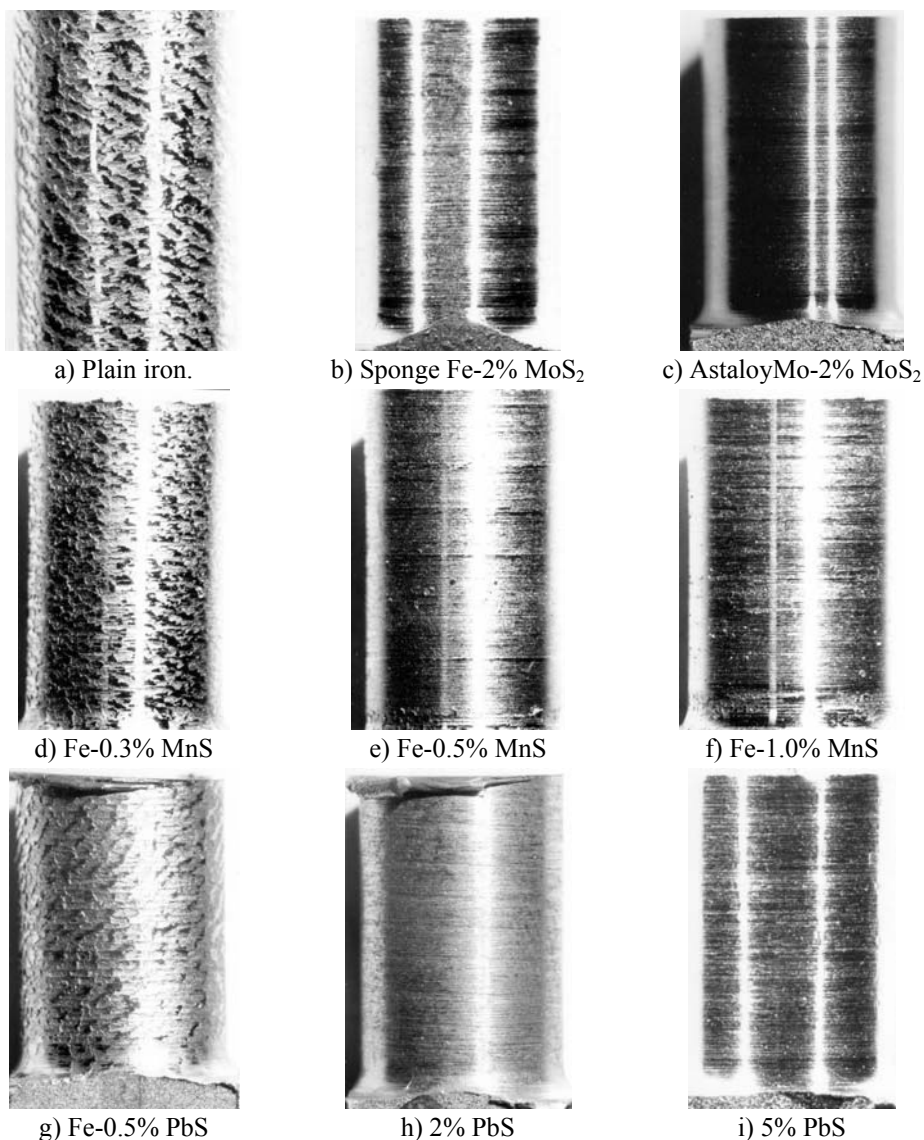


Fig.2. Machined surfaces of sintered steels containing different additives. Finish turning, hardmetal insert P20, $v_c = 15$ m/min, 0.15 mm/rev.

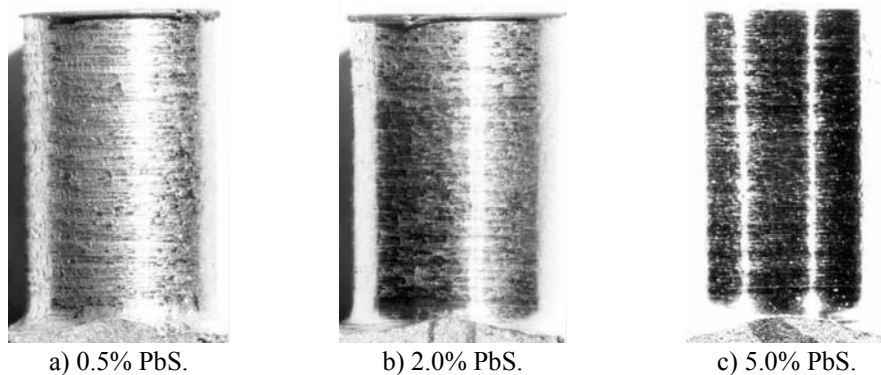


Fig.3. Machined surfaces of sintered steel Fe-0.8 %C containing PbS (admixed). Finish turning, hardmetal insert P20, $v_c = 15$ m/min, 0.15 mm/rev.

Non-sulfidic additives

In addition to the well known sulfides, also other additives that are definitely known to be solid lubricants were tested; these are Pb, traditionally used as machining aid in wrought steels, and the “twins” graphite and hexagonal BN, both with the typical layered structure.

The results of the tests are shown in Table 4 for a plain iron matrix and in Table 5 for the carbon steel based materials. In the former case, is evident that an addition of elemental Pb powder does not very much affect the dimensional and mechanical properties, while BN may have a drastically adverse effect on both. This however strongly depends on the sintering temperature: when sintering at 1120°C, BN, especially the fine grade, tends to promote swelling and lowers the impact energy. Generally, fine BN is more effective than a coarse one, which is clearly evident also from the green and sintered density values. After sintering at 1250°C, in contrast, at least the lower BN contents promote shrinkage and result in very satisfactory impact energy. Also here, at higher BN levels however, the impact energy tends to fall off significantly.

Tab.4. Properties of Fe (atom.) -x % additive, compacted at 600 MPa, sintered 60 min in H_2 .

Lubricant	Sintering temp. [°C]	Green density [g.cm ⁻³]	Sintered density [g.cm ⁻³]	$\Delta l/l$ [% lin]	KC [J.cm ⁻²]	Surface roughness Ra [μm]
---	1120	7.12	7.25	-0.24	>31	10.7
Pb (c)	1120	7.12	7.20	-0.17	28.7	2.9
Pb (f)	1120	7.25	7.23	-0.24	36.5	2.5
0.5 % BN (c)	1120	7.07	7.04	-0.10	9.16	n.d.*
	1250	7.07	7.14	-0.31	>28.9	6.95
2.0 % BN (c)	1120	6.84	6.85	+0.08	2.01	n.d.*
	1250	6.79	6.93	-0.23	7.73	>>*
0.5 % BN (f)	1120	7.12	7.21	-0.18	11.5	n.d.*
	1250	7.12	7.29	-0.71	>42.5	n.d.*
2.0 % BN (f)	1120	6.45	6.37	+0.27	0.78	n.d.*
	1250	6.40	6.57	-0.75	2.54	n.d.*

* specimens too fragile for machining

** roughness exceeded the measuring range

Tab.5. Properties of Fe (atom.) –0.8 %C-x % additive, compacted at 600 MPa, sintered 60 min in H₂.

Lubricant	Sintering temp. [°C]	Green density [g.cm ⁻³]	Sintered density [g.cm ⁻³]	$\Delta l/l$ [% lin]	KC [J.cm ⁻²]	Surface roughness Ra [μm]
---	1120	7.05	7.03	-0.01	11.7	8.3
2.0 % Pb(c)	1120	7.08	7.07	+0.07	11.6	2.2
0.5 % BN (c)	1120	6.95	7.01	-0.05	6.13	n.d.*
	1250	6.96	7.12	-0.33	19.4	8.7
2.0 % BN (c)	1120	6.73	6.70	+0.23	1.76	n.d.*
	1250	6.71	6.88	-0.50	13.10	6.4
0.5 % BN (f)	1120	6.99	7.08	-0.16	3.40	n.d.*
	1250	6.98	7.15	-0.73	16.5	n.d.*
2.0 % BN (f)	1120	6.24	6.12	+0.61	0.68	n.d.*
	1250	6.03	6.24	-0.76	6.49	n.d.*
C MFL	1070	6.89	6.77	+0.23	4.7	4.9
C KS75	1070	6.86	6.69	+0.57	1.0	4.2
C KS150	1070	6.74	6.42	+0.79	1.9	3.1

* specimens too fragile for machining

This effect can be explained by the chemical behaviour of BN during sintering in N₂-free atmospheres (vacuum, H₂): BN remains stable in these atmospheres up to the temperature of the Fe-B eutectic (1177°C [13]). If this temperature is exceeded, BN decomposes, and a persistent liquid phase is formed [14] that assists shrinkage and improves the mechanical properties up to a certain B content. If this content is exceeded, brittle boride networks are formed that drastically lower the ductility [15-17].

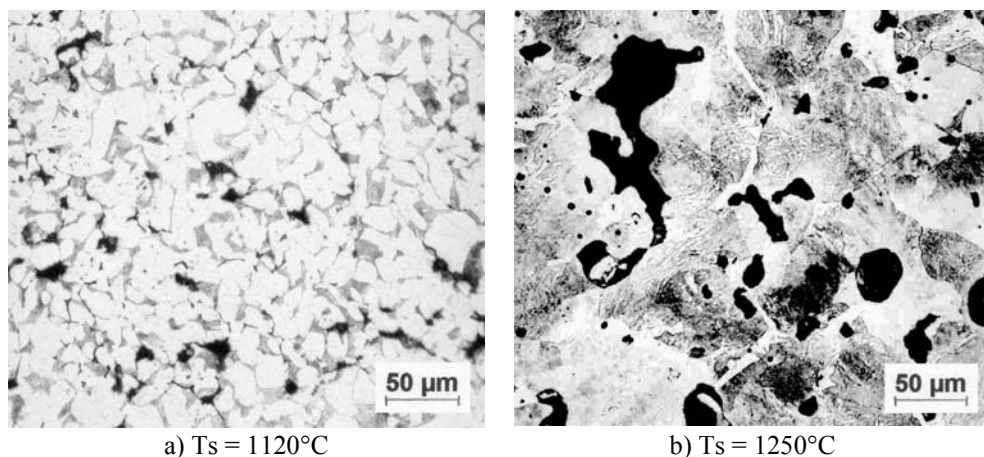


Fig.4. Microstructures of Fe-0.8% C-0.5% BN (fine). Compacted 600 MPa, sintered 60 min at various temperatures in H₂.

A further effect of the admixed BN, esp. the fine grade, can be seen from the metallographic sections: as long as BN is present, dissolution of graphite in the iron matrix is retarded. This is clearly visible from Fig.4a: this material, which contains 0.8 % admixed

carbon, after sintering should exhibit a fully pearlitic microstructure. From the ferritic-pearlitic structure that is actually displayed, a dissolved carbon content of about a 0.3 % maximum can be derived; the remaining carbon is apparently still contained as graphite that, if present in the pressing contacts, further lowers the interparticle strength. In carbon containing steels, the adverse effect of admixed BN towards the strength not only originates from BN particles included in the interparticle contacts, but also from inhibition of graphite dissolution, free graphite also adversely affecting the contact strength [18,19]. Only after sintering above the Fe-B eutectic the fully pearlitic microstructure is displayed (Fig.4b), indicating deactivation of the BN.

The reason why BN slows down the carbon dissolution still has to be identified; it might however be assumed that the BN flakes cover the iron particles preferentially, thus preventing direct contact between iron and graphite. This would indicate that carbon dissolution occurs through a solid state mechanism as claimed e.g. in [20,21], and not by a gas phase transport postulated in [22,23].

Admixed coarse graphite finally results in expansion during sintering and in very low impact energy values. This may be attributed to the springback effects well known from the pressing of friction materials; this springback results in microcracks around the larger graphite particles that are not removed during the sintering process (see Fig.5). The more rounded artificial graphite seems to be more detrimental here than the flaky natural grade.

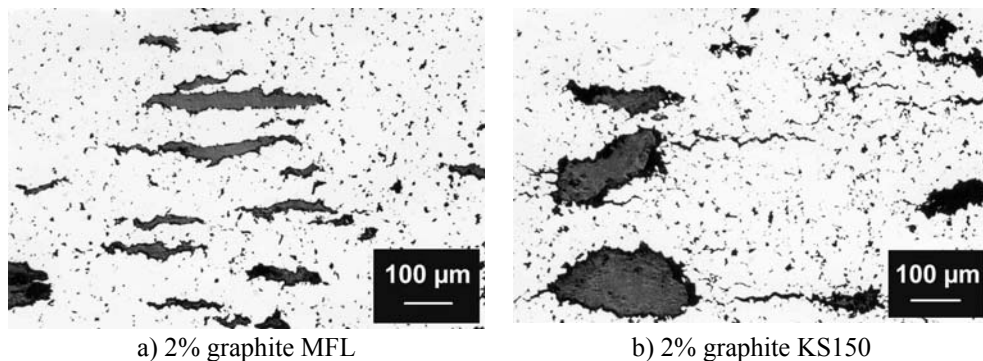


Fig.5. Microstructures of Fe-0.8% C base materials with admixed coarse graphite.
Compacted 600 MPa, sintered 60 min at 1070°C in H₂.

The machinability is decisively affected by the mechanical strength of the materials. Especially with BN containing materials, carrying out the machining tests was difficult and in many cases even impossible since the specimens broke during machining. Even those BN containing steels that were machinable – those prepared from coarse BN and sintered at 1250°C, which in fact do not contain BN any more but are boron alloyed steels – exhibited rather poor surface finish (Fig.6). This indicates that at least at higher contents, BN is not an effective machining aid.

Similarly, also coarse graphite, despite being a solid lubricant, did not result in satisfactory surface finish; also here the poor strength of the material resulted in rough, rugged surfaces as visible from Fig.7. The flaky natural graphite MFL was less detrimental, probably due to fewer microcracks being generated in this material.

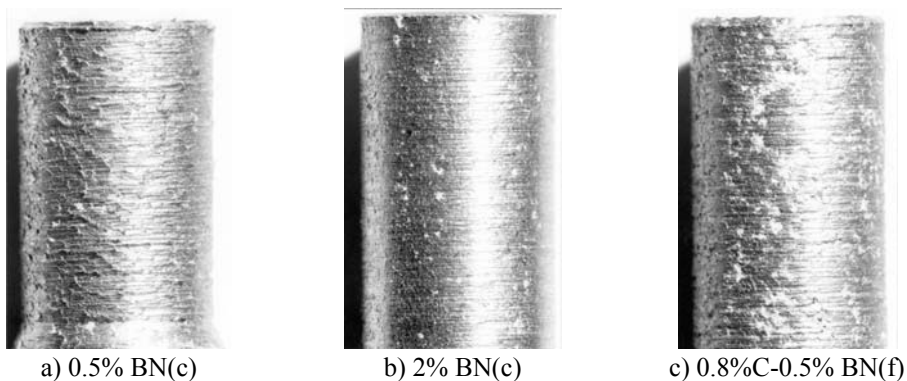


Fig.6. Machined surfaces of sintered iron containing BN (admixed). Finish turning, hardmetal insert P20, $v_c = 15$ m/min, 0.15 mm/rev.

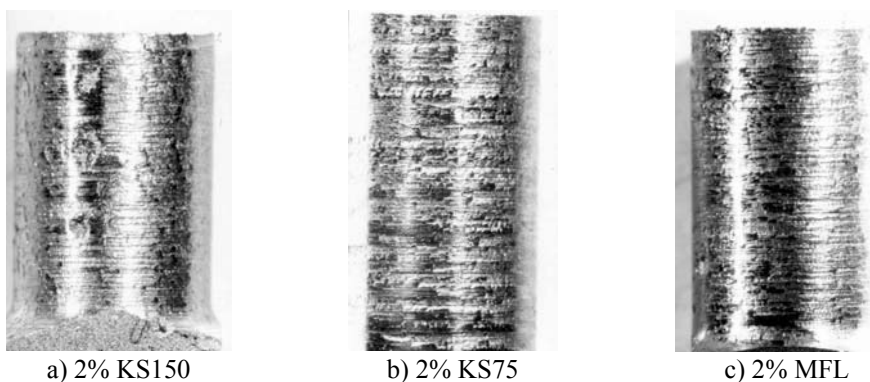


Fig.7. Machined surfaces of sintered Fe-0.8%C (fine) containing admixed coarse graphite grades. Sintered 60 min 1070°C in H_2 /getter. Finish turning, hardmetal insert P20, $v_c = 15$ m/min, 0.15 mm/rev.

MACHINABILITY AND DRY SLIDING BEHAVIOUR

Traditionally, machining aids are regarded as solid lubricants, and it might be supposed that testing sintered materials containing machining aids in dry sliding should yield useful results with regard to the lubricity of the additives. As described in [11], dry sliding wear tests carried out with the materials used here against bearing steel 100Cr6 (62-63 HRC) are described. If the friction coefficients obtained during these wear tests are plotted against the surface roughness (Fig.8), it can be seen that there is virtually no correlation between the two parameters.

This would indicate that lubricity does not play any role for machining aids; this would be a simplification however. The reason for the insignificant results is rather found in the different ways of material loading. As suggested in [11], dry sliding results in rapid lubricant depletion of the surface, the lubricating particles being removed during the sliding process (otherwise they would not have any lubricating effect). Only in the case of high wear rates, which means rapid exposure of fresh surfaces and thus fresh lubricant, lowering of the friction coefficient by the additive can be observed. Therefore, in [11] generally a negative correlation between friction coefficient and wear coefficient was recorded; the

materials that exhibited high wear tended to show low the friction coefficients and vice versa. The “high wear” condition is however exactly the case during machining, since the cutting edge always meets fresh material with its full content of additive. It must therefore be concluded that dry sliding tests seem to be of a very limited significance for assessing machining aids.

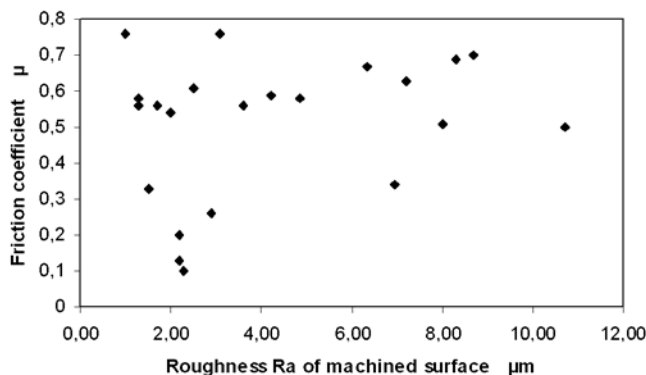


Fig.8. Roughness R_a of machined surface vs. friction coefficient in dry sliding (0.5 m/s, 60 N, vs. 100Cr6, from [11]).

CONCLUSIONS

Additives that can be used as machining aids, and to which lubricity is frequently attributed, can be introduced into PM steels through admixing them as fine powders, with subsequent pressing and sintering. However, sulfides especially tend to decompose during sintering, resulting in a formation of $Fe_{1-x}S$ - in a “heavy alloy” arrangement - in the structure, which cannot be regarded as a solid lubricant. Pb and (coarse) graphite as well as MnS are stable during sintering; the addition of graphites however results in rather poor mechanical strength. The same holds for BN, unless it is decomposed by sintering at $T > 1177^\circ C$ in a N_2 -free atmosphere. In this latter case, carbon is completely dissolved during sintering while BN, especially fine grades, tend to inhibit carbon dissolution, which results in further weakening of the interparticle bonds.

The machinability, taken as the roughness R_a of the machined surfaces, is significantly improved by the addition of MnS and also by MoS_2 , although the latter is not present after sintering but has been transformed into $Fe_{1-x}S$. PbS is slightly less effective, higher contents being necessary to obtain smooth surfaces. Among the non-sulfidic additives tested, only Pb can be regarded as effective; both for BN and coarse graphite, the poor matrix strength results in rather rugged surfaces and a poor finish. At least for BN it can be concluded that this additive, if chosen, has to be carefully dosed.

Since the machining aids are often claimed to be solid lubricants, lubricity measured in dry sliding should be significant also for the machinability effect. If the surface roughness is plotted versus the friction coefficient obtained through a dry sliding test, there is no major correlation. This can be attributed to the fact that in dry sliding, except in the case of very high wear, the surface is rapidly depleted of solid lubricants, and the lubricating effect is usually already lost during the run-in period, while in machining the tool always cuts into fresh, i.e. additive-containing, material.

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