MACHINABILITY OF P/M STEELS

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ABSTRACT

This paper will examine the potential to improve the machinability of sintered P/M steels by the addition of free-machining agents. Testing will examine the effects of free-machining agents upon the sintered properties and machinability in drilling of commercial P/M steels, including FC-0208 or FN-0205.

INTRODUCTION

Ferrous Powder Metallurgy is considered a net shape manufacturing process. The aim of many successful P/M part development programs is to eliminate or significantly reduce secondary machining operations. Despite this, the relatively poor machinability of P/M steels has been of concern to parts producers. Recent improvements in the properties of P/M steels appear to further reduce machinability, such that machining costs can be a significant proportion of final part costs. This paper examines some factors that influence the machinability of sintered P/M steels and alternative means of improvement.

MACHINABILITY OF P/M STEELS

The relatively poor machinability of P/M steels compared to competing wrought products is usually considered to originate from a combination of factors, including:

Porosity
Microcleanliness
Microstructure
Knowledge

Some understanding of these factors is necessary to distinguish as to how the machinability of P/M steels will be inherently different from wrought steels.

POROSITY

The presence of porosity in P/M components significantly changes the cutting process. The first and probably most significant effect is that cutting becomes discontinuous as the tool edge breaks out of the workpiece into pores. This action of successive small impacts on the cutting edge causes more rapid tool failure than continuous cutting operations (Figure 1).

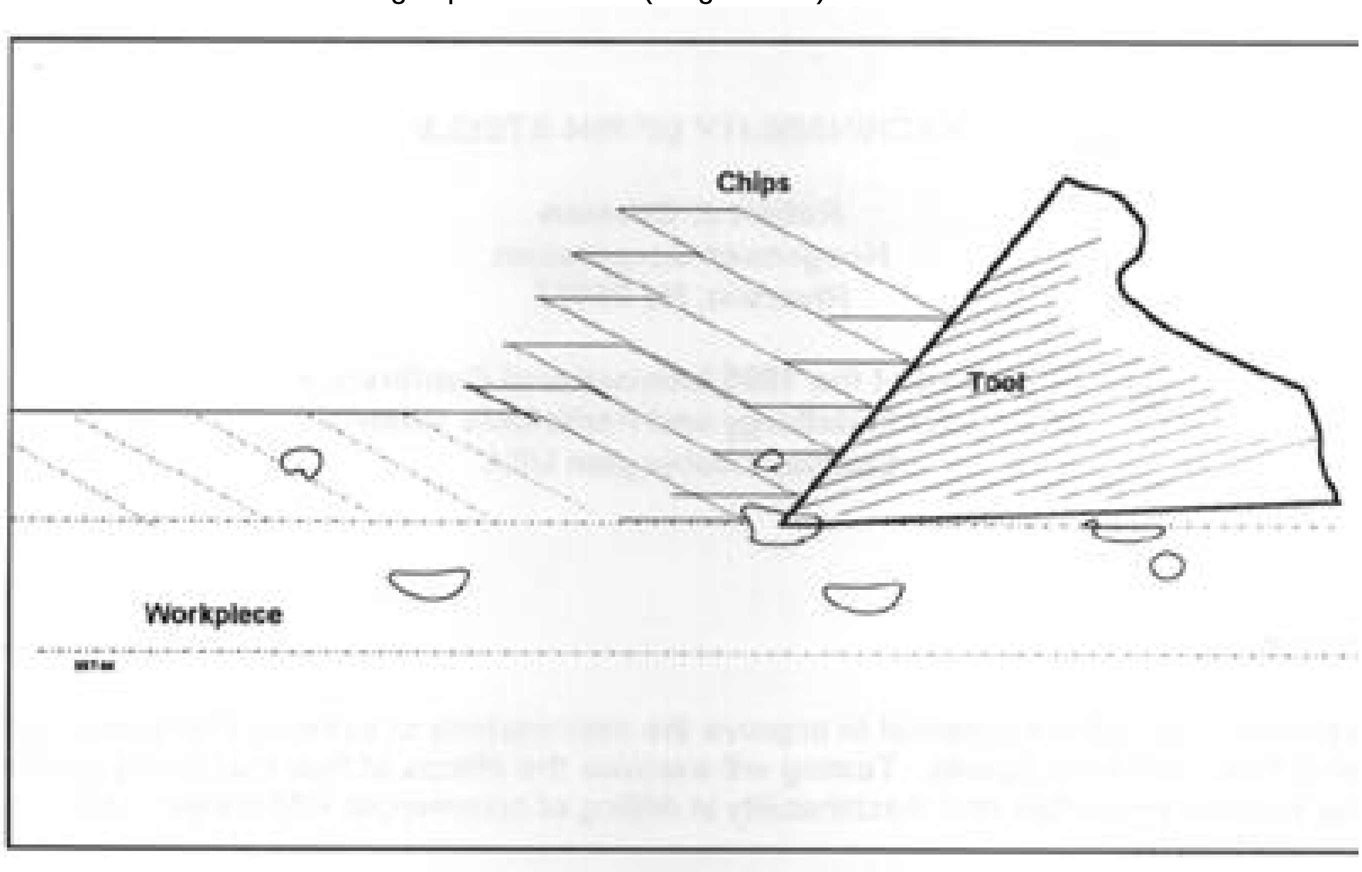

Figure 1: Schematic of the Effect of Porosity on Metal Cutting

Porosity reduces the thermal conductivity of P/M steels, thus temperatures of the cutting zone and cutting edge may increase rapidly. This can accelerate tool wear and harden the workpiece. Local hardening of the workpiece may make subsequent finishing cuts more difficult.

Interconnected porosity provides a path for cutting fluids to escape from the cutting area. This reduces their ability to cool and lubricant the cutting edge. It may also reduce their ability to wash chips from the cutting area. Such behavior may be critical to “spade drilling” or “gun drilling” operations that depend upon controlled coolant flow.

The porosity and remnants of prior particle boundaries inherent in P/M parts possess much greater surface area than wrought steels. This probably increases the potential for physical and chemical reactions between the tool and workpiece that may accelerate wear.

MICROCLEANLINESS

The microcleanliness, presence of undesirable non-metallic inclusions (Figures 2 and 3), of P/M steels has been quoted as a cause of poor machinability.

Porosity can contribute to poor microcleanliness and machining problems by allowing subsurface oxidation or carburization of pores during and particularly on cooling from sintering or heat treatment operations. In extreme cases, networks of oxide or carbide layers may significantly reduce machinability.

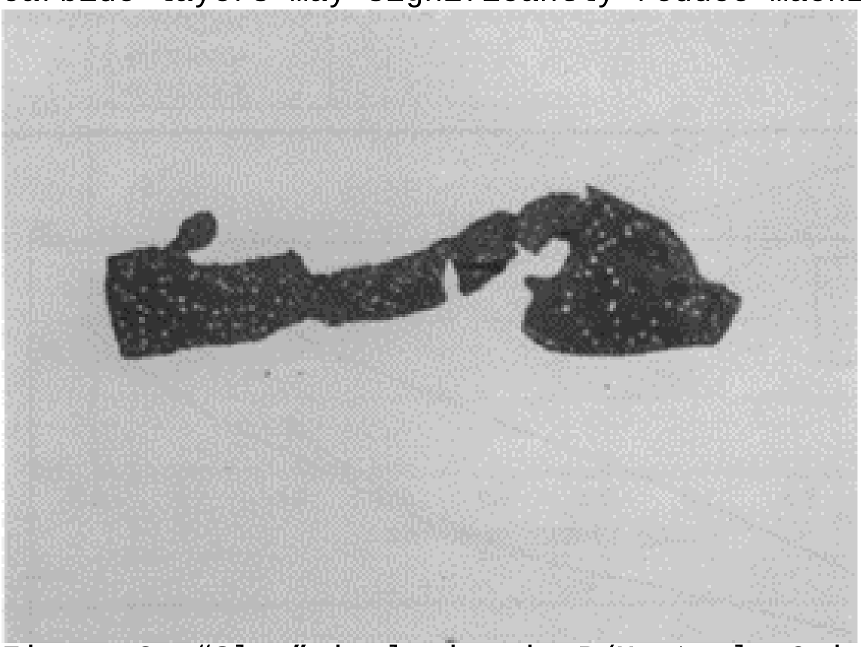

Figure 2: “Slag” inclusion in P/M steel. Original Magnification 500X.

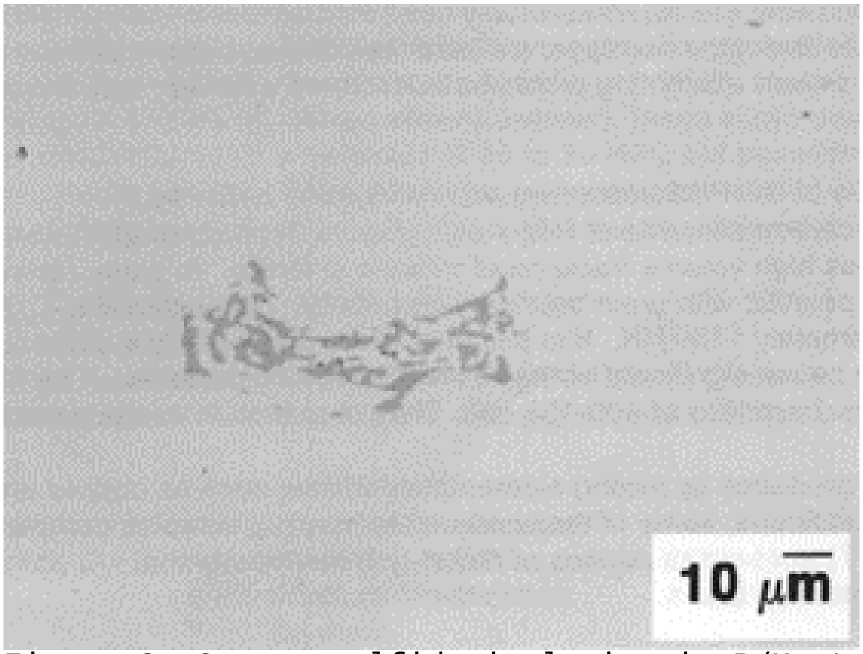

Figure 3: Coarse sulfide inclusion in P/M steel. Original magnification 500X.

MICROSTRUCTURE - PROPERTIES

P/M steels employed in structural P/M parts possess somewhat different microstructure-property relationships from wrought steels. Porosity has a significant effect upon properties. The most critical of which is to significantly reduce bulk properties, such as strength and hardness, from those of powder particles.

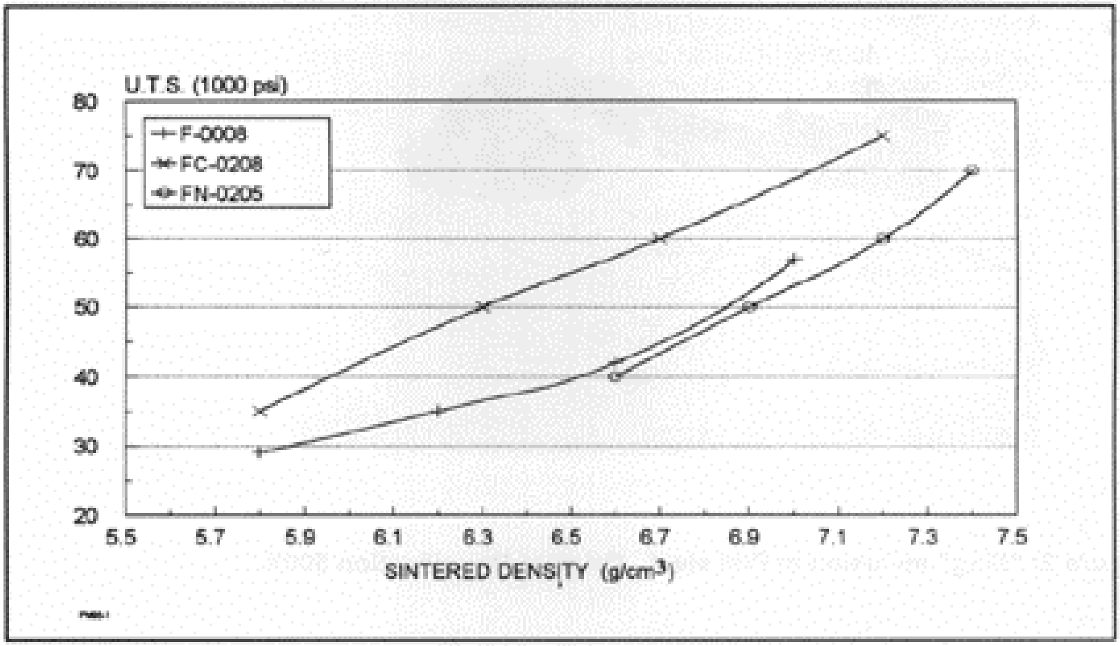

Figure 4: Ultimate Tensile Strength of Sintered PM Steels

The strong effect of density or porosity upon bulk properties is illustrated in Figures 4 and 5 of ultimate tensile strength and hardness for three widely used P/M steels: F-0008, FN-0205 and FC-0208. Neither the tensile strengths nor apparent hardness of these steels are exceptional. They should not cause the severe machining problems associated with very soft annealed steels or high strength steels.

In practice, the machinability of the P/M steels may be represented better by their microstructures. The high carbon contents of P/M steels (Figure 6) produce as-sintered microstructures that possess high volume fractions of pearlite in ferrite. In some cases, F-0008, the microstructure may be pearlitic with grain boundary cementite. Cementite, Fe_3C, possesses a microhardness of approximately 1150 HK. It is possible to envisage that the cementite lamellae in the pearlite can cause significant abrasive wear of cutting surfaces. The ferrite regions possess much lower hardness of 100-150 HV. They may tend to cause adhesive wear.

Frequently, P/M steels are produced by mixing elemental additives, such as copper and nickel. Under practical sintering conditions, some of these elements may not dissolve completely. For example, FN-0205 (Figure 7) possesses regions of nickel-rich martensite that will possess different properties to the pearlitic areas.

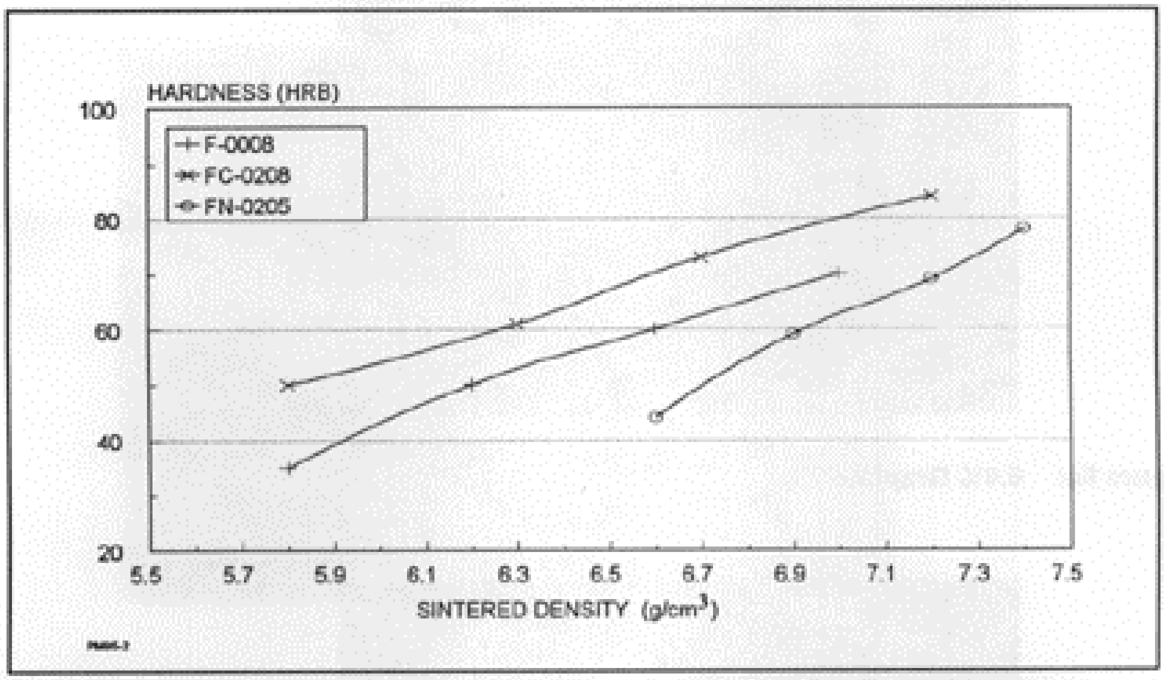

Figure 5: Apparent Hardness of Sintered P/M Steels

For P/M steels, such as FN-0205 or FC-0208, a change from minimum to maximum carbon changes the microstructure and properties significantly. For FN-0205, increasing carbon from 0.4 to 0.6 w/o appears to increase the pearlite and martensite content (Figure 7). For FC-0208, increasing carbon from 0.6 to 0.9 w/o produces an almost completely pearlitic microstructure (Figure 8). Higher carbon additions produce a much finer, almost irresolveable pearlite. The changes observed in both alloy systems would be expected to reduce machinability.

One recent trend is to use prealloyed powders as the basis of P/M steel design rather than pure iron. These steels possess significantly higher mechanical properties due to significantly higher hardenability. Consequently, they possess bainitic or partially martensitic microstructures in the sintered condition (Figure 9). When sinter-hardened, these alloys develop high strengths of 100,000 to 160,000 psi and a hardness of 25 to 30 HRC but possess microstructures of 20 to 70% martensite (Figure 10). Thus, although perhaps not as abrasive as the higher carbon steels, their higher strength and toughness reduce machinability significantly.

MEANS TO IMPROVE MACHINABILITY

The discussion above indicates that machining P/M steels presents problems. Several different approaches to improve machinability are discussed below. These include:

Closure of Porosity
Microcleanliness Improvement
Free-Machining Additives
Microstructure Modification
Tool Materials

The effects of free-machining additives, microstructure modification and tool materials are illustrated by controlled drilling tests conducted under laboratory conditions. Drilling is probably the most frequent machining operation conducted on P/M steels.

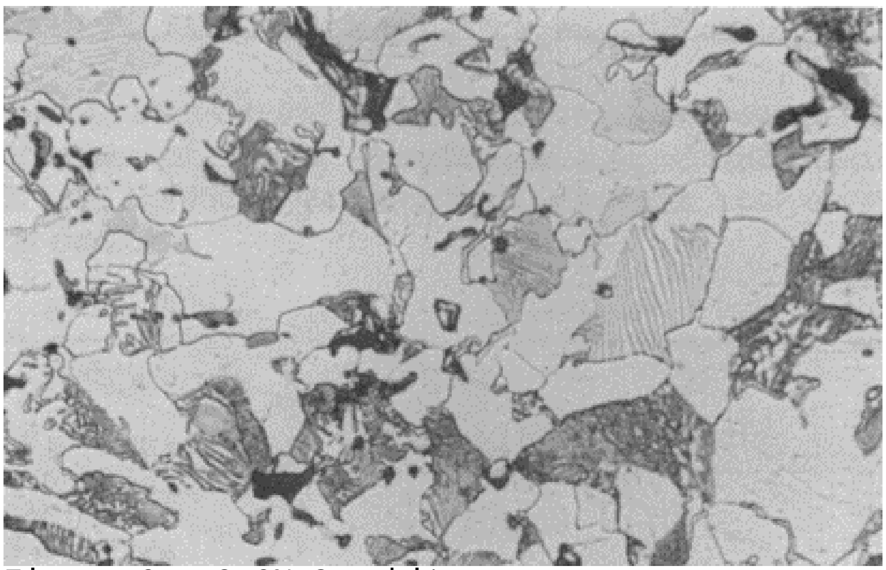

Figure 6a: 0.6% Graphite

Figure 6b: 0.8% Graphite

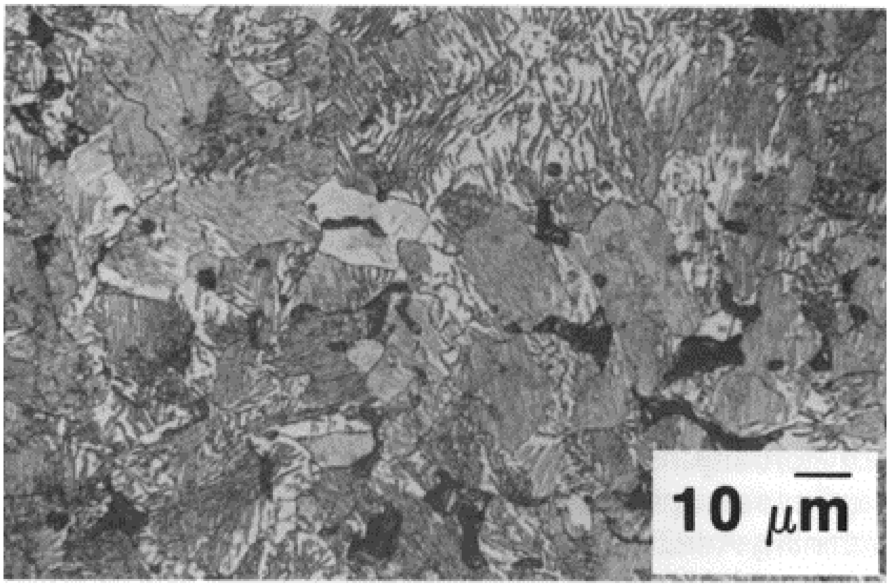

Figure 6c: 1% Graphite

Figure 6: Effect of carbon content upon microstructure of F-0008 atomized powder. Original magnification 500X. Etched 2% nital/4% picral.

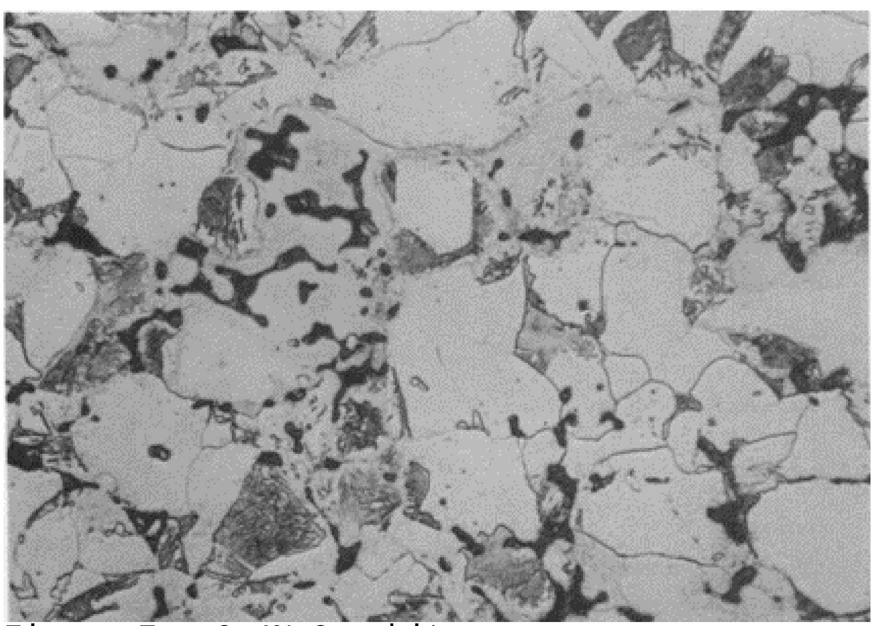
Figure 7a: 0.4% Graphite

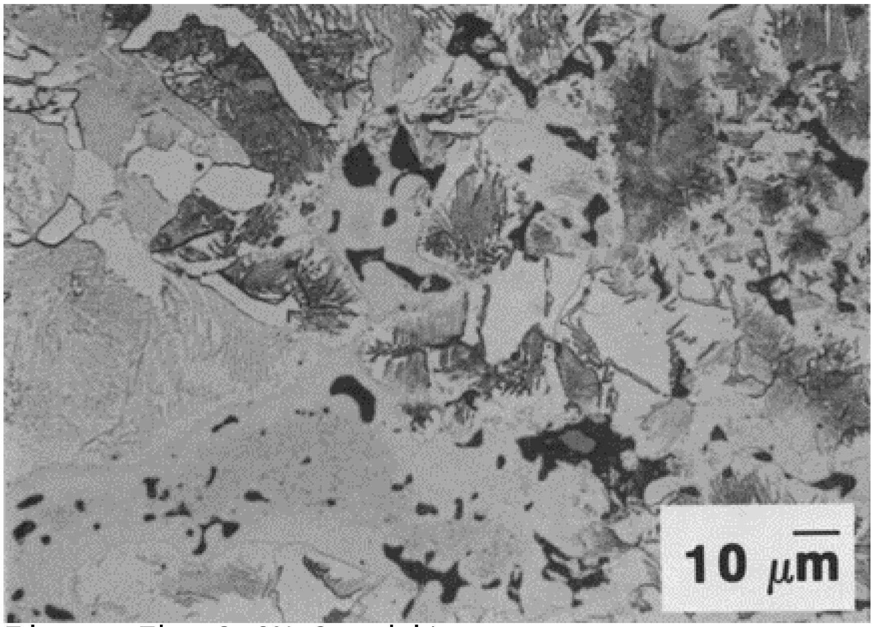

Figure 7b: 0.6% Graphite

Figure 7: Effect of carbon content upon microstructure of FN-0205 atomized powder. Original magnification 500X. Etched with 2% nital/4% picral.

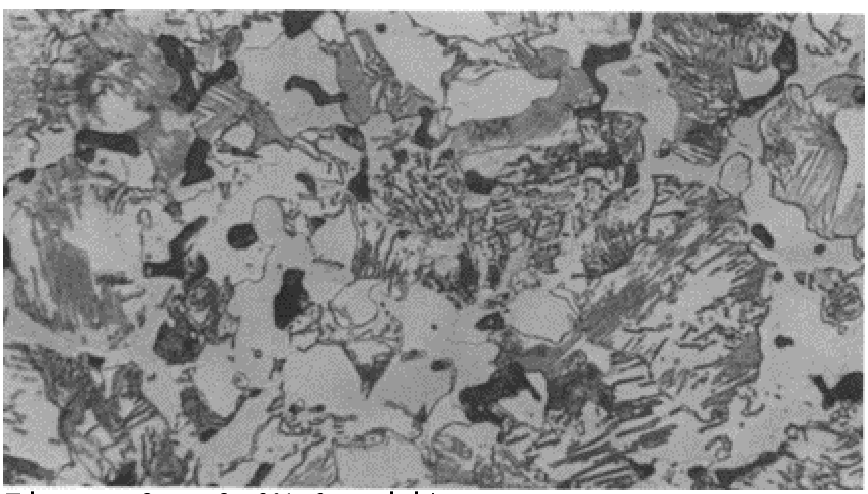
Figure 8a: 0.6% Graphite

Figure 8b: 0.8% Graphite

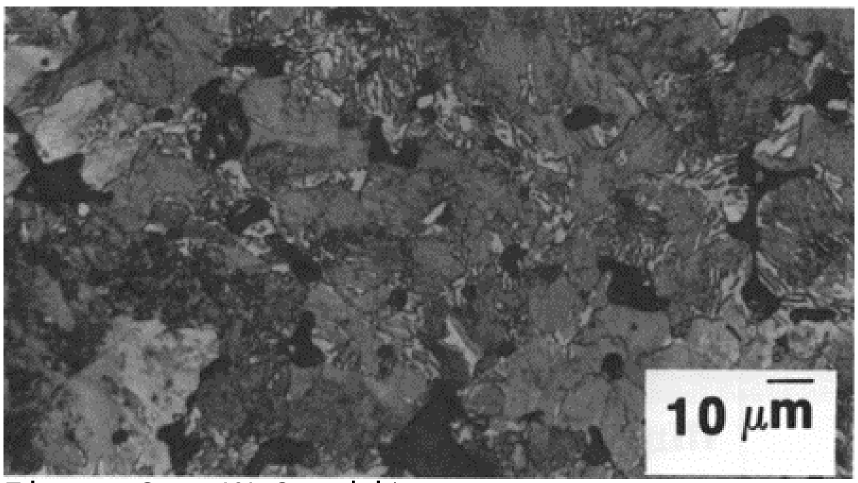

Figure 8c: 1% Graphite

Figure 8: Effect of carbon content upon microstructure of FC-0208. Original magnification 500X. Etched with 2% nital/4% picral.

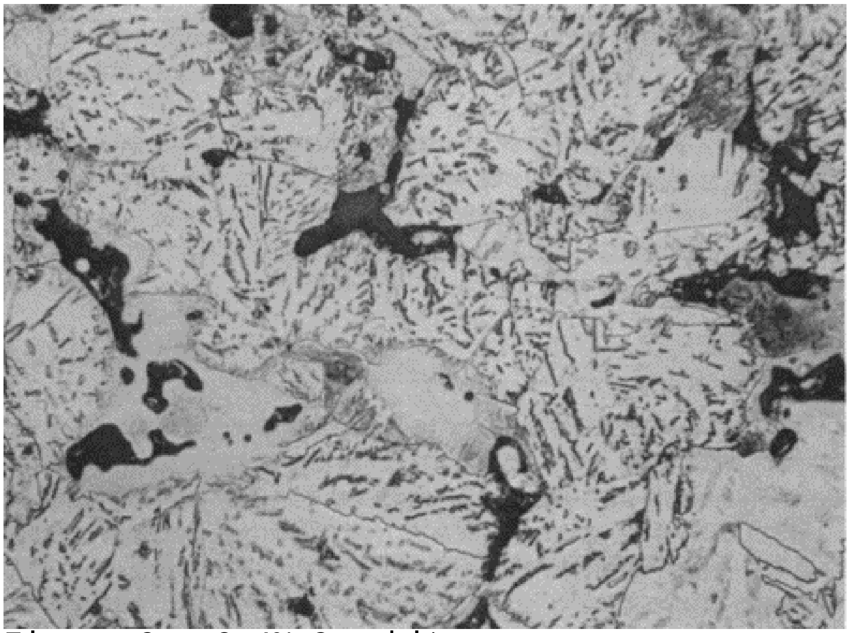

Figure 9a: 0.4% Graphite

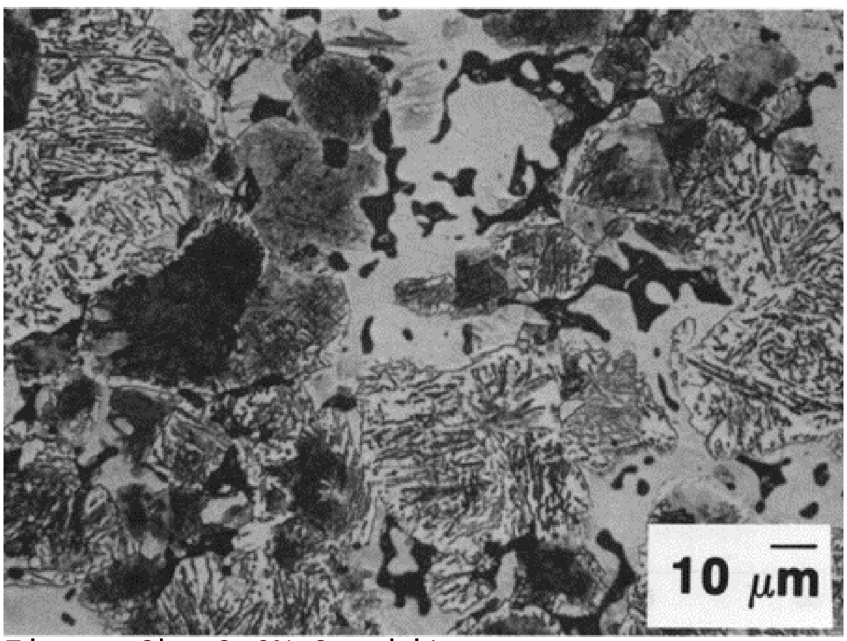

Figure 9b: 0.6% Graphite

Figure 9: Effect of carbon content upon microstructure of Ancorsteel 85HP:2 w/o nickel. Original magnification 500X. Etched with 2% nital/4% picral.

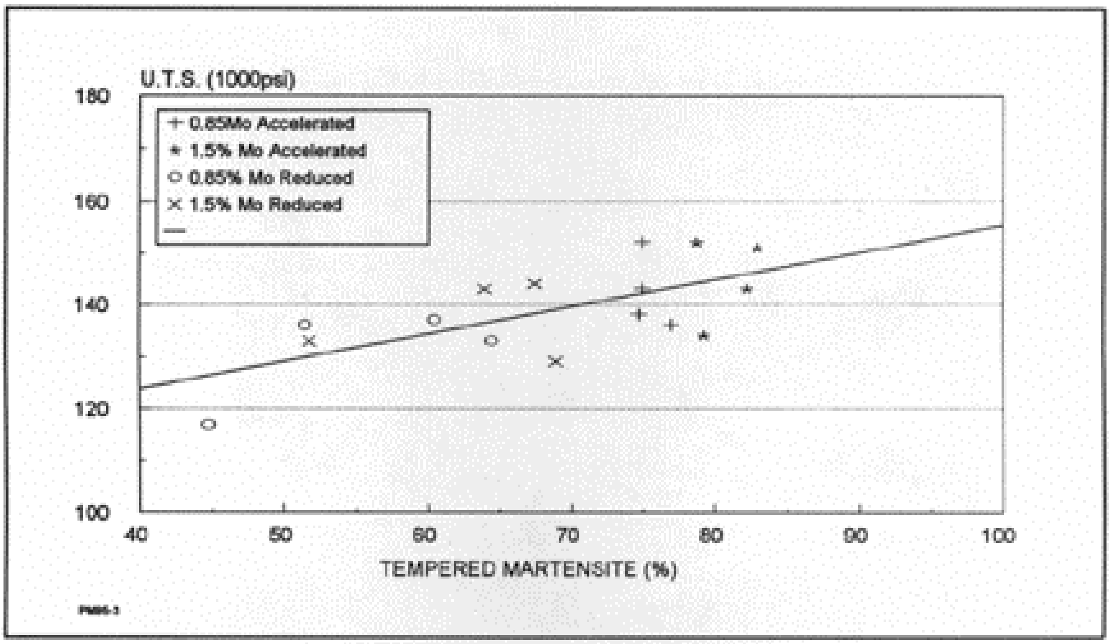

Figure 10a: Ultimate Tensile Strength of Molybdenum, 2 w/o Nickel, 0.5 w/o Graphite Steels Versus Tempered Martensite Content.

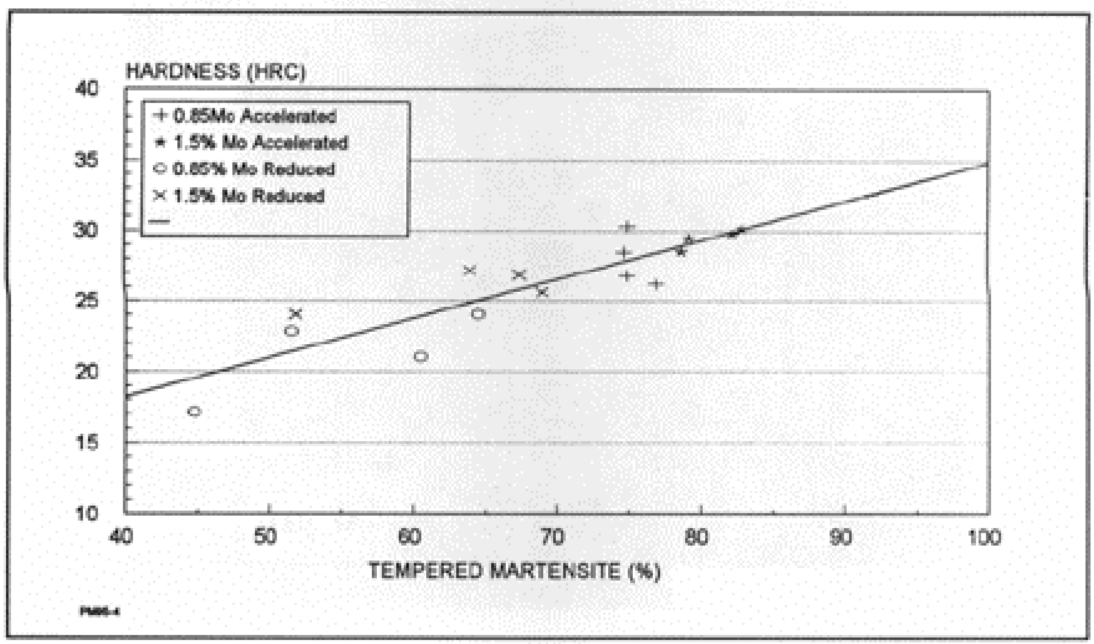

Figure 10b: Hardness of P/M Molybdenum, 2 w/o Nickel, 0.5 w/o Graphite Steels Versus Tempered Martensite Content.

CLOSURE OF POROSITY

Closing, or sealing, porosity improves the machinability of P/M steels significantly by changing the cutting process from intermittent to continuous. The reduction in vibration and chatter improve tool life and surface finish.

Copper infiltration and polymer impregnation are efficient means to close porosity. Both may require an additional process step. Thus, they are most efficient when dictated by the end use, such as fluid power applications. However, the improvement in machinability may justify their use in severe machining operations or when a machining operation is the rate-limiting step in a process sequence.

MICROCLEANLINESS IMPROVEMENT

The increase in the production and use of atomized rather than reduced iron powders has improved the microcleanliness of iron and low alloy steel powders. Driven largely by the requirements of powder forging, the content of coarse non-metallic inclusions in atomized powders has been reduced significantly. For an atomized FL-4600 (Figure 11), the median frequency of inclusions greater than 100um in size, F_4, has been reduced from approximately 2.5 to 0.25 per 100 mm^2. The maximum frequency, of inclusions greater than 100um, was reduced from 9 to 1.3 inclusions per 100 mm^2. These improvements suggest that the incidence of edge damage due to the presence of coarse inclusions should be reduced significantly. Since powder forging practices are employed to produce all low alloy steel powders, P/M users of these powders have benefited.

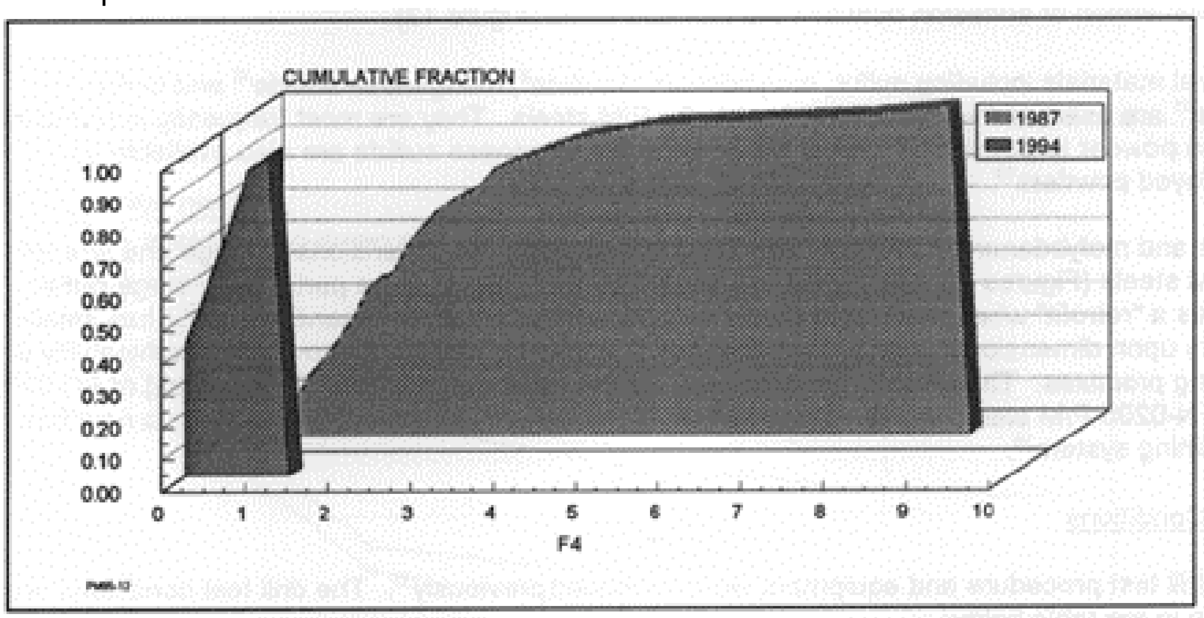

Figure 11: Microcleanliness of Ancorsteel® + 4600V

FREE MACHINING AGENTS

Free-machining agents may be added to P/M steels to improve machinability. These agents

are thought to perform several functions during the cutting process, including: initiation of

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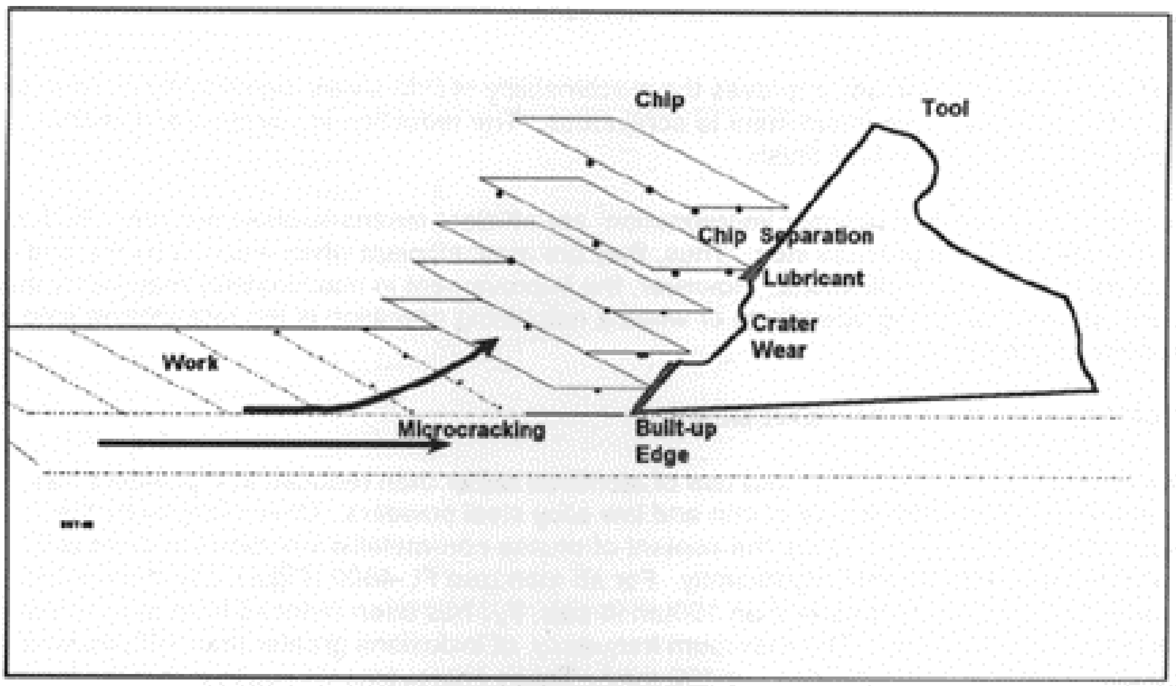

Figure 12: Potential Benefits of a Machining Agent

microcracks at the chip/workpiece interface, chip formation, lubrication of the tool/chip interface and prevention of adhesion between the tool and chips (Figure 12).

Several materials including sulfur, molybdenum disulfide, manganese sulfide and boron nitride are used as free-machining agents for P/M steels. They are most frequently introduced as fine powder to powder premixes, but sulfur and manganese sulfide are also available as
prealloyed powders

Sulfur and molybdenum disulfide have strong effects upon the dimensional change and strength of P/M steels (Figures 13, 14). Their use should be considered at the part design stage rather than as a “retrofit” when machining problems become apparent. Manganese sulfide has smaller effects upon dimensional change and strength. It may be used to improve the machinability of existing premixes. The effects of manganese sulfide upon the machinability in drilling of FC-0208 and FN-0205 P/M steels are illustrated below. They are compared to those of MnX, a new free-machining system.

Test Conditions

The drill test procedure and equipment were described previously. The drill test conditions are shown in the table below.

Drill Material	HSS	
Diameter	0.138 in	3.5 mm
Speed (rpm)	3285	3285
Feed (per rev.)	0.006 in	0.15 mm
Coolant	None	

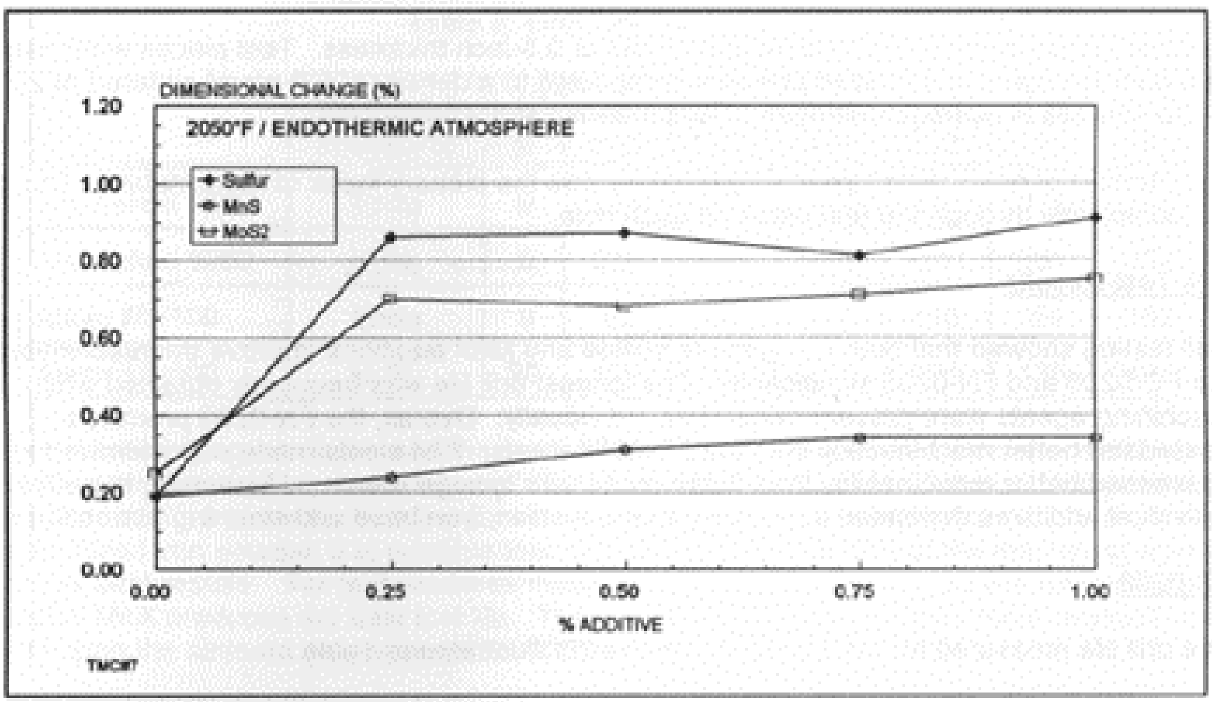

Figure 13: Effect of Machining Agents on Dimensional Change of FC-0280 Atomized Powder

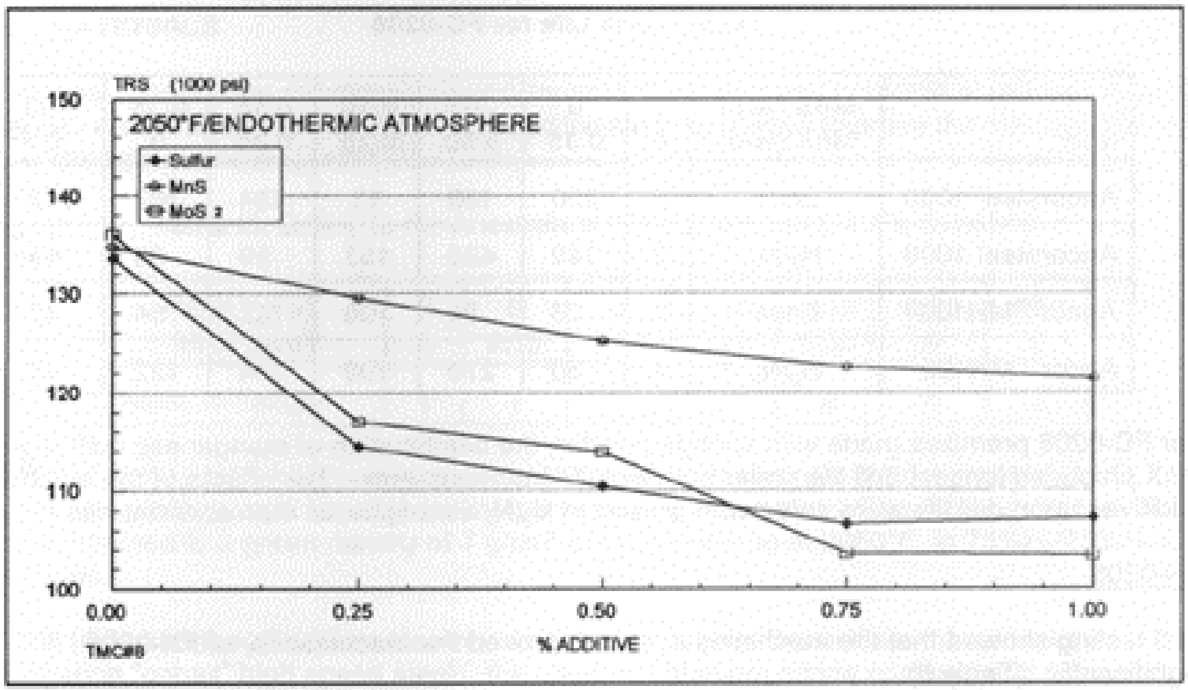

Figure 14: Effect of Machining Agents on Transverse Rupture Strength of FC-0208 Atomized Powder

The test pieces were 8″ x 2″ rectangular blocks of 0.5-inch thickness. Test pieces were made with both sponge and atomized powders compacted to a density of 6.8 g/cm^3 sintered at 2050°F for 30 minutes in hydrogen/nitrogen or endothermic atmosphere.

The number of holes drilled prior to drill failure was the primary index of machinability. The drill cut completely through the test piece on each hole.

Drill Test Results

Drill testing showed that both manganese sulfide and MnX additions improve the machinability of the FC-0208 and FN-0205 significantly. The longest drill life was frequently obtained when both machining agents were present rather than individually. Overall, the FN-0205 premixes possessed better machinability than the FC-0208 steels. P/M steels made with atomized powder possessed better machinability than those made with sponge powders. However, the effects of individual additives depended upon premix composition, iron base and sintering atmosphere.

FC-0208

The drill life measured for the FC-0208 premixes is illustrated in Table I.

Under the test conditions employed, all additives increased the machinability of FC-0208. For FC-0208 made with atomized powder, an 0.50 w/o manganese sulfide addition produced best drill life when sintered in endothermic atmosphere. However, when sintered in 75%H_2/25%N_2, 0.50 w/o MnX produced best performance. Earlier work has shown that 0.5 w/o additions of manganese sulfide can reduce strength and increase growth from die size. If this is unacceptable, then an 0.35 or 0.5 w/o addition of MnX increased drill life significantly.

Iron	MnS (w/o) MnX (w/o)	O O	0 0.35	0 0.50	0.10 0.25	0.15 0.35	0.35 0	0.50 0
Ancorsteel 1000	Endo	2	220	186	91	134	107	312
Ancorsteel 1000	H_2/N_2	2	149	428	153	99	89	49
Ancor++ MH100	Endo	2	23	55	108	157	64	42
Ancor MH100	H_2/N_2	4	30	270	100	584	122	48

Table I: Drill Life for FC-0208

For FC-0208 premixes made with sponge powder, the combination of manganese sulfide and MnX produced longest drill life under both sintering atmospheres. The effects of the machining additives upon drill life were somewhat greater in H_2/N_2 atmospheres than endothermic.

FN-0205

Drill testing showed that the machining agents improved the machinability of FN-0205 significantly. (Table II).

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	MnS (w/o) MnX (w/o)	O O	0 0.35	0 0.50	0.10 0.25	0.15 0.35	0.35 0	0.5 0
Ancorsteel 1000	Endo	9	250	275	1400	473	336	498
Ancorsteel 1000	H_2/N_2	8	280	816	1400	1251	331	352
Ancor++ MH100	Endo	9	62	120	111	416	54	152
Ancor MH100	H_2/N_2	26	109	172	481	991	136	497

Table II: Drill Life for FN-0205

All free-machining agents increased the machinability of the FN-0205 test pieces under the conditions employed. The combination of manganese sulfide plus MnX produced longer drill life than either additive alone for both iron bases and both sintering atmospheres. In premixes made with atomized iron powder, it is possible that an 0.35 w/o total addition of the machining agents produces best results. For test premixes made with Ancor MH1OO, an 0.50 w/o total addition of MnS plus MnX produces the best tool life. These levels of machining agent have relatively minor effects upon the sintered properties of FN-0205.

Summary

The drill tests show that additions of free-machining agents improve the machinability of P/M steels such as FC-0208 and FN-0205 significantly. In many cases, particularly FN-0205, a combination of additives produced better results than individual additives. The results are for laboratory tests with HSS drills. They should be used as a basis for initial production trials and verified by controlled tests.

TOOL MATERIALS

Drill testing showed that machining agents improve the machinability of P/M steels significantly. However, similar tests showed that these additives do not always improve the machinability of higher strength materials (Table III).

MnS (w/o) MnX (w/o)	O O	0 0.35	0 0.50	0.10 0.25	0.15 0.35	0.35 0	0.50 0
Holes to Failure	1	1	2	2	3	4	2

Table III: Drill Life for Ancorsteel 85HP:2% Nickel, 0.5% Graphite

A series of cutting tests was undertaken to assess whether changes to tool material, tool geometry or coating could improve cutting performance in this alloy. The rectangular test blocks were compacted to a green density of 7 g/cm^3 prior to sintering at 2050°F, in 75%H_2/25%N_2 for 30 minutes.

The drill test used the conditions described above. However, the test examined higher performance “cobalt” high speed steels, the effects of titanium nitride coatings and different tool geometries. such as parabolic flutes or “split points” (Figure

15).

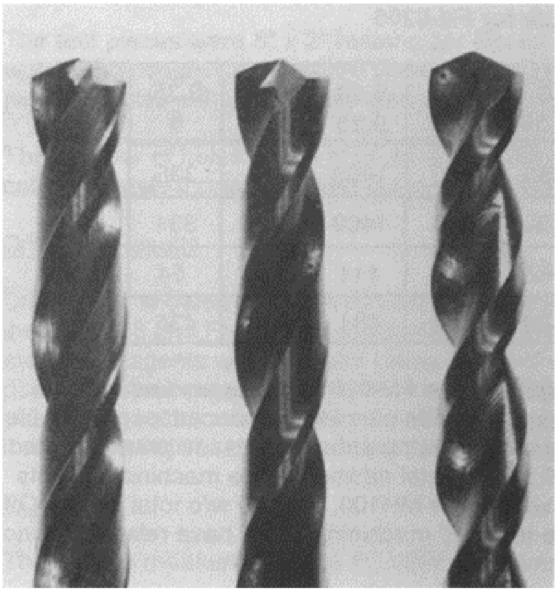

Figure 15a

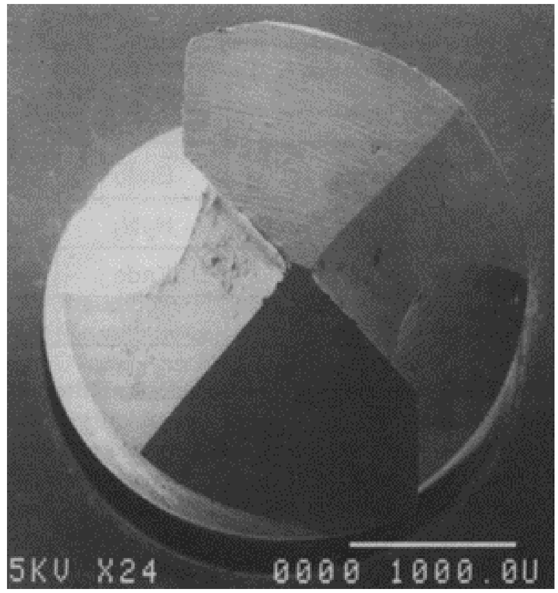

Figure 15b

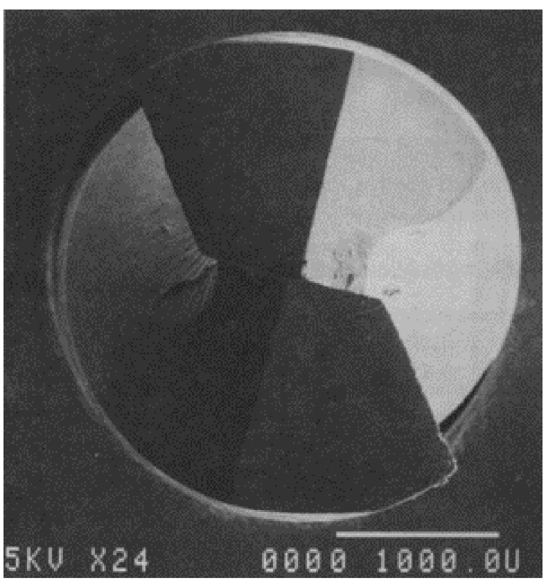

Figure 15c

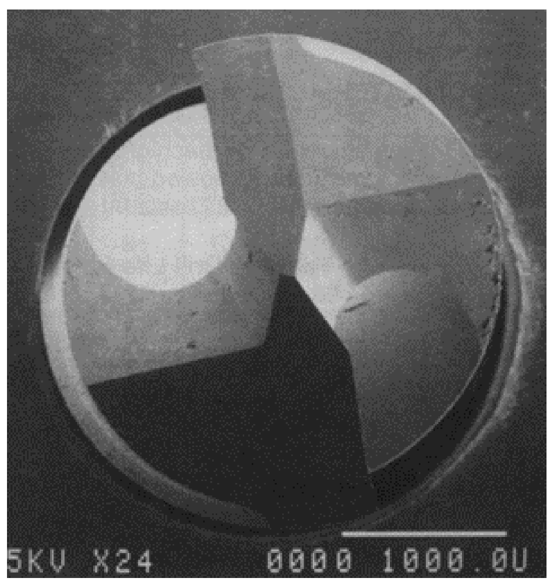

Figure 15d

Figure 15: Comparison of three HSS drill profiles used in cutting tests.
a: Macro-photograph of flutes
b: SEM image of conventional drill point
c: SEM image of parabolic flute point
d: SEM image of split point

The results illustrated in Table IV were somewhat surprising.

Steel Type	Coating	Flute Form	Point	Drill Life
Base HSS	None	Standard	135°	2
M42	None	Standard	135°	2
Base HSS	TiN	Standard	135°	1
HSS	None	Parabolic	135°	1
Cobalt HSS	None	Parabolic	135°	3
M7HSS	TiN	Parabolic	135°	44
Cobalt HSS	TiN	--	Split	85

Table IV: Effect of Drill Type Upon Drill Life When Cutting Ancorsteel 85HP:2% Nickel, 0.5% Graphite

They indicated that individual improvements to high speed steel, flute form or coating, had relatively little effect upon drill life under the test conditions employed. However, when combined, drill life increased significantly.

Attempts to improve drill life further by using solid carbide drills were unsuccessful. The solid carbide drills appeared to be too brittle for the test conditions and drilling system employed.

The test results did show clearly that drilling of very high strength P/M steels can be improved using similar improvements in tool materials and design to those used for high strength wrought steels.

MICROSTRUCTURE MODIFICATION

Wrought steels are frequently heat heated by producers to possess optimum machinability. Annealing or normalizing treatments are used to produce a relatively coarse pearlitic or spheroidal microstructure that possesses good machinability. Higher carbon steels require longer heat treatment cycles intended to produce coarse carbides dispersed in ferrite. In contrast, low carbon steels may be partially hardened to produce a microstructure that is less ductile and adhesive than fully annealed steels.

Recent work has shown that reducing cooling rates from sintering can improve the machinability of FC-0208. However, the coarser microstructure reduces mechanical properties somewhat. A limited series of experiments was conducted to assess whether tempering or simple annealing treatments could improve the machinability of the 0.85 w/o molybdenum, 2 w/o nickel steel.

The results were generally disappointing. The simple tempering and annealing cycles used produced less improvement in machinability than tool improvements (Table V)

It was noticeable that the annealing treatment at 1600°F changed the failure mode of the HSS drill. The drill appeared to adhere to the workpiece and snap rather than overheat.

The treatments changed the microstructure and properties of this high strength steel (Figure 16). The tempering treatments had less effect upon the microstructure and properties of the

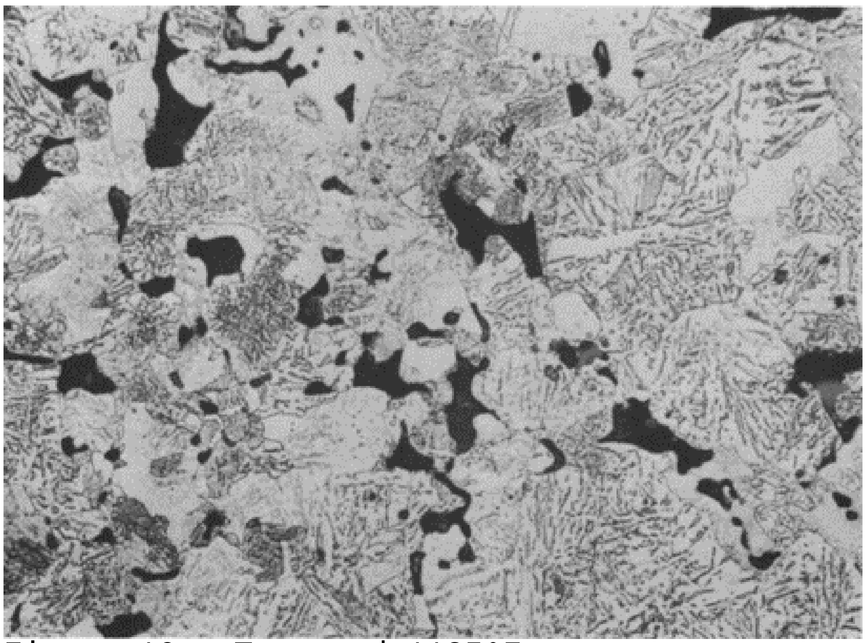

Figure 16a: Tempered 1125°F

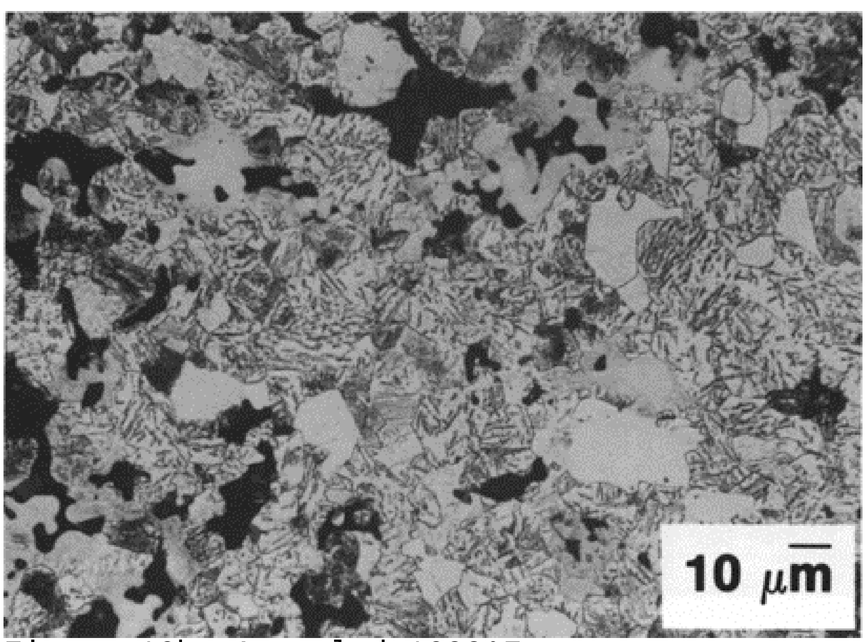

Figure 16b: Annealed 1600°F

Figure 16: Microstructure of heat treated Ancorsteel 85HP: 2 w/o nickel, 0.5 w/o graphite. Etched with a combination of 2% nital/4% picral. Original magnification 400X.

Treatment	Temperature (°F)	Time (hrs.)	Cool	Holes to Failure	Hardness HRB
Temper	300	1	Natural	4	78
Temper	575	1	Natural	8	71
Temper	850	1	Natural	14	82
Temper	1125	1	Natural	6	74
Temper	1600	1	Furnace	7	57
As-Sintered		--		3	73

Table V: Effect of Heat Treatment Upon Machining of Ancorsteel 85HP:2 w/o Nickel, 0.5 w/o Graphite

Ancorsteel 85HP:2 w/o nickel steel than anticipated. The steel proved to be very temper resistant. Even when tempered at 1125°F, its yield strength was close to as-sintered values. Ultimate tensile strength was reduced from 84,000 to 71,500 psi as shown in Table VI.

The microhardness results suggest that a form of precipitation hardening may have occurred in the pearlitic or bainitic areas of the microstructure. This may account for the increase in yield stress and loss of ductility with increasing tempering temperature. In contrast, the nickel-rich areas show a slight reduction in microhardness on tempering.

Annealing at 1600°F reduced both apparent and microhardness. It also changed the microstructure from a fine dispersion of carbides in ferrite (Figure 16a) to more discrete coarser ferrite in fine bainite or pearlite (Figure 16b). Annealing did not produce the desired coarse pearlite. Nor did it increase drill life. Annealing may have changed the failure mode from abrasive to adhesive. The drill appeared to “stick” to the workpiece when cutting the annealed test pieces, rather than overheating or breaking.

Treatment	Temp. (°F)	Density (g/cm^3)	Yield (10^3 psi)	UTS (10^3 psi)	Elong. (%)	App. Hard. HRB	MicroHardness (HV_{50g})	
							Pearlitic	Ni-Rich
As-Sintered	--	7.16	56.8	84.0	2.3	82	245	442
Temper	300	7.17	62.1	84.9	2.4	82	285	442
Temper	575	7.17	65.1	82.1	1.8	80	277	346
Temper	850	7.16	66.4	77.4	1.7	87	285	326
Temper	1125	7.16	58.5	71.5	1.4	84	245	366
Anneal	1600	7.18	21.7	42.2	6.3	36	251	346

Table VI: Effect of Heat Treatment Upon Tensile Properties of Ancorsteel 85HP:2 w/o Nickel, 0.5 w/o Graphite

Compaction: 0.5 w/o ethylene bisstearamide, 40 tsi
Sintering: 2050°F, 75%H_2/25%N_2, 30 minutes, belt furnace

The experiment indicates that the heat treatments employed did not change the microstructure and machinability of P/M steels sufficiently. The results do not indicate the extra process step is justified. Further study is necessary to define the optimum microstructure and heat treatment for machinability. It is possible that: increasing “tempering” temperatures to 1200-1350°F, sub-critical annealing or controlled transformation annealing after sintering may improve machinability further.

Since such treatments add an extra process step, they are justified only where parts require extensive machining prior to heat treatment.

DISCUSSION

The results above illustrate that the machining of P/M steels can be improved by several techniques including pore closure, free-machining agents, tool materials and tool design. Control of microstructure by annealing was less successful.

The experimental results indicate that there is no universal solution to machining problems. Free-machining agents are very successful in general purpose materials, such as FC-0208 or FN-0205 but much less successful in high strength P/M molybdenum nickel steels. These steels responded better to changes in tool material and tool design.

In applications where machining is key to the success of a P/M part, evaluation of tool materials, free-machining agents and composition should begin at an early stage in part development. Ideally, it requires interaction between part producer, tool supplier and powder supplier.

The test results also illustrated the limitations of accelerated tests that result in total tool failure Firstly, they destroy the tool and evidence of wear modes. They also produce very limited tool life. Optimum heat treatment increased drill life in the molybdenum nickel steel from 3 to 14 holes. This does not appear to be practically significant. However, if a similar relative increase from 30 to 140 holes is obtained under less severe conditions, it may be of practical benefit

The heat treatment experiments illustrate the lack of knowledge of the fundamental behavior of P/M steels compared to competing wrought products. There are very few published isothermal or continuous cooling transformation curves for P/M steels. Such curves are necessary to design efficient annealing, sinter-hardening and heat treatment cycles.

CONCLUSIONS

The machinability and machining response of P/M steels can be explained partially by their porosity, composition and microstructure.

The laboratory trials indicate:

1. The machinability of general purpose P/M steels, FC-0208 and FN-0205, can be improved significantly by free-machining agents such as manganese sulfide and MnX, particularly when used together.

2. Increasing the amount of a free-machining agent does not always improve machinability.

3. Relatively high additions, 0.5% and above, of sulfur or sulfide free-machining agents increase the dimensional change and reduce the strength of P/M steels, particularly FC-0208 made with atomized powder.

4. Machining agents are less successful in higher strength P/M molybdenum nickel steels. Improvements to tool materials and tool design improve the machining of P/M steels.

5. Annealing or tempering treatments may improve the machinability of P/M steels but reduce mechanical properties. They may be justified for complex parts that require heat treatment to meet performance requirements.

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