

Machinability: A Material Property or Process Response?

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INTRODUCTION

Although P/M is considered a net, or near-net shape process, many pressed and sintered ferrous parts are machined prior to final assembly. During part conversions, the potential differences in machining response between P/M and conventional, particularly cast iron parts may cause concern. These concerns are frequently supported by personal experience when prototype P/M parts are machined using the tools and conditions used for the conventional part. Alternately tables of relative machinability for cast irons and steels are used to justify concern over the machinability of P/M steels. This approach to comparative machinability ratings is questioned in Machining Data Handbook, "There appears to be an endless desire to provide machinability ratings for materials" (Ref. 1).

A more radical view of machinability was expressed by Trent who suggests, "There is no clear cut unambiguous meaning to this term" (Ref. 2). However, changes in tool life under defined conditions clearly change manufacturing costs and lead to the classification of materials as having good or poor machinability. An alternative viewpoint is that the microstructures of P/M steels differ considerably from those of wrought steels or cast irons of equivalent strength, so that we should anticipate a difference in machinability and allow for such differences at the design stage

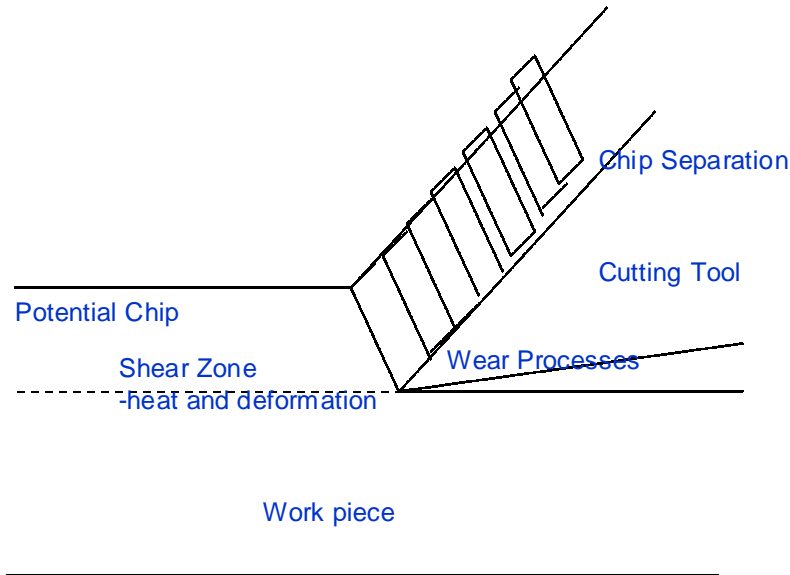
This paper will try to illustrate that the "machinability" of P/M steels is a response to the machining process, not an inherent material property, and that by changing the cutting process we can reduce cutting forces, reduce tool wear and increase tool life.

MACHINING AS A PROCESS

If machining is considered as a process and machinability is considered as the result of interaction between the material, cutting tool and machining conditions, then by improving the process it should be possible to reduce tool wear under a given set of conditions. It should also be possible to develop machining processes including changes to: materials, cutting tools and machining conditions to machine P/M steels successfully with "machinability" equivalent to competing materials.

Using the example of orthogonal cutting, we can see that chip formation is a complex process in which stresses ahead of the cutting tip initiate micro-cracks and separation of the chip from the work-piece. The separated chips flow over the tool and are removed from the cutting area.

Fig. 4. Schematic of Cutting Process



Metal cutting subjects both the cutting tool and the “chips” to high forces and shear rates that cause intense local heating close to the cutting edge that can cause plastic deformation or fracture of the cutting edge. The relative motion of the “chip” across the cutting tool can cause a variety of wear mechanisms including: sliding wear, adhesive wear, deformation of the tool edge and chemical reactions between the cutting tool and work or chip. The observed machinability of a material thus results from reactions between the composition and microstructure of the work-piece and that of the cutting tool under the cutting conditions.

These problems are observed when cutting wrought materials and can be resolved by changes to cutting conditions such as: speed, depth of cut and feed rate. Correct choice of speed, depth of cut and feed rate often produces large reductions in tool wear and increased productivity without other changes to the tool material (Ref 3). Whenever possible suppliers of wrought and cast products will supply a material that has a microstructure that is controlled to meet the requirements of forming or machining processes.

P/M STEELS

The composition and microstructures of sintered P/M steels, particularly those used in structural parts, differ significantly from those of wrought steels. The most obvious differences (Fig. 2) are the presence of porosity and the high pearlite contents that result from the high carbon contents of many MPM standard steels.

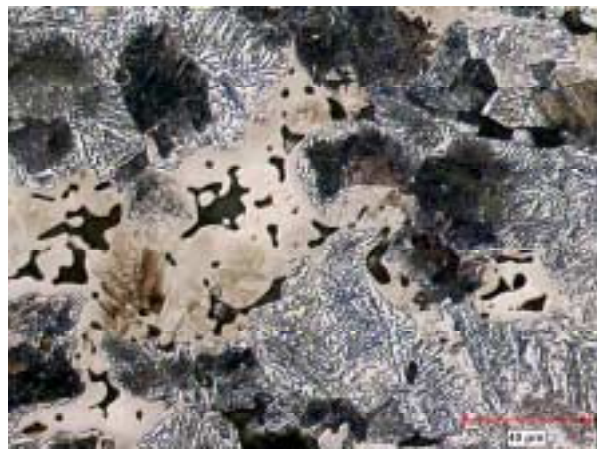


Fig. 2: Microstructures of Sintered FC-0208 and FLN2-4405

The presence of porosity reduces thermal conductivity and provides a path for coolant loss into the sintered part. The pores may cause local “micro-impacts” as the tool enters and leaves the work-piece the part. Sintering does not produce a uniform distribution of admixed alloying elements, such as copper and nickel. Consequently, the microstructure of a high strength sintered P/M steel may also contain areas of bainite and martensite that result from the differences in composition and hardenability. The differences in microstructure change the local cutting at the cutting edge.

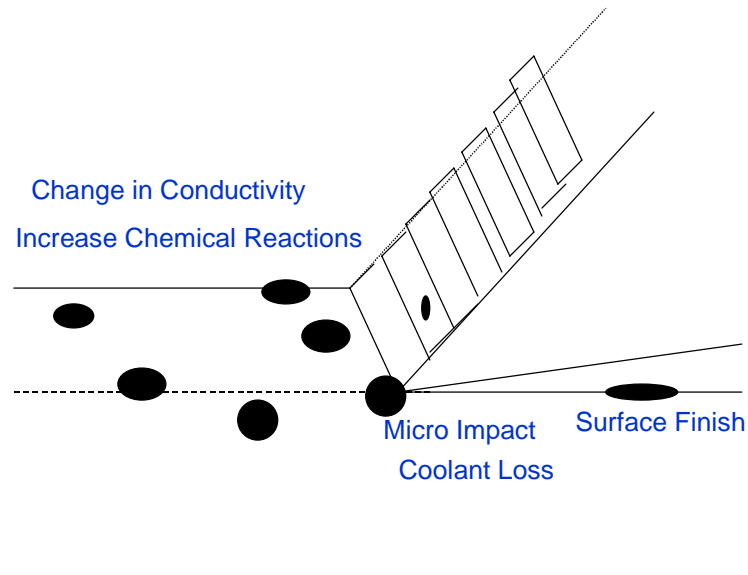


Fig. 3: Potential Effects of Porosity on Cutting

When combined these effects tend to produce more tool wear under conditions optimized for a wrought part of equivalent strength and lead to the view that P/M steels are difficult to machine. The recent widespread application of sinter-hardening steels that possess microstructures and properties close to those of heat-treated cast irons and steels has tended to reinforce this view.

MACHINABILITY IMPROVEMENT

There are several proven techniques to reduce tool-wear when machining P/M steels. These include:

- Porosity Reduction
- Change Microstructure
- Free Machining Additives
- Change Conditions
- Improve Cutting Tool
- Green Machining

Many of these techniques were developed for wrought steels and have been adopted successfully in P/M. More recently the greater flexibility of the P/M process has enabled further improvement to these techniques.

POROSITY REDUCTION

Reducing, or closing, the porosity in sintered P/M steels will generally reduce tool wear. Proven techniques include resin impregnation and copper infiltration (Ref. 4). Both techniques introduce an extra process step and tend to increase part cost. Where sealed or closed pores are required for part function the improved machinability of an impregnated part can be a major advantage.

CHANGE MICROSTRUCTURE

Many cast and wrought products are heat-treated to produce a more easily machined microstructure. Examples include spheroidizing of high carbon steels and normalizing of low-carbon ductile steels. The same processes can be applied to P/M steels (Ref. 5), however the thermal cycles add an extra process step or require extensive modifications to sintering furnaces.

An alternative means to modify microstructure is to add an iron powder of different composition to the premix (Ref 6). The difference in composition is intended to produce deliberate segregation within the sintered microstructure. Local differences in ductility enhance chip formation or may change the balance of ferrite and pearlite so as reduce crater wear. Drill testing confirmed that additions of a second alloy can increase drill life when machining FC-0208 compositions (Fig. 4).

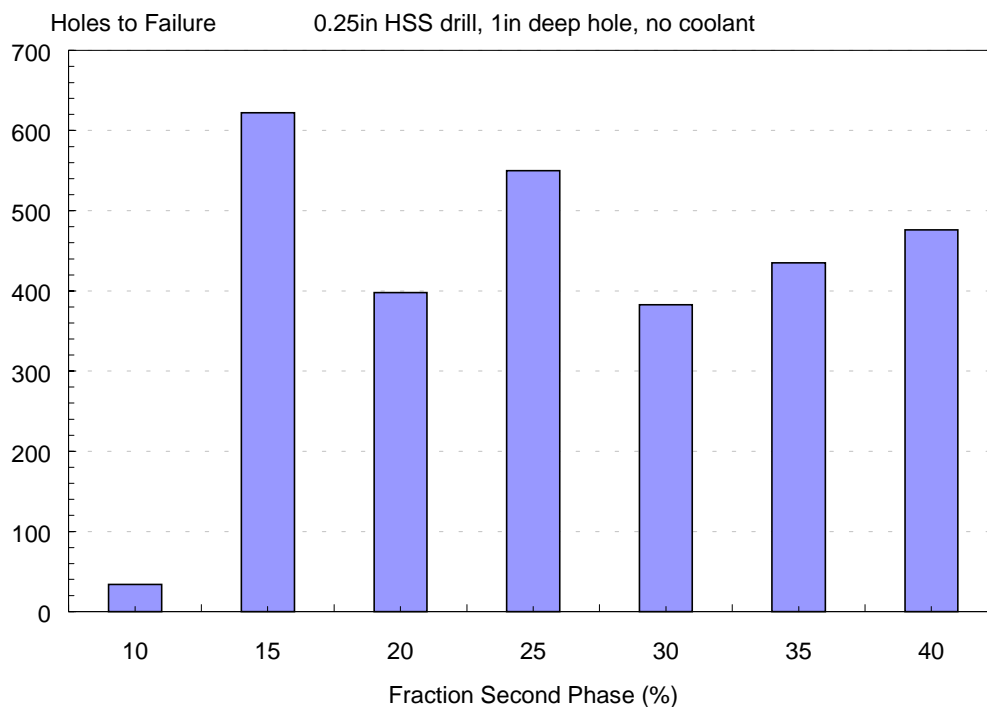


Fig. 4: Effect of Second Phase on Drill Life in FC-0208

This technique is most efficient at the part design stage when changes in alloy composition can be combined with changes in sintered carbon content to meet requirements for strength, ductility and machinability.

FREE-MACHINING ADDITIVES

A more widely practiced means to enhance machinability is to add a free agent to the iron powder or premix. Free machining agents combine several functions close within the cutting process (Fig. 5) including chip formation, lubrication of the tool face and reduction of crater wear.

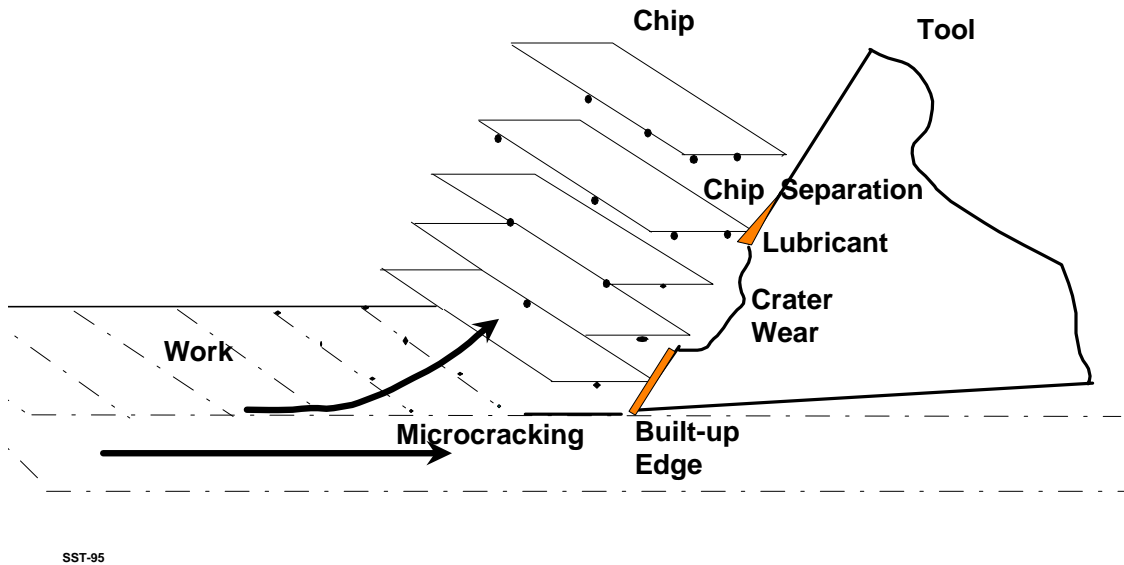


Fig. 5: Possible Functions of a Free-Machining Additive

Although several materials have been examined as free-machining additives, sulfides, particularly manganese sulfide have proven most successful in a wide range of P/M steels.

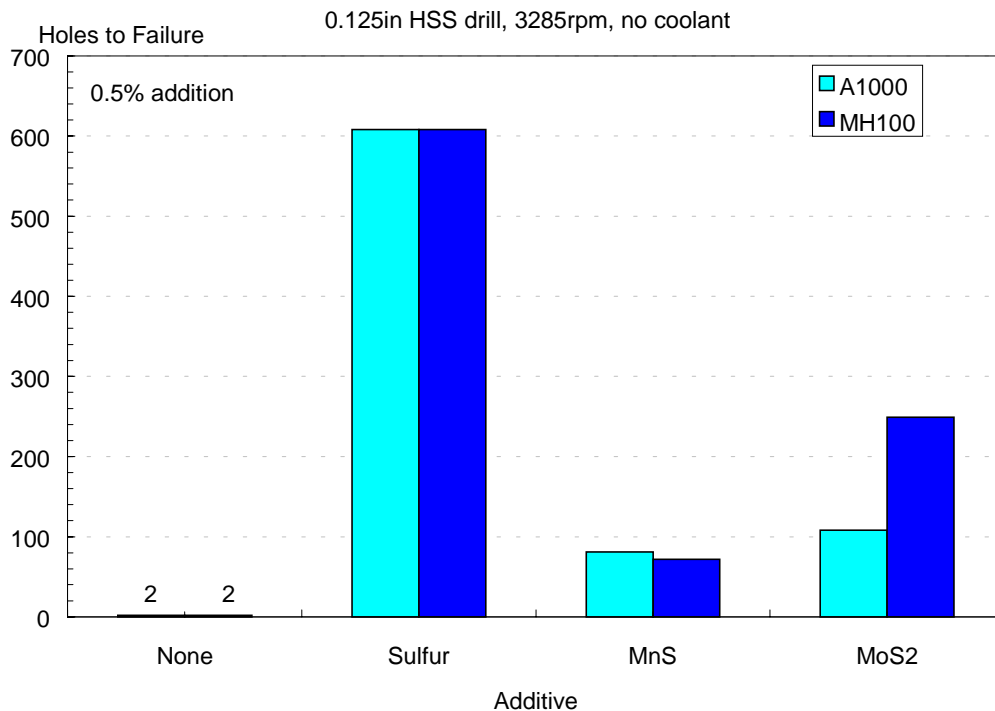


Fig. 6: Effect of Sulfide on Drill Life in FC-0208

Additions of sulfur or molybdenum disulphide can produce large improvements in tool life (Fig. 6). However, their lack of stability and effects upon dimensional change during sintering (Ref. 7) make them less suitable than manganese sulfide, unless a machining operation is the major “bottleneck” in part production.

P/M processing allows considerable flexibility in design of alloys and microstructure through the ability to combine different alloys as pre-alloys or premix ingredients. One example of this is a modified FC-0205 composition intended to displace a cast-iron. By combining a second phase additive with admixed manganese sulfide, the modified P/M steel has equivalent mechanical properties to the cast iron and superior machinability as indicated by a drill test (Fig. 7).

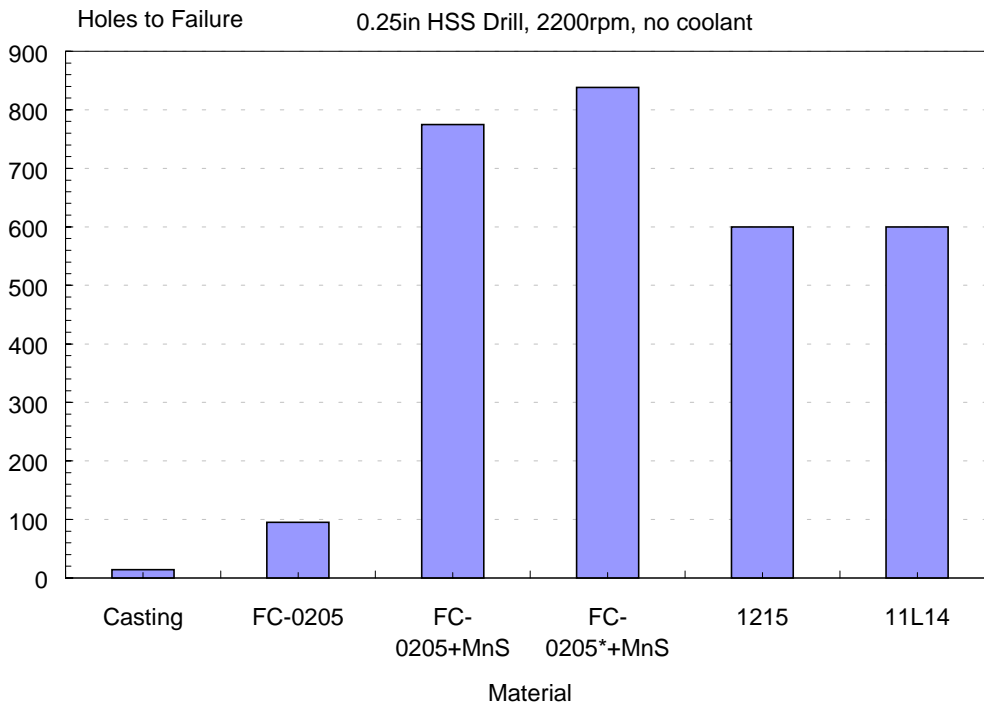


Fig. 7: Comparison of drill life in modified FC-0205

Introducing the second phase increased the yield and tensile strength of the FC-0205 without increasing carbon content which would have reduce ductility and drill life. The presence of the second phase and manganese sulfide increased drill life significantly, and reached the target of 600 holes offered by the wrought 1215 and 11L14 steels. Drill wear in the modified FC-0205 plus MnS was slightly higher than for the 11L14.

IMPROVED CUTTING TOOLS

When machining higher performance steels, the introduction of manganese sulfide may not provide the required increase in tool life under a defined set of machining conditions. In this case improvements to tool materials and cutting tool design are beneficial. Under test conditions, an as sintered FLN2-4405 proved difficult to drill. Addition of 0.35% manganese sulfide did not increase drill life (Fig. 8).

Under the same conditions progressive improvements in: tool material, from a standard high speed steel, to “cobalt HSS, then addition of TiN coating plus refinement to drill point geometry increase drill life from two holes to over 80 holes under the same test conditions.

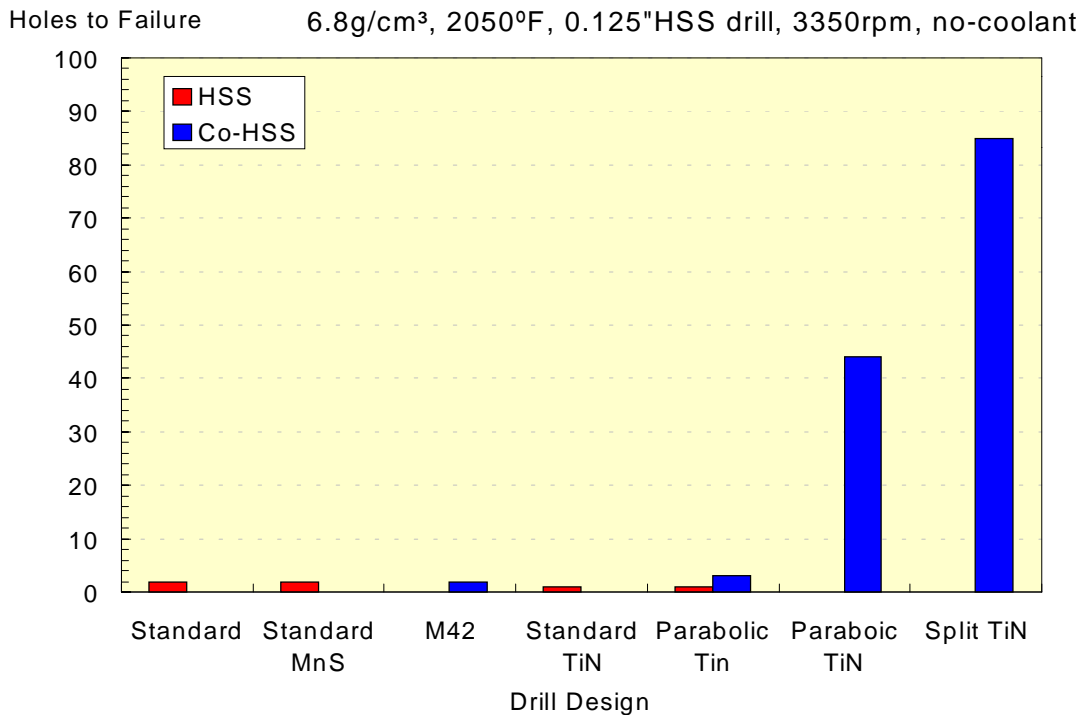


Fig. 8: Effect of drill design on drill life in FLN2-4405

In this test sequence it is apparent that the major increase in life required an optimized combination of tool design, tool coating and a high performance base material. None of the individual changes alone produced a significant increase in drill life.

The importance of tool design is shown during development of a ductile P/M steel to replace an SAE 604010 ductile iron. The primary requirements were to meet the strength and elongation of the casting while maintaining good machinability. The steel developed to meet these requirements possessed a ferrite microstructure very similar to that of the casting (Fig. 9).

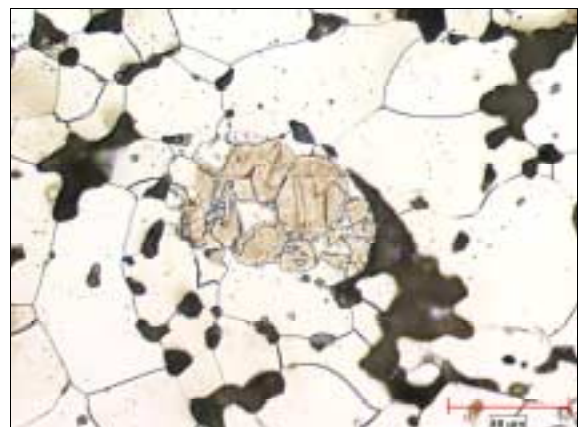
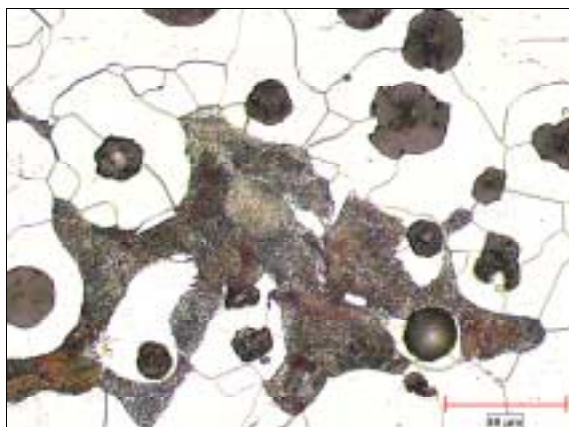


Fig. 9: Microstructure of 604010 cast iron and P/M equivalent

Manganese sulfide was added as a free machining agent. Cutting tests, consisting of a single point face milling operation, confirmed the beneficial effects of manganese sulfide (Fig.10). The P/M steel with manganese sulfide produced longer tool life than the casting.

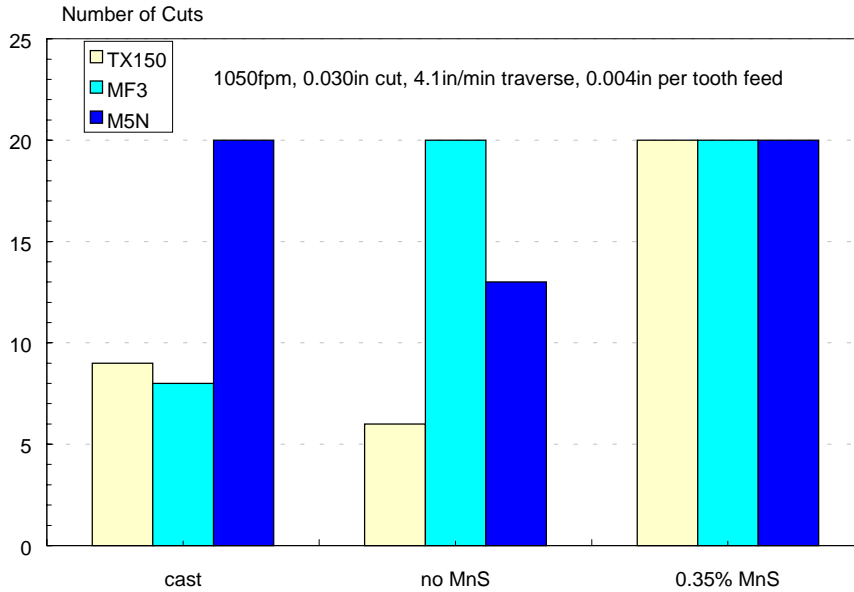


Fig. 10: Comparison of Tool Life for cast and P/M 604010

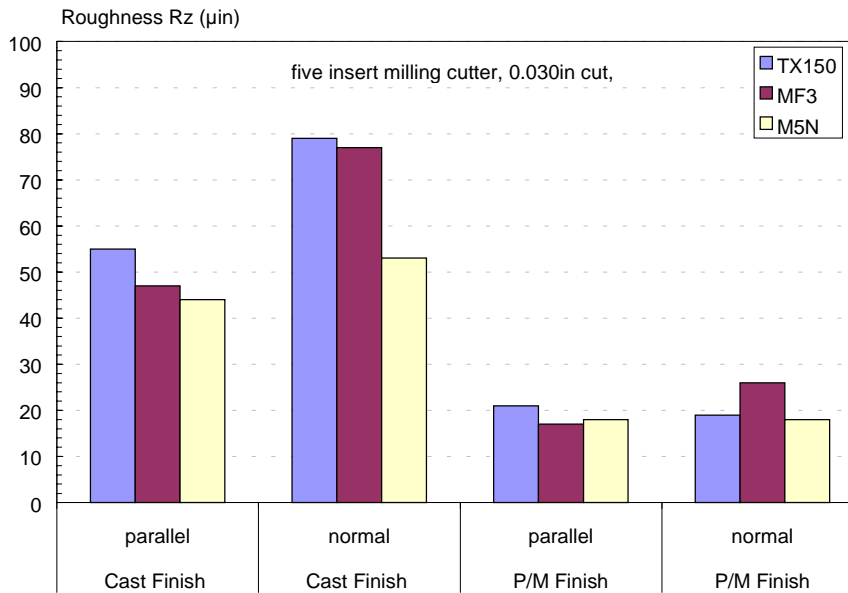


Fig. 11: Surface Finish of Cast and P/M 604010

Use of a chip-breaker pressed into the coated cutting tool reduced tool wear, reduced cutting forces and improved surface finish. The surface finish of the P/M steel with manganese sulfide was superior to that of the cast iron and less sensitive to insert geometry when cut with a multiple insert milling-cutter.

Machining a tough ductile P/M steel is a relatively unusual problem. The machining of sinter-hardening P/M steels is becoming a more common operation due to the economic attractions of the sinter-hardening process compared to more conventional heat treatments. Sinter-hardening steels possess high macro-hardness of 30 to 45HRC due to their microstructure of high carbon martensite (Fig. 12) with a micro-hardness of 700 to 850HV.

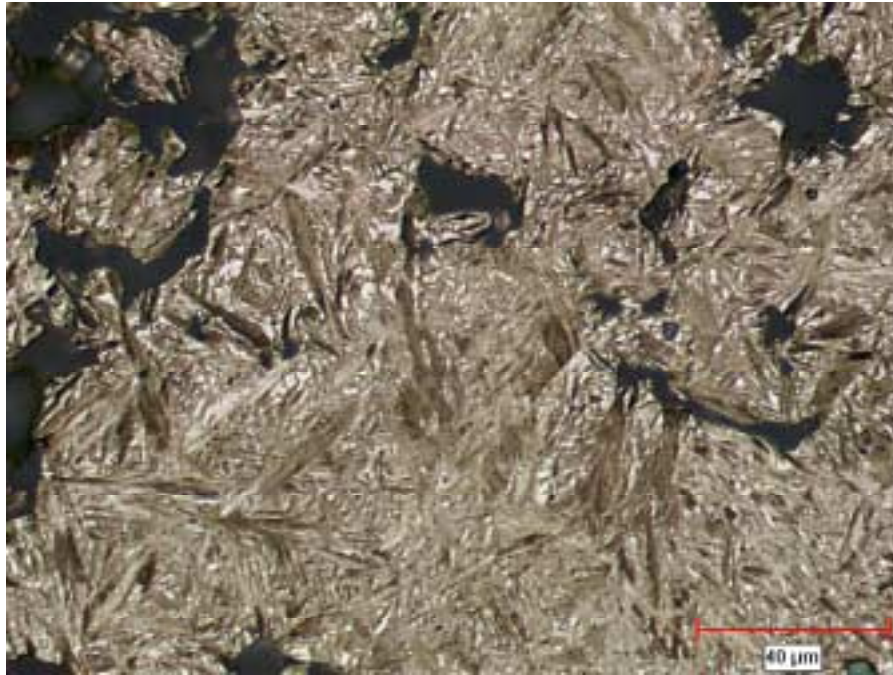


Fig. 12: Microstructure of Sinter-Hardened Ancorsteel 737SH, 2% Copper, 0.9% Graphite.

Despite these challenges, sinter-hardening P/M steels can be machined successfully with careful attention to tool materials and tool design. The results confirm that polycrystalline boron nitride is the most successful tool material (Fig. 13) experiencing very low wear.

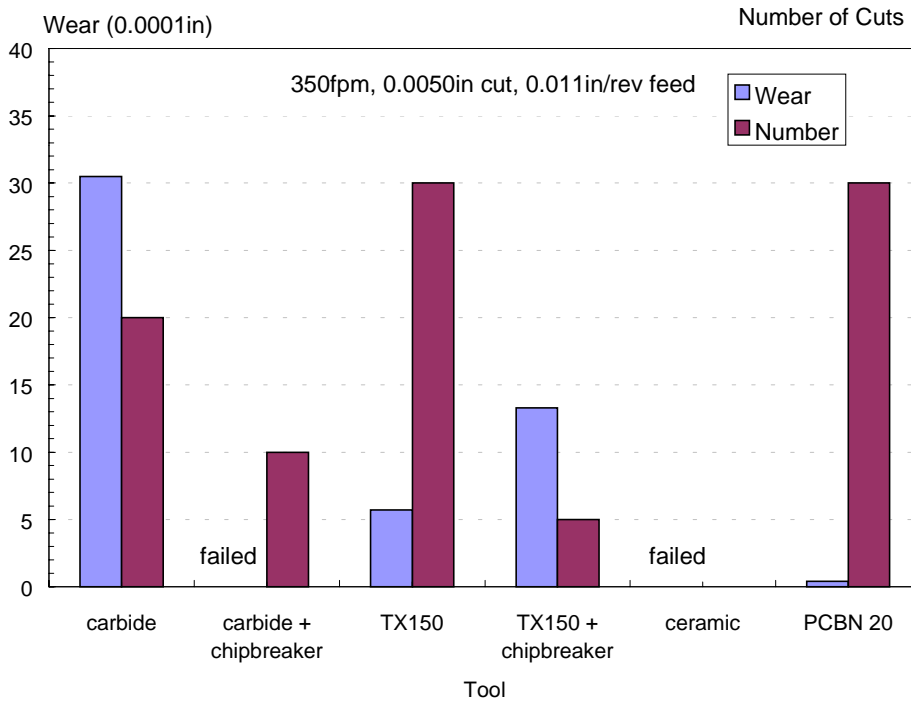


Fig. 13: Hard Turning of Sinter-Hardened Ancorsteel 737SH, 2% Copper, 0.9% Graphite

An advanced cemented carbide insert that possesses a multi-layer coating produced acceptable tool but slightly more wear than the PCBN under the cutting conditions employed. The “standard “ carbide insert experienced high wear and failed before the end of the test. It did not possess the hardness and wear resistance to cut the microstructure. A ceramic failed catastrophically on entering the test piece. It appears that the cutting material did not possess the toughness to withstand the impact of cutting the P/M steel. This may account for the relatively poor performance of the carbide inserts that contain a chip-breaker. Both the “standard” carbide and the TX150 experienced premature failure when used with chip-breakers”. It appears that the thinner cutting edge of the chip-breaker compared to the standard edge does not possess the mechanical strength and shock resistance to machine the porous martensite.

Drilling of sinter-hardened P/M steels with HSS drills is relatively more difficult than turning. Even the higher performance drill employed successfully for FLN2-4405 experience rapid tool wear and failure due to edge deformation. With further development of cutting conditions it is possible that newer coated HSS and carbide tools may be used to drill some sinter-hardened steels.

GREEN MACHINING

Given the challenges of machining, particularly turning, of high carbon martensite, it is advantageous to consider machining sinter-hardening P/M steels in the green condition prior to sintering. Green machining has several potential advantages including lower cutting forces and lower tool wear. Machining of green compacts should also offer more shape flexibility than die pressing alone.

A key requirement is that the green compact possesses sufficient green strength to withstand the stresses imposed during handling, clamping and machining operations. The green strength of compacts produced with conventional lubricants is marginal or too low to withstand conventional machining processes. Newer premix technologies such as ANCORDERNSE and AncorMix HGS increase green strength significantly (Fig. 14) so that green parts can be handled and machined efficiently.

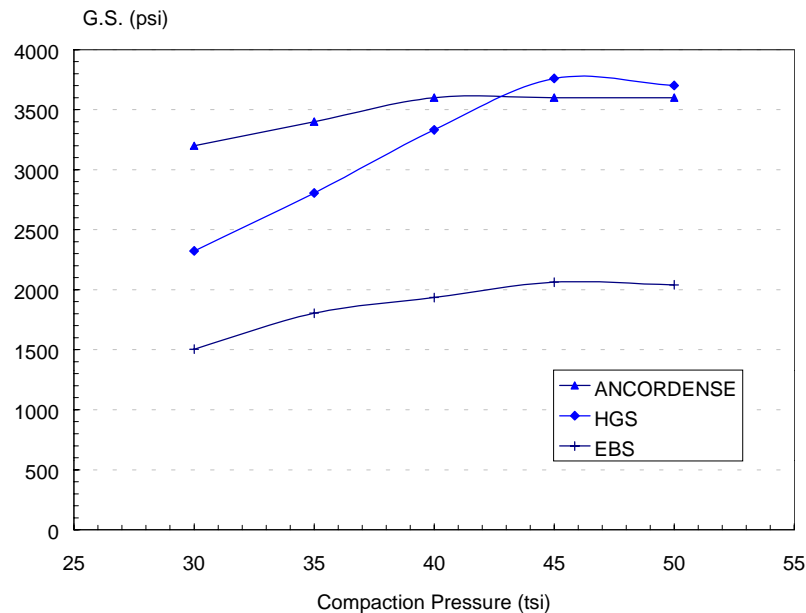


Fig. 14: Comparison of Green Strengths for Premix Systems

These proprietary premix technologies increase green strength by 50 to 100% depending upon compaction pressure. ANCORDERNSE, in which both powder and die are preheated, offers superior properties at low compaction pressures and in larger parts. In pressing AncorMix HGS premixes it is beneficial to heat the die only to about 65°C (145°F), although in many cases the heat introduced by compaction and ejection is sufficient to maintain good lubrication and improved part performance. The higher green strength offers advantages of less part damage during handling and provides excellent drilling of green sinter-hardening steel compacts (Fig. 15).

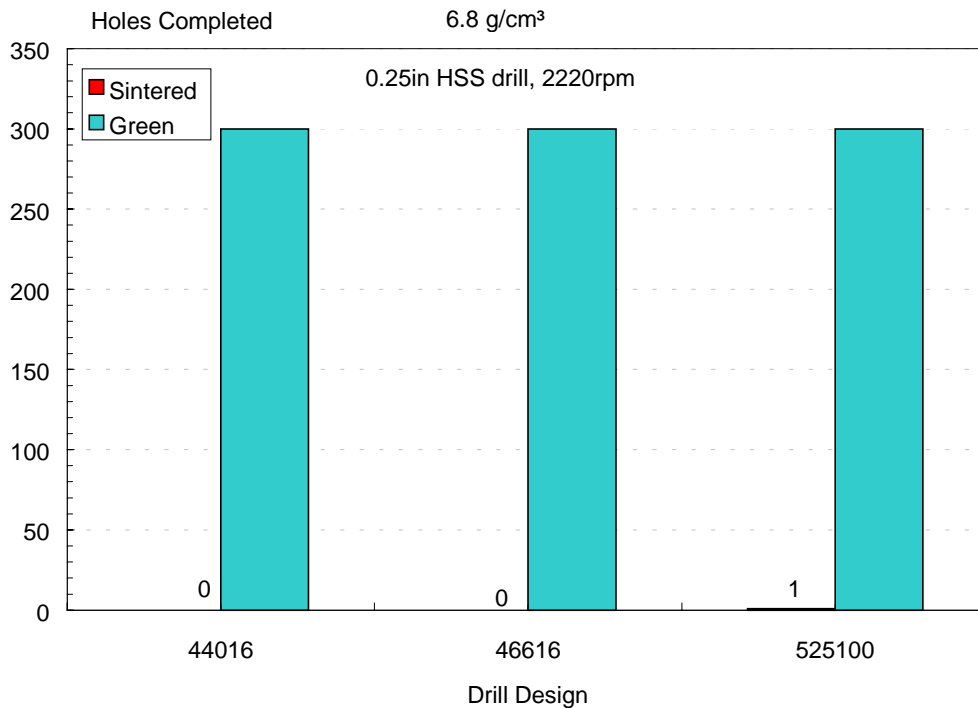


Fig. 15: Comparison of Drilling Ancorsteel 737SH, 2% Copper, 0.9% Graphite

Machining tests confirm the anticipated advantages of green machining. When drilling Ancorsteel 737SH, 2% Copper, 0.9% Graphite with HSS drills, drill life is excellent with both standard and higher performance drills and cutting forces are low. As reported previously, there are interactions between drill design and hole quality when drilling through holes (Ref. 8).

The improved tool life offered by green machining extends to turning operations, where it can be seen that green compacts can be machined successfully with a range of cutting tools (Fig. 16). All tool materials reached the end of the cutting test. However, there were differences in tool wear and cutting forces.

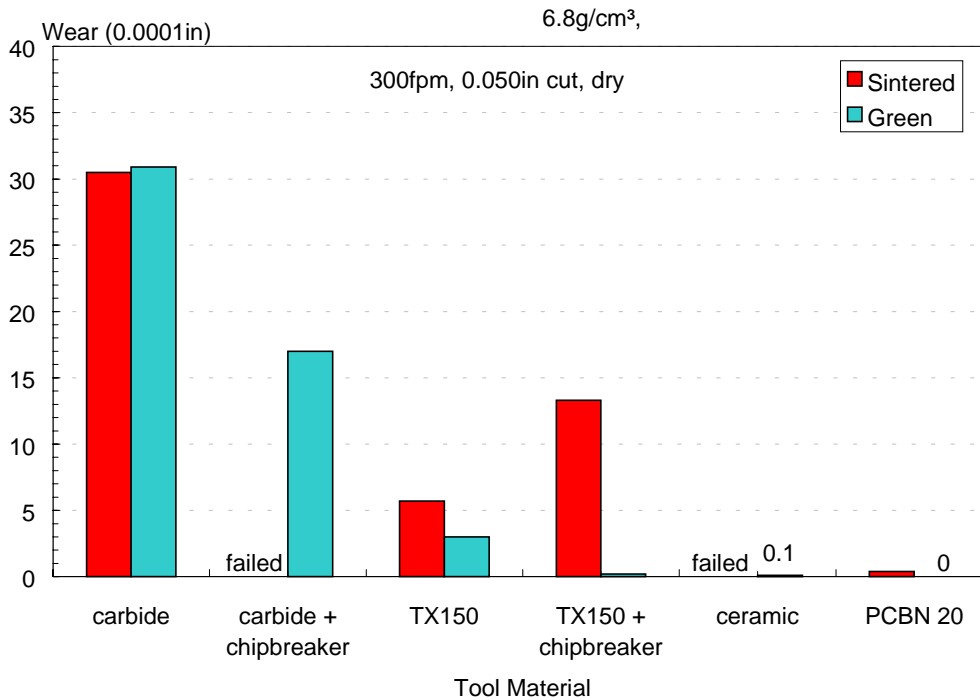


Fig. 16: Tool Wear in Green and Sintered Machining of Ancorsteel 737SH, 2% Copper, 0.9% Graphite

The results suggest that a hard tool surface provided by the PCBN, ceramic and TX150 is beneficial even in the green condition. The lower cutting forces required for green test pieces enable a chip breaker to be beneficial when using the carbide inserts. The lower forces also allow the ceramic insert to be used successfully in turning the green compacts.

CONCLUSIONS

P/M steels frequently possess different microstructure to cast and wrought materials of similar strength and performance.

The porosity and microstructure of P/M steels present different interactions with the tool material to conventional materials and produce different patterns of tool wear.

If the differences in microstructure are understood P/M steels and machining conditions can be developed to be machined as successfully as competing materials.

Green machining of high green strength compacts offers considerable benefits in machining operations.

Machinability is a response of the material and cutting tool to the machining process under a given set of conditions, not a material property.

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