

Lubrication & Machining of Compacted Graphite Iron

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Scope:

Compacted graphite iron (CGI) continues to gain use within the automotive industry. The material is being used for the manufacture of brake disks, exhaust manifolds, cylinder heads, as well as diesel engine blocks.¹ The higher strength properties of CGI, compared to those of gray iron, enables the manufacture of engines with higher pressure operating combustion chambers, yielding more efficient engines with reduced emissions levels. In addition, the use of CGI enables the production of thinner walled parts, generating lighter engines, and a subsequent further increase in fuel efficiency. Current limitations associated with the use of CGI lie in its lower machinability properties relative to gray iron, with higher tool wear rates experienced. For this reason, a deeper understanding of the machining properties of CGI, along with an understanding of the metalworking fluid properties required to reduce wear and extend tool life in CGI machining, would greatly benefit industry and the continued expansion of CGI use. This paper will discuss the results of studies done to investigate the machining properties of CGI, and the metalworking fluid properties and composition which impact and potentially extend tool life in CGI machining.

Results & Discussion

Properties of Gray Cast Iron & Compacted Graphite Iron

With much effort currently underway in industry to replace standard gray cast irons with compacted graphite iron to produce lighter and higher strength parts, it is useful to describe the differences both structurally and compositionally which give rise to the differences in the material properties and machinability of these two metals. Gray cast iron has traditionally been used for the production of engine blocks, cylinder heads, as well as various other automotive components. The graphite in gray cast iron has a flake-like structure. The predominance of interconnecting graphite flakes gives rise to a high level of discontinuities and stress concentration effects in the matrix and subsequently gives rise to the properties characteristic of gray irons. These being good thermal conductivity, damping capacity, along with good machinability properties.² Thus gray cast iron is easily machined at low production costs, (higher metal removal rates with long tool life). Different from gray cast iron, compacted graphite iron, has a graphite structure much like that of coral. Such a graphite structure produces lower levels of discontinuities and stress concentration effects within the metal, giving rise to higher strength and toughness properties, as well as lower machinability.

In addition to graphite structure differences, there are significant compositional differences between gray cast iron and CGI which also are largely responsible for the differences in the machinability of these two metals. The presence of sulfur in gray cast iron is considered to be a critical factor associated with the high machinability of this metal.^{3,4} During machining of gray cast iron, the sulfur alloyed in the metal, combines with manganese to form manganese sulfide (MnS) inclusions.⁵ During cutting, the MnS inclusions are believed to assist in the chip breaking process as well to adhere to the cutting tool surface forming a lubricating layer which reduces friction, protects against oxidation and diffusion, and subsequently minimizes tool wear (especially at high cutting speeds). In machining of compacted graphite iron, formation of such a layer does not occur since the normal amount of sulfur added to CGI is around 0.01%, which is approximately ten times lower than that added to gray iron. In addition, the residual sulfur in compacted graphite iron tends to combine with magnesium, (element added to enhance graphite nodulization), so there remains little sulfur free to combine with manganese and form the MnS protective layer. Thus the lack of sulfur in compacted graphite iron is believed to be a primary reason for the poorer machinability and higher tool wear associated with the machining of this metal.

Due to these two factors (graphite morphology and sulfur concentration) the machinability of CGI is considerably lower, and tool wear is considerably higher than that experienced in gray cast iron machining. Previously reported studies, show that tool life for milling and drilling operations of CGI can be one half, while tool life in CGI boring operations have been seen to be just one-tenth of that obtained in comparable machining operations with gray cast iron.⁶ Thus it is clear that obtaining a better understanding of the lubrication and fluid requirements needed for improving the machinability of CGI will greatly benefit its current and future use.

Machinability of Gray Cast Iron versus Compacted Graphite Iron

To study the differences in machinability between gray cast iron and CGI, machining tests were conducted on a Bridgeport V2XT machine using a standard water based metalworking fluid. The fluid used was an o/w macroemulsion which is known to provide high levels of lubrication in ferrous machining operations. Testing involved the drilling and subsequent reaming of Grade 450 compacted graphite iron as well as a Class 40 gray cast iron. Assessment of the machinability of the metals was made by measurement of the cutting forces and tool wear occurring during the operation. Figure 1 below shows the machining conditions used, while Figure 2 shows a photomicrograph of the two cast iron types. As seen in Figure 2, the layered, morphology of the gray iron microstructure is easily seen, while the CGI has a more non-oriented, amorphous structure. As mentioned, such differences contribute to the important differences in strength and toughness, as well as machinability that exist between these two irons.

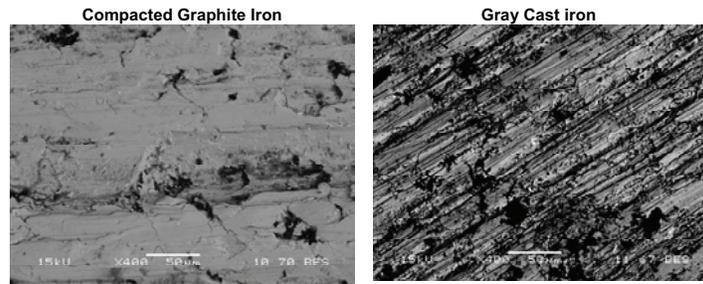
Figure 1

Machining Conditions

CGI Drilling		CGI Reaming	
Workpiece	Grade 450 CGI	Workpiece	Grade 450 CGI
Tool	Gehring # 5514 0.25" dia. Firex coated solid carbide	Tool	0.266" dia. Six straight fluted Solid carbide
Speed	3000 RPM (196 SFM)	Speed	900 RPM (62.6 SFM)
Feed	10.4 IPM (.00346 ipr)	Feed	5.1 IPM (.00566 ipr)
Depth	1.25" through hole	Depth	1.25" through hole
Fluid	8% in 130 ppm water	Fluid	8% in 130 ppm water
Measured Parameters	Cutting Forces Tool Wear	Measured Parameter	Hole Finish

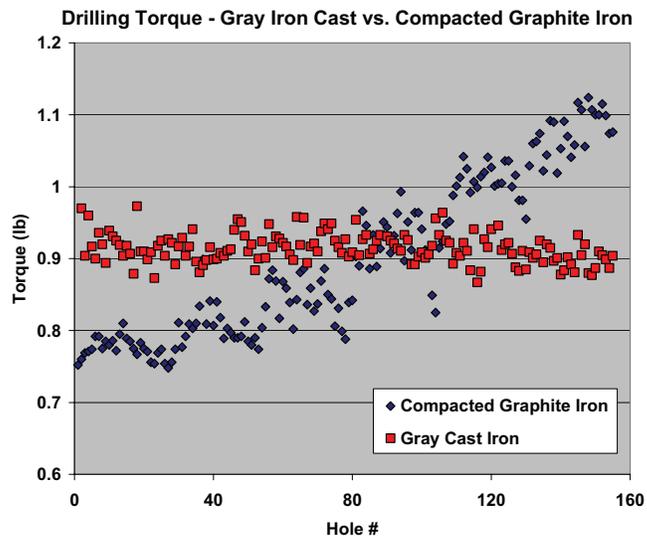
Figure 2

Scanning Electron Micrographs of CGI & Gray Cast Irons



The machining forces (torque) measured during drilling of the gray cast iron and CGI are shown below in Figure 3. The torque measured during machining provides a useful indication of the friction in the cutting zone and the lubrication provided by the metalworking fluid. The change in the torque measured as drilling continues provides a useful indirect measure of the change or deterioration in the condition of the tool, typically arising from tool wear and/or metal adhesion on the cutting edge. As expected, and seen in the results obtained, CGI is significantly more difficult to machine than gray cast iron. The cutting forces measured during machining of the Class 40 gray cast iron were consistent and steady during the entire process. In contrast the forces measured during machining of the grade 450 CGI show a distinct transition at about the twenty seventh hole followed by a rapid and consistent increase in cutting forces through the remainder of the test. Results consistent with a high rate of tool wear and metal adhesion on the cutting edge.

Figure 3

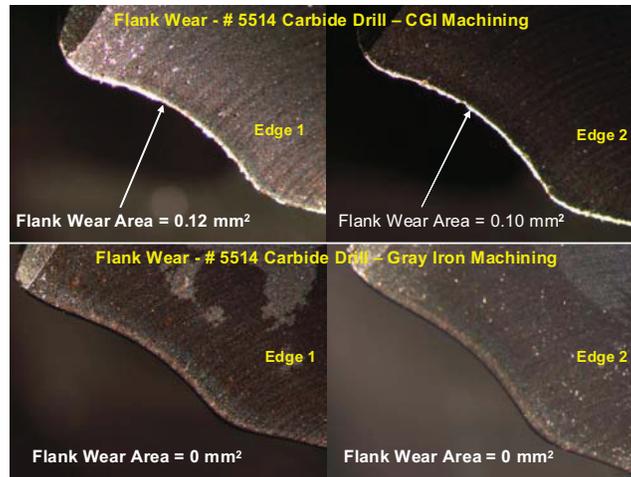


Tool Wear

As previously discussed, a critical factor associated with the machining of CGI is the rapid tool wear which occurs. Following machining, the tooling was examined to compare the conditions and the severity of wear which occurred during machining of both metals. Examination of the tool condition and measurement of the wear area on the flank face of the tool's cutting edges were made under 40x magnification using a Nikon

SMZ 800 stereo microscope and Eclipse Net software. As seen in Figure 4 below, the tool edge and flank surface of the drill used for machining the gray cast iron remained in good condition with no visible wear observed. In contrast, the tool used for CGI machining shows noticeable wear on the cutting edge. Thus consistent with the cutting forces measured, the resulting tool wear clearly shows the greater severity and difficulty in machining compacted graphite iron relative to standard gray cast iron.

Figure 4
Microphotographs & Tool Wear Measurements in CGI
and Gray Cast Iron Machining



The manganese sulfide inclusions formed during machining gray cast iron are known to deposit or coat on the tool surface providing a protective and lubricating layer. The lack of this coating with CGI is felt to be a factor largely responsible for the higher friction, heat and accelerated tool wear experienced. This was of particular interest in the current study because of its relevance in providing direction for the design of new CGI metalworking fluid technology. To examine this further, analysis of the test drills was conducted to assess the differences in the sulfur and manganese levels on the cutting surfaces and to provide support to the conclusion that formation of sulfur based lubricating layers are critical for improved machinability in cast iron machining. Following drilling of both the gray cast iron and compacted graphite iron, the tools were analyzed via scanning electron microscopy and energy dispersive spectroscopy using a Joel JSM 6480 scanning electron microscope with an EDX capability. Elemental mapping was conducted on the margin and relief angle surfaces of the drills as shown in Figure 5. The results of the elemental mapping (Figure 6) clearly show the higher levels of manganese and sulfur on the surface of the tool used for the machining of the gray cast iron. In contrast, as expected, analysis of the surface of the tool used for the CGI machining showed only minimal sulfur and no manganese. Thus the results of the EDX analysis of sulfur and manganese on the surfaces of the used tools is consistent with the current thinking regarding the lack of manganese sulfide inclusions and the absence of a MnS lubricating layer formed on the tool during CGI machining.

Figure 5

Scanning Electron Microscope/Energy Dispersive Spectroscopy

EDS - Elemental Mapping of 5514 Firex Coated Carbide Drill Following Gray Cast Iron & CGI Machining

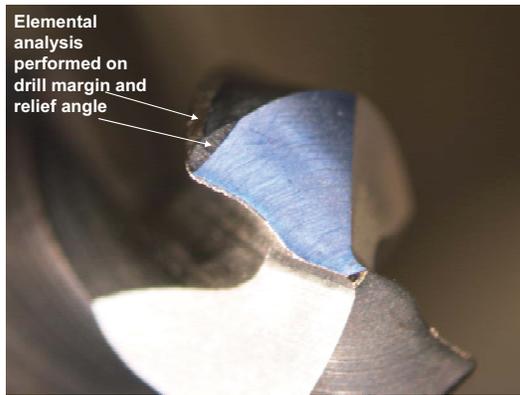
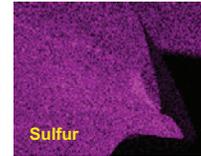
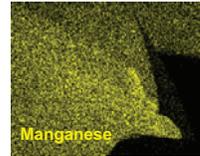


Figure 6

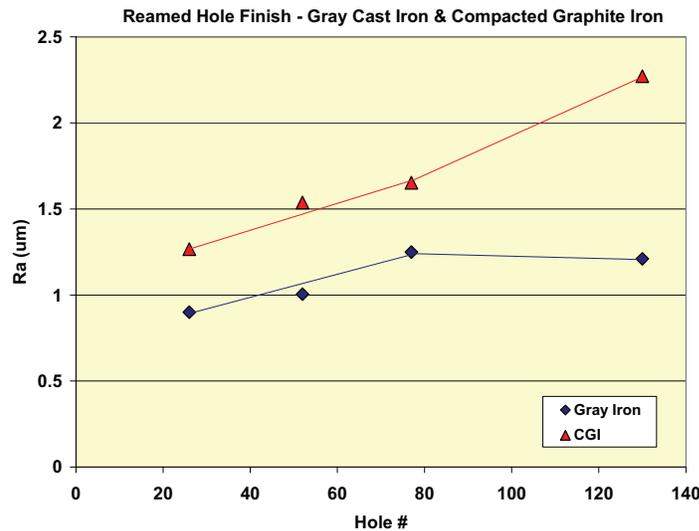
EDS Analysis - Manganese & Sulfur on Tool Surface

Tool	Gray Cast Iron	CGI
Surface Manganese Level	0.76%	0%
Sulfur Level on tool surface	0.17%	0.06%



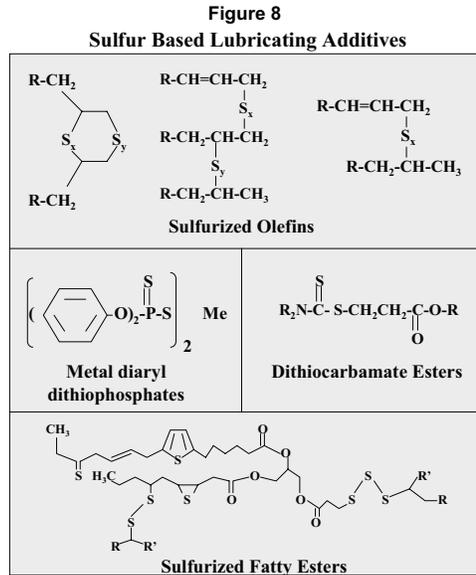
The higher difficulty in machining compacted graphite iron can also be seen in the reaming operation. Following the drilling, subsequent reaming was performed to assess the differences between the metals with regard to the reamed hole finish obtained. Figure 7 below shows the finish measured over the 130 holes reamed for both of the metals. As seen with both metals, a steady increase in reamed hole roughness occurs over the first eighty holes, at which point the roughness levels off and becomes fairly constant for the gray cast iron, while it continues to increase in roughness for the CGI.

Figure 7

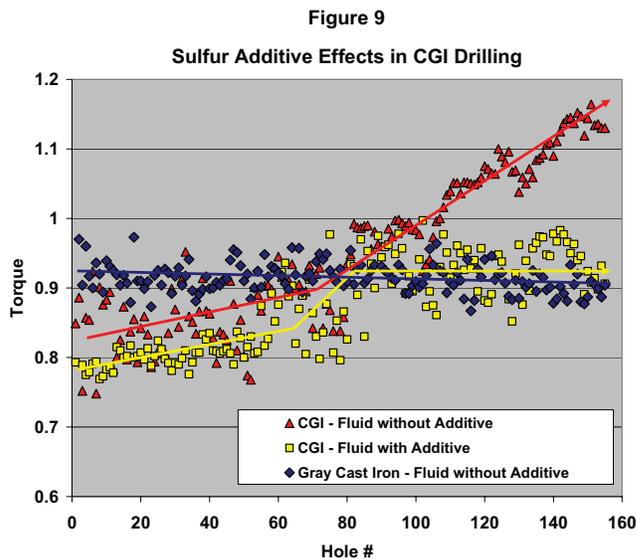


From the results of the drilling and reaming tests described above, it is apparent that compacted graphite iron presents a greater challenge in machining compared to that of standard gray cast iron. It is also likely that the absence of sulfur and the lubrication provided by manganese sulfide inclusions, is a principal reason for the higher friction, higher cutting forces, accelerated tool wear, and rougher reamed hole finish obtained in the machining of CGI. With this in mind, the potential to compensate and provide comparable lubrication from the metalworking fluid becomes extremely important for achieving improved CGI machining performance. While it is difficult to stabilize

manganese sulfide complexes in the metalworking fluid, it is possible to utilize various types of sulfur based compounds in the fluid to provide the needed lubrication. Elemental sulfur and numerous organo-sulfur compounds can serve as powerful lubricating additives which function at elevated temperatures to minimize friction and welding during cutting. With common organo-sulfur compounds, such as sulfurized fats, olefins and terpenes, lubrication is achieved via initial cleavage of the S-S bonds followed by formation of metallic sulfides and/or metallic organo-sulfides, on the tool and/or workpiece surface. General structures of some commonly used sulfur based lubricant additives are shown below in Figure 8.

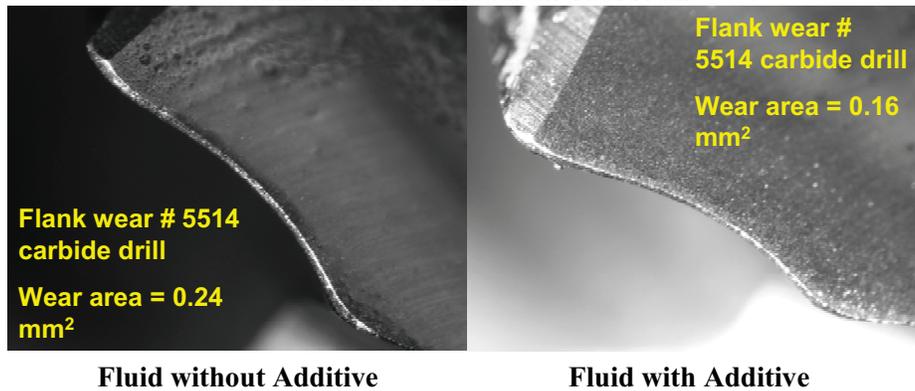


To assess the validity and effectiveness of such an approach to fluid design, a sulfur based additive was incorporated into the same metalworking fluid used for the previous machining tests described above, and using the same machining conditions, drilling and reaming operations were performed. Figure 9 shows the cutting forces measured during CGI drilling using the fluid containing the lubricating sulfur compound. The results are shown versus those obtained during drilling of both CGI and gray cast iron using the metalworking fluid without the addition of the additive. As seen, the incorporation of the sulfur based additive has a significant effect on reducing the cutting forces.



In assessing the impact on the tool wear which occurs, it was seen that the flank wear formed on the drill used during machining with the additive containing fluid did have significantly lower (33% reduction) wear measure on the tool's flank face surface. Microphotographs of the tools and wear areas measured are shown in Figure 10. Thus the use of the sulfur containing additive in the metalworking fluid to compensate for the lack of sulfur in the metal itself, does show benefit and can yield reduced cutting forces and reduced tool wear in CGI machining.

Figure 10
Microphotographs & Tool Wear Measurements in CGI Machining – Sulfur Additive Effects on Tool Wear



To develop a better understanding and insight into the role and significance of the sulfur additive in enhancing CGI machining and reducing tool wear, further analysis of the tooling was carried out. It was felt that if sulfur additives formed a protective and lubricating film on the tool surface comparable to that formed from the manganese sulfide inclusions in gray cast iron, then noticeable sulfur should be present on the tool surface during and after machining. To verify this, scanning electron microscopy and energy dispersive spectroscopy was conducted on the tool surface used with the additive containing fluid. It was seen (Figure 11), that while only trace levels of sulfur were present on the tool surface using the sulfur free metalworking fluid, analysis of the tool used with the additive containing fluid showed a considerably higher sulfur level, comparable to that found on the tool used for gray cast iron machining. This result provided support for the potential importance of sulfur and its mechanism of action involving formation of a lubricating film on the tool surface.

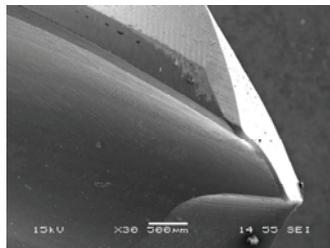


Figure 11
EDX Analysis of Tool Surface Following Machining

	Metalworking Fluid without Additive Gray Cast Iron	Metalworking Fluid without Additive CGI	Metalworking Fluid with Additive CGI
Sulfur level on tool surface	0.17%	0.06%	0.14%
Manganese level on tool surface	0.76%	0%	0%

Further SEM/EDX analysis was also conducted on the cutting edge rake face surface to gain further knowledge on the wear which occurs and the potential action of the sulfur in enhancing machining performance. Based on this analysis, it is seen (Figure 12) that wear likely proceeds via initial abrasive wear and loss of the titanium aluminum nitride coating, followed by a degree of plowing or deformation of the underlying substrate. It is felt that this wear likely occurs during the initial stages of the machining prior to thermal activation of the lubricating sulfur additive. This premise is consistent with the steady increase in cutting forces seen early in the drilling test. If allowed to continue, additional and more severe wear would likely occur. In support of this, EDX analysis of the surface sulfur content (Figure 13) shows high sulfur levels on the cutting edge surface where high friction, heat generation and wear occurs. In contrast, only trace sulfur levels were detected farther up on the rake face where minimal metal-metal contact likely occurred.

Figure 12

Tool Rake Face Wear

SEM/EDX Analysis of Tool Rake Face – Tool Used with Additive Containing Fluid

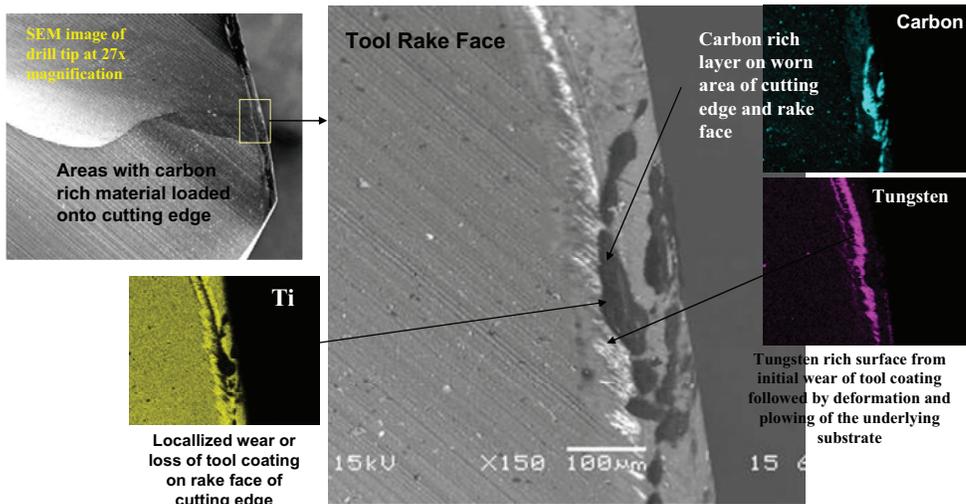
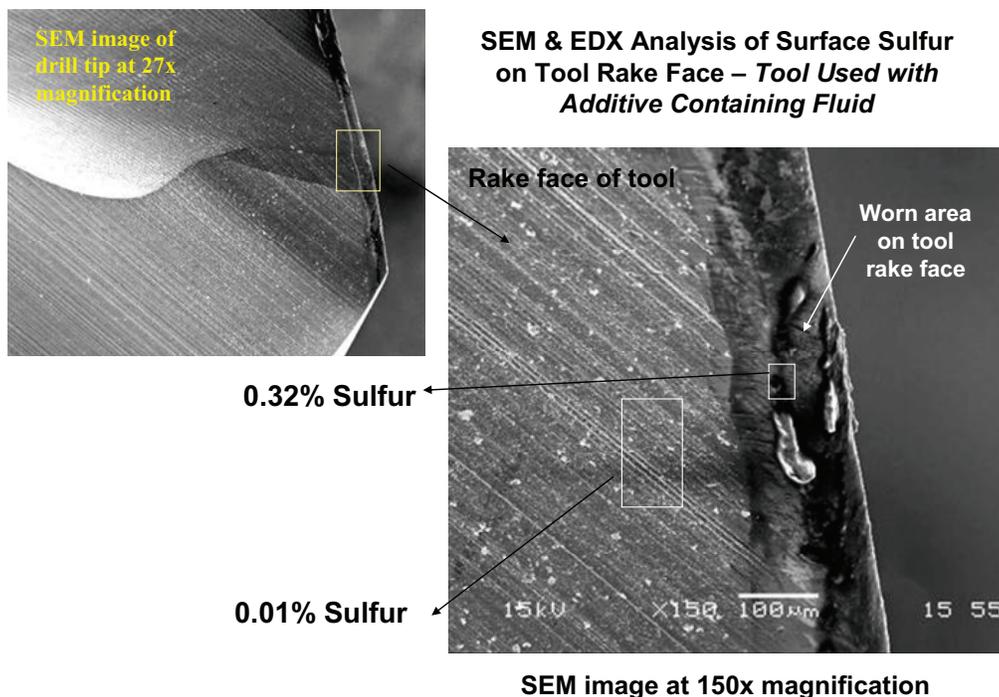


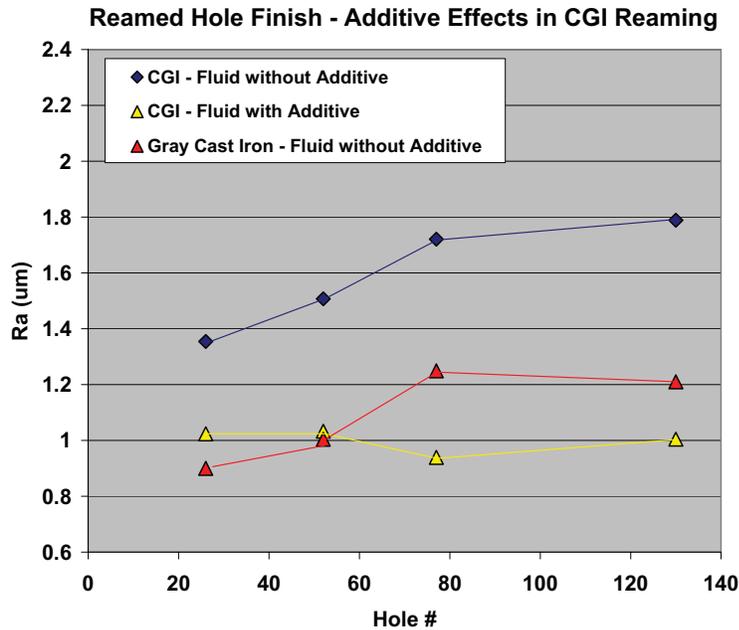
Figure 13

SEM & EDX Analysis of Surface Sulfur on Tool Rake Face – Tool Used with Additive Containing Fluid



Although the finishing operation, which is performed at lower cutting speeds with less metal removal, is considered to be a less severe operation to that of drilling, there was still significant performance improvement obtained through use of the sulfur based additive in the metalworking fluid. Following drilling, the holes were reamed using a six fluted solid carbide reamer. The surface finish measured over the one hundred thirty holes reamed are shown in Figure 14. As seen the fluid containing the additive produced extremely smooth and consistent reamed hole finish.

Figure 14



Conclusions

The results of the machining tests presented clearly show the higher level of difficulty encountered in the machining of compacted graphite iron compared to the machining of standard gray cast irons. This was seen in both the cutting forces and tool wear measured.

While it is understood that differences in graphite morphology is largely responsible for the differences in the machinability of CGI relative to gray cast iron, it is also believed and supported further by the SEM/EDX analysis conducted, that the lack of sulfur in CGI and the inability to form lubricating manganese sulfide inclusions during cutting, also give rise to the poor machinability of this metal.

While it is necessary to cast CGI with minimal sulfur content, it was shown that lubricating sulfur based additives can be utilized in the machining fluid to compensate for the lack of sulfur in the metal, and to provide enhanced lubrication necessary for reducing cutting forces and tool wear.

The role of sulfur based additives in the metal working fluid in forming a protective lubricating layer on the workpiece and/or tool surface during machining was supported by SEM/DX analysis of the used tool. The analysis showed high sulfur content on the

tool surface following machining. This level of sulfur was found to be comparable in concentration to that found on the tool used for gray cast iron machining. It is also believed that the formation of a sulfur based tribological film requires a level of heat. This is supported by results of EDX analysis showing high sulfur levels on the cutting edge surface where high friction, heat generation and wear was occurring, in contrast to only trace sulfur levels at locations farther up on the tool rake face where minimal metal-metal contact occurs.

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