Analysis of Tool Wear in CGI Machining

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ABSTRACT

In this study the tool wear and wear mechanisms on coated cemented carbide inserts were investigated in turning of Compacted Graphite Iron (CGI) materials with different nodularity. Investigation of how small changes in nodularity affect the wear behaviour of inserts in CGI machining has not earlier been done. The inserts were examined in LOM, SEM and in EDX. The tool wear could on the basis of their wear appearance be classified in three different wear categories; A, B and C. In the wear category A, abrasive wear, adhesive wear and delamination wear could be seen. In the wear category B, the predominant wear mechanism was chipping. The wear appearance in wear category C indicated attrition wear and dissolution via diffusion. Classification of the wear mechanisms gave knowledge that could be used in tool design. The results showed that increasing nodularity has impact on wear at moderate and high cutting speed but not at lower cutting speed. Machining of all materials at high cutting speed, 400 m/min, led to complete degradation of the edge line. A small difference in nodularity from 5 % to 20 % has more significant impact on wear than from 20 % to 62 %. This seemed to be correlated with the difference in ultimate tensile strength between the materials. Keywords: Compacted Graphite Iron, machining, tool wear, coated cemented carbides, nodularity.

1. INTRODUCTION

1.1 CGI as engine material

The truck manufacturers have raised their interest towards Compacted Graphite Iron (CGI). The increasing environmental demands to reduce the emission can be overcome by increasing the peak pressures in the cylinders. This gives a more efficient combustion but also higher load on the engine. Alloyed gray iron, which is commonly used today, has insufficient strength. CGI has sufficient strength but is limited due to difficulties regarding machinability. When changing to CGI, the wall thickness can be reduced or the loads increased, compared to alloyed gray iron. This opens opportunities for new engine design with smaller wall thickness [1]. The decreasing section size gives on the other hand faster solidification rates. Higher cooling rates promote the formation of nodular graphite, with higher strength, which is more difficult to cut [2]. Showman demonstrated that CGI castings as thin as 1.5 mm, could be cast with acceptable levels of nodularity using low density aluminum-silicate ceramics in the mold and/or core [3]. The varying nodularity in the engine blocks requires good simulation tool for predicting nodularity and cooling rates. Heisser showed that the simulated values for the nodularity were between 12-70 % in one engine block which was very near the real inspected values [4]. The 40 % increase in elastic modulus of CGI causes a positive shift in resonant frequencies of the block which means that the decreasing damping ratio, lighter engines and thinner walls, compared to gray, actually could give more quiet engines [1]. This shows that the engines tomorrow can be stronger, lighter and quieter.

1.2 Machining of CGI

Machinability of engineering materials depends on their microstructures that determine the mechanical and physical properties of these materials. Many truck manufacturers use alloyed gray iron in engine blocks and cylinder heads. All gray iron materials contain flake graphite dispersed in a silicon–iron matrix. The sharp edges of the flakes provide a very effective stress riser for the machining loads exerted by the cutting edge. When the shear plane approaches a graphite pocket, cracks starts to propagate from the edge of the flake and the iron fractures. The fracture starts at the stress riser and ends in an adjacent pocket until the shear load builds up to the fracture strength of the next stress riser. In CGI, the graphite form is vermicular. When machining CGI, it will shear, as for gray, through a graphite pocket which has the least resistance to shear forces. The round edges of the compacted graphite does not initiate cracks as easy as the sharp edges of the flake graphite in gray iron which leads to higher cutting forces when machining CGI. Ductile iron has spheroidal shaped graphite which deforms by the compressive load prior to the chip separation. There are no natural crack initiators, as for gray, leading to a more continuous chip with a following constant load on the tool. The graphite in cast iron also affects the thermal conductivity of the material. In gray iron, the flake graphite effectively leads the heat away. The spheroidal
graphite in ductile iron is not as effective which is an important reason it's not used for engine blocks or cylinder heads [2], [5].

1.3 Aim of study
The research literature shows that many studies focus on investigating the difference in machinability between gray iron and CGI [e.g. 6-8]. Since this is done and CGI as engine material increases, the focus must be turned to investigate what is limiting the performance of cutting CGI and how it can be improved. It is in addition to this, necessary to closely investigate the influence of nodularity on CGI machining since variations in nodularity appear in engine blocks as mentioned in 1.1. In this study, the affect of small changes in nodularity on the wear behaviour of inserts in CGI machining is studied. This has not earlier been done.

2. EXPERIMENTS

2.1 Studied materials
Two CGI materials (nodularity 5 % and 20 %) and one high nodular material (nodularity 62 %), measured according to ISO 16112, all with high pearlite content, 98, 92 and 96 % respectively were investigated. Images of the microstructure are shown in Figure 1 and the chemical composition is given in Table 1.

![Figure 1: Microstructure of the CGI materials and the high nodular material with a nodularity of 5 % (a), 20 % (b) and 62 % (c).](image1)

Table 1: Chemical composition (wt. %) of the cast irons.

<table>
<thead>
<tr>
<th></th>
<th>5 %</th>
<th>20 %</th>
<th>62 %</th>
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<tbody>
<tr>
<td>C</td>
<td>3.8</td>
<td>3.76</td>
<td>3.67</td>
</tr>
<tr>
<td>Si</td>
<td>2.13</td>
<td>2.2</td>
<td>2.22</td>
</tr>
<tr>
<td>Mn</td>
<td>0.31</td>
<td>0.35</td>
<td>0.32</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.005</td>
<td>0.01</td>
<td>0.012</td>
</tr>
<tr>
<td>S</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Cr</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Ni</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Mo</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cu</td>
<td>0.93</td>
<td>0.84</td>
<td>0.9</td>
</tr>
<tr>
<td>Sn</td>
<td>0.074</td>
<td>0.063</td>
<td>0.067</td>
</tr>
<tr>
<td>Ti</td>
<td>0.006</td>
<td>0.007</td>
<td>0.011</td>
</tr>
<tr>
<td>Sb</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Mg</td>
<td>0.008</td>
<td>0.02</td>
<td>0.02</td>
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The mechanical properties of the cast irons were tested using a test bar with a diameter of 14 mm according to SS-EN 10 002-1 and the hardness was measured according to SS-EN ISO 6506-1/6507-1, see Table 2.

Table 2: Mechanical properties of the cast irons.

<table>
<thead>
<tr>
<th></th>
<th>5 %</th>
<th>20 %</th>
<th>62 %</th>
</tr>
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<tbody>
<tr>
<td>$R_{p0.2}$ [MPa]</td>
<td>321</td>
<td>377</td>
<td>393</td>
</tr>
<tr>
<td>$R_m$ [MPa]</td>
<td>450</td>
<td>579</td>
<td>667</td>
</tr>
<tr>
<td>A [%]</td>
<td>17</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>HBW 5/750</td>
<td>222</td>
<td>230</td>
<td>229</td>
</tr>
<tr>
<td>HV 0.5 (in pearlite) [kg/mm²]</td>
<td>281</td>
<td>286</td>
<td>284</td>
</tr>
</tbody>
</table>

2.2 Wear investigation
The investigations were done in turning of cylindrical test specimens with an outer diameter of 145 mm, inner diameter of 98 mm and a length of 204 mm. The inner diameter of the test cylinders, at the clamping area, was reduced to 36 mm in order to reduce deformation due to the clamping force. Place Sandvik CVD coated cemented carbides (TNMA160408-KR3210) were used. The coating layers on the flank face are from the outside: TiN, Al₂O₃ and Ti(C,N). On the rake face the coating layers from the outside are; Al₂O₃ and Ti (C,N). With the present tool holder (DTGNL 2525M 16) and insert, the rake angle, $\gamma$ is -6° and the clearance angle, $\alpha$ 6°. The entering angle, $\kappa$ is 91°.

The cast irons were machined at different cutting speeds, 200 m/min, 300 m/min and 400 m/min, to investigate the wear behaviour of the inserts. The feed was 0.3 mm/revolution and depth of cut 1.5 mm. All machining tests were done to a predefined cutting length, 1700 m. The machining was done in a Swedturn 300 (40 kW) turning centre. Since the best performance of the inserts is achieved in wet machining, cutting fluid was used in the wear tests. After machining, the inserts were etched in an equal solution of H₂O and 37 % HCl in order to remove the built up workpiece material so that more careful investigation of the wear behaviour could be done. To measure the wear and determine the predominant type of wear, the worn inserts were examined in a Light Optical Microscope, LOM, Scanning Electron Microscope, SEM and in Energy Dispersive X-ray, EDX.

3. RESULTS

3.1 Tool wear
All inserts from the machining tests on the three cast irons at different cutting speeds were investigated. The wear on the inserts were after machining first studied in LOM, see Figure 2. It is evident that machining of more ductile cast irons (higher nodularity) lead to more built up workpiece material on the cutting edge. Increasing cutting speed has the same effect. The built up workpiece material, on the inserts, were removed through etching, so that the wear behaviour became clearer, see Figure 3. Comparison of Figure 2 and Figure 3, shows that the built up workpiece material only appears when the wear has reached the substrate of the tool and it also increases if the substrate is more worn.

A more complete picture of the wear behaviour was given after studying the flank wear on the primary cutting edge in SEM. The images are shown in Figure 4. The inserts could, after analyzing Figure 2 - Figure 4, be classified in three different categories on the basis of their wear appearance, wear category A, B and C. In the wear category A, the wear reached the Ti(C,N) layer on the primary cutting edge. The kind of wear appears after...
cutting all three cast irons at 200 m/min and after cutting the 5% nodularity material at 300 m/min. In the wear category B, some of the Ti(C,N) layer has been worn off on the primary cutting edge and on the nose. The category B wear appears when cutting the 20% and 62% nodularity material at 300 m/min. The wear category C is characterized by severe wear of the substrate and that the edge line is completely degraded on the primary cutting edge and on the nose. This category C wear is observed after cutting all three cast irons at 400 m/min. From the flank wear on the primary cutting edge it is evident that the Al₂O₃-layer show poor wear resistance, on the other hand, the Ti(C,N)-layer prove good wear resistance.

From the SEM images in Figure 4, the maximum flank wear of each coating layer on the primary cutting edge was measured, see Figure 5. Noticeable is, that on the lowest cutting speed, 200 m/min, no influence of the nodularity on the flank wear is seen. For the higher cutting speeds, 300 and 400 m/min, the slopes of the lines in the diagrams are steeper between 5-20% nodularity than between 20-62% nodularity. These indicate a nonlinear decreasing impact of nodularity on flank wear on the coating layers at the higher cutting speeds.

Figure 2: LOM images of the wear on the inserts after machining the cast irons at the selected cutting speeds.

Figure 3: LOM images of the wear on the etched inserts.

Figure 4: SEM images of the flank wear on the primary cutting edge of the inserts after machining the cast irons at different cutting speeds.
3.2 Tool wear mechanism

Classification of the wear mechanisms gives knowledge that can be used in tool design. To determine the wear mechanisms, the inserts were investigated at higher magnifications. One insert from each wear appearance category (defined in 3.1) was studied. The chosen inserts were, the insert that cuts the 5% nodularity material at 300 m/min for wear category A, the insert that cuts the 62% nodularity material at 300 m/min for wear category B, and the insert that cuts the 20% nodularity material at 400 m/min for wear category C.

3.2.1 Wear category A: On the clearance face on the primary cutting edge of the tool, the grooves in the vertical direction, Figure 6b and 6c, indicates abrasive wear.

(a) 
(b) 
(c)

Figure 6: Category A wear on the clearance face on the primary cutting edge, represented by the insert that cuts the 5% nodularity material at 300 m/min.

Adhesive wear of the Al₂O₃ and Ti(C,N) layer can be observed on the entrance (with respect to the chip direction) of the rake face (Figure 7b) and a mixture of abrasive and delamination wear of the Al₂O₃ and Ti(C,N) layer can be seen on the exit (with respect to the chip direction) on the rake face (Figure 7c). The delamination wear is believed due to cracks in the layers and the beach marks, indicating propagation of fatigue fracture. EDX-analyses verified that the layers were Al₂O₃ and Ti(C,N).

(a) 
(b) 
(c)

Figure 7: Category A wear on the rake face, represented by the insert that cuts the 5% nodularity material at 300 m/min.

3.2.2 Wear category B: In the wear category B, chipping of the Ti(C,N) layer, both on the clearance face and the rake face of the tool (Figure 8a) can be observed. The chipping is...
more potent on the insert cuts the 62 % nodularity material compared to the insert cuts the 20 % nodularity material (Figure 3 and Figure 4, second row). A closer investigation of the Al₂O₃ and Ti(C,N) layer further down on the clearance face indicates abrasive wear of both layers (Figure 5b). At the upper part (Figure 5b) of the Ti(C,N) layer, some delamination can be noted.

Figure 8: Category B wear, represented by insert that cuts the 62 % nodularity material at 300 m/min.

Attempt was made to investigate the surface of fracture where chipping occurred with higher magnifications. Unfortunately the original surface of fracture was worn and thus not possible to determine the fracture mechanism. Although, the predominant wear mechanism in this wear category B is chipping.

3.2.3 Wear category C: In Figure 9, one insert from the wear category C is shown.

Figure 9: Category C wear, represented by the insert that cuts the 20 % nodularity material at 400 m/min.

The surface of the worn substrate (Figure 9a) shows an uneven wear pattern with areas of more lost material. Examination in one of those areas (Figure 9b) showed that material have been torn or plucked off from the substrate. The number of worn areas increases with lower nodularity (Figure 3, last row). Nevertheless, the total wear, indicating that other wear mechanisms is involved. These analyses support a mix of wear mechanism on the substrate, with attrition wear creating the more worn areas and dissolution via diffusion creating the smoother areas, in an increasing extent with higher nodularity. Periodic detachment of the built up workpiece material around the cutting edge is likely when cutting spheroidal cast iron at 200 m/min [9], dissolution via diffusion at 400 m/min is reasonable, as in this case.

4. DISCUSSIONS AND CONCLUSIONS

To better understand the influence of nodularity on wear, some previous studies are considered. Regarding mechanical properties, Reuter [6] found a relation between wear and a strength value, based on hardness (Brinell) and ultimate tensile strength, after studying a number of cast irons in the range from CGI to SGI (spheroidal graphite iron). Viewing Table 2, the hardness is almost equal for the three cast irons but the ultimate tensile strength is much lower for the 5 % nodularity material. Reuter's result verifies the wear measurements in Figure 5. It is reasonable that the largest increase in wear is in the step from 5 % to 20 % nodularity.

CGI with nodularity less than 5 % is found to be in-between gray iron and SGI with respect to cutting forces [6, 10]. Cutting force measurement in the range between CGI (5 % nodularity) and SGI is not to be found in the literature. Despite this, increasing cutting forces with increasing nodularity can be expected within the range of nodularity in this study. Dearnley [9] found that machining of SGI gave higher cutting forces compared to gray iron and that the chip-tool contact length were equal for the two material an thus he suggested that the average compressive and shear stress acting on the tool is higher for SGI compared to gray iron. The chip-tool contact length in the interval of 5-62 % nodularity does not either differ according to Lefverman [11]. Concerning this, if the chipping was caused by fatigue fracture, the more potent chipping when machining the 62 % nodularity material compared to the 20 % nodularity material, the reason could be the higher cutting forces.

Dearnley et al [12] proved the close correlation between tool wear and tool-chip/tool-workpiece interface; accordingly, knowledge of the chip formation is of importance. Georgiou [5], Reuter [6] and Seyda [10] have studied the chip formation of gray iron, CGI (nodularity less than 5 %) and SGI. From those studies it is stated that larger deformations occur in the cutting of SGI compared to CGI and together with the higher strength of SGI, more heat is generated. Therefore higher cutting temperatures are expected with increasing nodularity in this study. The thermal conductivity of CGI and SGI is approximately the same at higher temperatures (above 400 °C) [13], thus the thermal conductivity of the cast iron in this study can be expected to be the same during machining. Comparing these results with the determined wear mechanisms, it can be summarized as follows. In the wear category A, with low cutting temperature expected, the wear mechanism is not particularly temperature dependent and thus it might not be surprising that the wear is the same for all levels of nodularity. In addition, abrasive carbide forming elements such as Ti and Cr [14] in the
From this study the following conclusions could be drawn:

In the wear category A, the less coating adherence expected at high cutting speed, 400 m/min. from 20 % to 62 % wear mechanisms were acting in the wear categories: A, B and C. Several different wear mechanisms were acting in the wear categories:

a. Wear category A with abrasive wear, adhesive wear and delamination wear.

b. Wear category B with chipping as the predominant wear mechanism.

c. Wear category C with attrition wear and dissolution via diffusion as wear mechanisms.

II. Increasing nodularity has impact on wear at moderate and high cutting speed but not at lower cutting speed.

III. Small differences in nodularity, in the range from 5 % to 20 % have a significant impact on wear, larger than the step from 20 % to 62 % in nodularity. This seemed to be linked to the difference in ultimate tensile strength that is larger in step from 5 % to 20 % nodularity compared to the step from 20 % to 62 %.

IV. The edge line was completely degraded after cutting all cast irons with different nodularity at the highest cutting speed, 400 m/min.

5. ACKNOWLEDGEMENTS

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6. REFERENCES


