IMPROVEMENT OF COMPACTED GRAPHITE IRON DRILLING OPERATIONS WITH CUSTOMIZED CUTTING FLUID

Degree Project

Author
Yaoxuan Zhu & Xiaoting Huang

Supervisor:
Qilin Fu, KTH Royal Institute of Technology

Examiner:
Amir Rashid, KTH Royal Institute of Technology

Stockholm 10/18/2017
Abstract

With its higher strength, Compacted Graphite Iron (CGI) is widely used in automotive industry. However, the machinability of CGI is challenging, mostly due to the high temperature in the cutting zone and the higher cutting force. This paper studies the influence of the different cutting fluids on the machinability of CGI material in drilling operations. The investigation compared a few customized cutting fluids having alkaline phase and oil phase, to a conventional cutting fluid. The oil phase of customized cutting fluid can help reduce the friction force in the machining process. The flank wear measurements showed there is no significant difference among the fluids. The thrust force measurements, however, showed that the customized cutting fluids could effectively reduce the cutting force by nearly 20%. By using the customized cutting fluid, the machining of CGI materials could either use higher feed rate to reduce cycle time when keeping the cutting force same, or use the same process data while reducing energy consumption.
Sammanfattning

# Table of Content

Abstract ............................................................................................................................................. 1
Sammanfattning ................................................................................................................................. 2

1. **Introduction** .................................................................................................................................. 4
   1.1 Project Research Background .................................................................................................. 4
       1.1.1 Introduction to the CGI and its’ Machinability ................................................................. 4
       1.1.2 Introduction to Cutting Fluid ........................................................................................... 5
   1.2 Purpose of the Thesis .................................................................................................................. 6

2. **Design of Experiment** .................................................................................................................. 7
   2.1 Indicators of the Machinability of CGI ...................................................................................... 7
   2.2 Design of the Experiment Groups ............................................................................................. 7
   2.3 The Evaluation of Machinability ............................................................................................... 8
       2.3.1 Experiment Setup ............................................................................................................... 8
       2.3.2 CGI Test Workpiece Selection and Design ....................................................................... 14
       2.3.3 The Measurement of Tool Wear ......................................................................................... 15
       2.3.4 The Measurement of Thrust Force ................................................................................... 15

3. **Result Analysis** ........................................................................................................................... 17
   3.1 Result Analysis of the Tool Wear .............................................................................................. 17
   3.2 Result Analysis of the Thrust Force .......................................................................................... 19
       3.2.1 Thrust force Analysis ......................................................................................................... 19
   3.3 Thrust force analysis over frequency ....................................................................................... 24

4. **Discussion and Conclusion** ......................................................................................................... 27
   4.1 Result of Hardness Measurement of CGI Test Workpieces ...................................................... 27
   4.2 Performance of cutting fluid at different concentration ........................................................... 28
   4.3 Conclusion .................................................................................................................................. 29

Acknowledgement ............................................................................................................................... 30
Reference .............................................................................................................................................. 30
Appendix ............................................................................................................................................... 32
1. Introduction

1.1 Project Research Background

The Compacted Graphite Iron (CGI) materials are widely used in automotive industries. Compared to the gray iron, CGI has excellent strength characteristic which allows a higher pressure in the combustion chamber in engines. The engine made by CGI has higher efficiency and lower emission level, at the same time becomes lighter with thinner walls [1]. However, the superior properties also make the CGI materials component more difficult to shape and machine. Hence, it is important to select the adaptable cutting fluids to achieve better cooling and lubricating function in machining process.

1.1.1 Introduction to the CGI and its' Machinability

CGI is one class in the iron family. Comparing with gray iron, LGI and SGI, the graphite particles in Compacted Graphite Iron (CGI) appear as individual 'worm-shaped' or vermicular particles, see Figure 1 [2]. When viewed in two dimensions, deep-etched SEM micrographs show that the individual ‘worms’ are connected to their nearest neighbors within the eutectic cell. This complex coral-like graphite morphology, together with the rounded edges and irregular bumpy surfaces, results in strong adhesion between the graphite and the iron matrix, see the Figure 1. Due to this unique morphology and microstructure, CGI has superior performance of its material physical properties such as 75% higher in tensile strength [3], 40% higher elastic modulus and 100% higher fatigue strength than gray iron [4]. When the nodularity [5] and pearlite increase, the mechanical properties of CGI can be gradually improved which strengthens the performance of CGI engine block. However, its cast ability and machinability are dramatically degraded leading to the shorter tool life and higher power consumption [3][6][7]. The application of customized cutting fluid can optimize CGI machining process and avoid the adverse influence of poor machinability caused by its high strength [6][8].
1.1.2 Introduction to Cutting Fluid

Typical CGI machining processes use a conventional cutting fluid in form of dilatable semi-synthetic fluid containing high mineral oil, suitable for general machining operations of steel and cast iron [9]. The customized cutting fluid composed of oil phase and alkaline phase which are mixed in different ratios and then mixed into water, to form a few different types suitable for different machining processes [10]. Meanwhile, customized cutting fluid can also be reused as cleaner to further fulfill minimized water consumption and waste water emission [10]. In the Figure 2, it illustrates the differences and comparison between these two types of the cutting fluids.
1.2 Purpose of the Thesis

The purpose of this thesis is to design, implement and verify a suitable method to test and compare the performances of two types of cutting fluids during CGI drilling operation.
2. Design of Experiment

The experiment focuses on measuring and analyzing the flank wears and thrust forces, under the conventional and customized cutting fluids.

2.1. Indicators of the Machinability of CGI

The cutting fluid performance can be reflected by the assessment of CGI machinability which is further evaluated by numerous parameters containing cutting force, surface roughness, tool life, chip formation and so on. In this project work, tool wear mechanics and cutting force are selected as the main indicators [3].

2.2. Design of the Experiment Groups

During the whole experiment, the conventional cutting fluid and few customized cutting fluids with three mixing ratios between oil phase and alkaline phase were tested. The complete experiment was fulfilled by four groups’ experiments. In each group experiment, each cutting fluid was tested for three times. During each test, a new drilling tool is deployed and then the flank wear and thrust force were measured to assess performance of tested cutting fluid.

The test group numbers, cutting fluid's types and constitutions are shown in the Table 1.

<table>
<thead>
<tr>
<th>Group NO.</th>
<th>Name of Cutting Fluid</th>
<th>Type Specification</th>
<th>Constitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>Fluid 1</td>
<td>Conventional Cutting Fluid</td>
<td>5%-10% OIL &amp; ALCA</td>
</tr>
<tr>
<td>Group 2</td>
<td>Fluid 2</td>
<td></td>
<td>3.5% ALCA Phase + 3.5% OIL Phase</td>
</tr>
<tr>
<td>Group 3</td>
<td>Fluid 3</td>
<td>Customized Cutting Fluid</td>
<td>4.2% ALCA Phase + 6.1% OIL Phase</td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
<td>---------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Group 4</td>
<td>Fluid 4</td>
<td></td>
<td>4.6% ALCA Phase + 9.8% OIL Phase</td>
</tr>
</tbody>
</table>

*Table 1. Name, type specification and constitution of cutting fluids.*

### 2.3. The Evaluation of Machinability

In this chapter, it articulates the experimental setup and the measurement methods on thrust force and flank wear.

#### 2.3.1. Experiment Setup

The experiment setup is illustrated in Figure 3. The CGI drilling operation test was conducted on the Hermle C50 5 axis CNC machining center. The thrust force ($F_z$) was measured by dynamometer with less than 1% uncertainty and it composists a Kistler 9265B base unit and a Kistler 9443 clamping unit, connected with Charge Amplifier of Kistler 5011. The machining force were converted into output voltage and this voltage signal was processed in charge amplifier.
Simultaneously, force signal was recorded into PC with AC coupling as input mode. The force measurements in time domain were then converted into frequency domain with, 2 Hz revolution over a frequency band up to 1024 Hz. The recorded data was loaded into PC via LMS Test lab software. A typical measurement of thrust force is shown in Figure 4.

Figure 3. Thrust force measurement equipment of connection
Holes were drilled on the CGI test workpiece by a 6mm diameter carbide twist drill (named Stock 51781) which was coated with a TiNAL layer.

Figure 5 illustrates the different steps in the drilling process.
Firstly, the feed rate (entry feed rate) was kept constant at 0.08 mm/r until the drill reached a depth of 3 mm. Then the feed rate was changed into 0.16 mm/r until the hole was finished.

During the drilling process, the spindle speed was fixed at 7500 rpm and the fluid jetting pressure was set at 30 bars as a constant value.

3.2.1. The Change of Thrust Force During One Hole Drilling Process

An example of thrust force derivative over time is shown in Figure 6. The thrust force derivative was integrated over time to obtain the actual thrust force during the drilling process and an example is shown in Figure 7. Figure 7, the positive values of thrust forces present the thrust force during the downwards drilling process and negative values of thrust forces describes upwards moving process of the drill.

The drilling process involves seven stages. Initially, drilling tool approached
the surface of CGI test workpiece with feed rate 0.08mm/r and then enter the CGI workpiece. The thrust force sharply increased from zero to a maximum value. In the next stage, the drilling tool keeps drilling with same feed rate until the drilling depth reaches 3mm. After that, the NC machine changes the gear and increase the federate to 0.16 mm/r. Meanwhile the main drilling process was initiated and thrust force maintained in an increase to a maximum value which is regarded as value of peak thrust force in unit time. After the 35mm drilling depth was completed, the drilling tool started extracting shown in sixth and seventh stages. The full schematic view of drilling process is demonstrated by the different steps in Figure 8.

Figure 6. Derivation of thrust force within one hole drilling process
Figure 7. Thrust force within one hole drilling process after transformation

Figure 8. Corresponding Schematic View of Drilling Process
2.3.2. CGI Test Workpiece Selection and Design

The diverse types of CGI have separated microstructures affected by nodularity, pearlite content, chemical composition and section effect which determine the distinctive mechanical properties and its machinability[3]. To avoid workpiece material differences, the experiments were conducted by using CGI workpiece produced from the same batch.

The CGI test workpiece was designed as cuboid with the dimension of 170mm length, 100mm width and 100mm thickness to fit the size of dynamometer and was then mounted onto the dynamometer with four bolts. (See Figure 9) The top surfaces of the workpieces were machined to be flat, prior to the drilling process.

![Figure 9. The CGI test workpiece with dimension](image)
2.3.3. The Measurement of Tool Wear

During experiments, the flank wear of drilling tools was measured as the criterion of tool life. They were measured and photographed by the optical microscope after every 30 holes drilling operations. The measuring position of the flank wear and measuring method are illustrated in Figure 10. Two maximum flank wears were measured on both edges, such as A and B position in Figure 10. Then, the average value of flank wear at the A and B position were calculated as the maximum flank wear of the drilling tool. The tool life limit is set at 300µm of maximum flank wear [11]. Once maximum flank wear reached 300µm, the drilling tool became totally worn out and approached the breakage. After that, the test of this drilling tool was stopped.

![Figure 10. Measurements of the flank wear [12]](image)

2.3.4. The Measurement of Thrust Force

The dynamometer measured three cutting forces along the three axes x, y, and z in the fixed coordinate system related to the working table in the CNC machine. During the experiments, the thrust force measurement on Z axis was recorded, see in Figure 11.
Figure 11: Cutting forces $F_x$, $F_y$ and $F_z$ (Thrust Force) along X, Y, and Z axes
3. Result Analysis

The experimental results were presented by the analysis of flank wear in time domain and thrust forces in both frequency domain and time domain.

3.1. Result Analysis of the Tool Wear

In Figure 12, it illustrates the flank wear growth under one subgroup test of cutting fluid No.4 during the whole tool life cycle.

![Image](image_url)

*Figure 12. A whole gradual wear process of drilling bits*

In the Figure 13, it shows the values of flank wears under the four different cutting fluids standing for four different group tests. In each group, flank wears at three time points were selected and compared at 30 holes, 210 holes and 450 holes respectively.
After each 30 holes drilling, the flank wear growth during drilling experiments was measured to form the line chart in the Figure 14 in which there was no any apparent differences of flank wear between the cutting fluid No.1 (conventional cutting fluid) and the customized cutting fluids (No.2, No.3 and No.4). Besides, no significant difference in flank wear was found among the three-customized cutting fluids.
3.2. Result Analysis of the Thrust Force

3.2.1. Thrust force Analysis

The analysis of thrust forces in whole drilling process was split into two parts in entry drilling process with feed rate 0.08mm/r and in the main drilling process with 0.16mm/r which are separately presented in Figure 15 and Figure 16. In each series of 30 holes drilling process, the peak thrust forces of first three holes was averaged as the peak thrust force in the full process.
In Figure 15, it shows the comparison of peak thrust force in the entrance of drilling process under different cutting fluids. The comparison shows insignificant difference between the peak thrust force in the entry of drilling process. The green lines represent the cutting fluid No.2 and shows the highest thrust force among the four fluids.
On the contrary, Figure 16 shows that almost all the thrust forces under customized cutting fluids with different mixing ratios were lower than those under the conventional cutting fluids when the feed rate is 0.16mm/r, in the main drilling process. Besides that, Figure 17, Figure 18, and Figure 19 compared the thrust force under the cutting fluid No.1 with the thrust forces under three customized cutting fluids (No.2, No.3, and No.4) at four different time spots, i.e. the 31st hole, the 121st hole, the 241st hole, and the 361st. These comparisons show that the customized cutting fluids can reduce the peak thrust forces by 20% to 30% compared to the conventional cutting fluid. It is also found that there is insignificant difference among these three customized cutting fluids. Changing the mixing ratios in the customized cutting fluids didn’t affect the thrust force apparently in these comparisons.
Figure 17. Thrust force comparison under cutting fluid 1 and 2 separately from 31st hole, 121st hole, 241st hole, 361st hole
Figure 18. Thrust force comparison under cutting fluid 1 and 3 separately from 31st hole, 121st hole, 241st hole, 361st hole.
3.3. Thrust force analysis over frequency

The measurement and analysis of thrust force in frequency domain is achieved by fast Fourier transformation of the measured time domain data, see the example in Figure 20. With two flutes, the drilling process has a tooth passing frequency of 250 Hz (Mode 2 in Figure 20). The unbalance of the two flutes introduces a tooth passing frequency at 125Hz (Mode 1 in Figure 20). And the Figure 21 and Figure 22 show the change of thrust forces in different test groups at frequency of 125Hz and at frequency of 250Hz respectively. The peak value of the thrust force in Mode 1 and Mode 2 was compared in Figure 21 and Figure 22 for the four cutting fluids.
In Figure 21, all the thrust forces generated under the conventional cutting fluid had no obvious differences with those generated under three customized cutting fluids. Figure 22 summarized the thrust force amplitude on the second mode at 250 Hz. The direct comparison does not show any significant different among the four cutting fluids. The dynamic force exhibited a random behavior during the test of each cutting fluid as the amplitudes have a large variation.
Figure 21. FFT analysis at 125 Hz

Figure 22. FFT analysis at 250 Hz
4. Discussion and Conclusion

4.1 Result of Hardness Measurement of CGI Test

Workpieces

The hardness measurement of CGI workpieces used for testing cutting fluid No.4, and the results are shown in Figure 23. The hardness of CGI workpieces used the test of cutting fluid No.4 is illustrated, and its standard deviation is represented by the error bars. It is found that the average hardness of all CGI workpieces in three different subgroup tests are almost the same. However, the hardness variations in the three workpieces have significant difference. In the subgroup test of workpiece 2, the hardness variation is higher than the others. From Figure 24, it shows the measured flank wear in drilling the selected three workpieces. The flank wear of drilling tool used in the workpiece 2 grew faster than other two workpieces. It is seen that the flank wear is strongly related to the hardness variation of CGI.

![Hardness Difference in Different Workpiece of Cutting Fluid 4](image_url)

*Figure 23. The hardness variation of workpieces and standard deviation in cutting fluid No.4 test*
4.2 Performance of cutting fluid at different concentration

During the experiment, the performances of customized cutting fluids at three different mixing ratios tend to be similar. This is mainly because the mixing ratio is over critical value. The critical value of mixing ratio strictly controls the performance of cutting fluid. Within certain range of critical value, the different mixing ratios can generate varying performances. However, if mixing ratio is lower or higher than certain range of critical values, the performance of cutting fluid tends to be similar no matter how to change mixing ratio. This is an example of the influence of cutting fluids at different concentrations on machining performance shown in Figure 25. This example illustrates how water based cutting fluid at different concentrations from 0% to 10% affects the performance of machining grade 450 compacted graphite iron. And the growth of abrasive wear, crater wear and overall wear were measured separately at different concentrations. It is obviously found that during experiment, compared with the crater wear and overall wear, the growth of abrasive wear on tools seemingly cannot be changed by the cutting fluid at different concentrations [13].
4.3 Conclusion

From the study the following conclusion could be drawn:

- The flank wear of the drills tended to have similar behavior among four cutting fluid.

- Compared with conventional cutting fluid, the customized cutting fluids did not make any obvious improvement in the tool life.

- By using the customized cutting fluids for workpiece materials, the peak force is reduced by 20% to 30%. And this reduction can dramatically lower the energy consumption and improve the drilling process reliability.

- The mixing ratios of the different phases in the customized cutting fluid didn’t the change of flank wear and drilling thrust force with the possible reason that these mixing ratios are over their critical values.

- In terms of CGI machinability test, it is very important to strictly control
the variation of workpiece hardness if tool wear is used as a machinability indicator.

Acknowledgement

The authors are thankful to the Vinnova project 2016-02506 Testbädd för framtidens processvätskor inom hållbar production, XPRES (Excellence in Production Research) and appreciates the support provided by Binol AB in Sweden for supplying of the cutting fluids and discussion.

Reference


Tool Wear of Drill Bits Under Cutting Fluid No.1

Tool Wear of Drill Bits Under Cutting Fluid No.2
The number of drilled Holes

Vmax (mm)

The number of drilled Holes