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High-Throughput Dry and Minimum Quantity Lubrication Drilling of Compacted Graphite Iron

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Abstract

This research investigates the high-throughput drilling of the compacted graphite iron (CGI), a high strength, lightweight material for automotive powertrain applications, at 26.5 mm/s feed rate using 4 mm diameter coated carbide drill. The CGI drilling experiments show that maximum 1740, 3150 and 2948 holes were drilled in two repeated tests under the dry, dry with through-the-drill compressed air, and minimum quantity lubrication (MQL) conditions. The Joule-Thomson cooling effect due to expansion of high pressure air from holes at the drill tip and mechanical effect of chip formation and evacuation are studied. Results demonstrate that high-throughput sustainable dry drilling of CGI is technically feasible.

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Keywords: Drilling; Wear; Chip; Productivity

1. Introduction

Gray iron (GI), compacted graphite iron (CGI) and ductile iron (DI) are three grades of iron widely used in automotive industry [1]. The morphology of graphite is different in these iron materials: GI has long, randomly oriented graphite, CGI has short, thick, and worm-like compacted graphite, and DI has spherical graphite [2]. The shape of graphite affects the mechanical and physical properties of GI, CGI, and DI [2-4], which are compared in Table 1. CGI is generally stronger than GI and can achieve 10-30% weight reduction (than GI) for diesel engine block applications [5]. However, machining of CGI is challenging comparing to GI due to high tool wear rate caused by the graphite morphology, high strength and pearlite content, and lacking of manganese sulphide (MnS) as lubricant in machining of GI [6,7]. Machinability is one of the key barriers for large-scale adoption of CGI in automotive industry [8].

Table 1. Mechanical and thermal properties of GI, CGI, and DI [4].

Properties	GI	CGI	DI	CGI in this study
Ultimate Tensile Stress (MPa)	150-450	250-575	350-900	420
Elastic Modulus (GPa)	66-143	130-160	159-176	140
Hardness (BHN)	156-277	179-269	160-360	210-265
Elongation (%)	1	1-3	2-22	-
Thermal Conductivity (W/mK)	36-57	36-47	31-37	-

Drilling, the most common machining process in automotive industry [8], has been studied in four key research publications for CGI [6-9]. Alves et al. [6] found that sulfur-based extreme pressure (EP) additive in metal working fluid (MWF) could double the tool life for CGI drilling. Mocellin et al. [7] investigated the drilling of five CGIs with different levels of pearlite. Using drill flank wear as the tool life index,

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the CGI with 100% pearlite had only 44% machinability of GI. The CGI with lower level of pearlite had lower strength but better machinability. Oliveira et al. [8] identified that drill geometry affected the drill life and found that the drill with tip radius had the best tool life. Pavia et al. [9] compared the wear of three types of coating (TiAlN/TiN, AlCrN and TiSiN/AlCrN). Two Cr-based coatings had higher tool life at 80 m/min cutting speed, while the tool life of multilayered coating was better at 150 m/min cutting speed.

The drill and process parameters of the past four and this CGI drilling studies are summarized in Table 2. The high-throughput drilling of CGI with over 1592s mm/min feed rate (more than twice higher than previous studies) in dry and minimum quality lubrication (MQL) conditions.

Table 2. Summary of CGI drilling process parameters.

Ref.	Feed Rate (mm/ min)	Drill Dia. (mm)	$\frac{L}{D}$	Coating	Drill peripheral speed (m/min)	Feed (mm/ rev)	Lubrication
[6]	350	10	2	TiAlN	110	0.1	Flood
[7]	637	10	2.2	TiAlN	80	0.25	Dry
[8]	637, 716, 796	6	5	TiAlN	80, 90, 100	0.15	Flood
[9]	254, 478	10	2	TiAlN/TiN, AlCrN, TiSiN/AlCrN	80, 150	0.1	Flood
This study	1592	4	6.3	TiAlN/TiN, AlCrN	100	0.2	Dry, MQL

Dry and MQL are environmentally-benign machining processes to eliminate or reduce the use of MWF, save energy, improve quality, and lower overall cost over the traditional flood cooling method [10]. MQL utilizes a minute amount of MWF for lubrication. The MQL drilling of CGI has not been studied. This study combines high-throughput and dry/MQL drilling of CGI to simultaneously meet the productivity and sustainability goals.

Drill temperature is high in CGI drilling which causes lower tool life [9]. This study investigated the Joule-Thomson (J-T) cooling, the temperature drop due to gas expansion from high to low pressure [11], at the exit of through-the-drill holes of the drill tip. The drill temperature is measured to quantify the effect of J-T cooling in the drill. Chip evacuation also plays a significant role on tool life in drilling [12,13]. Chip size and morphology are two important factors affecting the drill life. This research studies the drill temperature and chip evacuation effects on high-throughput drilling of CGI.

In this paper, the drill, workpiece, and experimental setup are first introduced. Results of drill wear, temperature, and chip morphology are presented. Effects of the J-T cooling and chip evacuation effects on CGI drilling are discussed.

2. Experimental setup and design

Drill: The 4 mm diameter, two-flute tungsten carbide drill with 135° point angle (Kennametal B255A04000YPC KCK10), as shown in Fig. 1, was used in this study. The tool material has 1 to 3 µm grain size WC and 10% Co. The drill has 5 µm thick multi-layer coating (AlCrN base layer, TiAlN/AlCrTiN middle layers, and AlCrN outer layer). The drill has a S-shaped chisel edge and with 0.7 mm diameter spiral through-the-drill holes.

CGI Workpiece: CGI plates, 270 mm in length, 206 mm in width, and 32 mm in thickness, were used for drilling tests (Fig. 2b and 2c). The CGI work-material has 420 MPa tensile strength, 140 GPa elastic modulus, and 210-265 Brinell hardness number (BHN) (Table 1). The material has more than 80% pearlite and less than 0.015% titanium, 0.10% chromium, and 0.40% manganese. Before drilling, a 1 mm thick heterogeneous cast surface layer was removed by face milling to prepare a flat surface for drilling. As shown in Fig. 2, a CGI plate has arrays of 4 mm diameter, 25.4 mm deep blind holes with 7 mm spacing and a total of 450 holes.

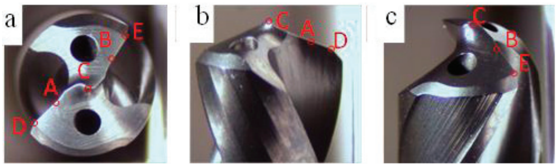

Fig. 1. The drill: (a) top view; (b) side view; and (c) angled view of drill tip.

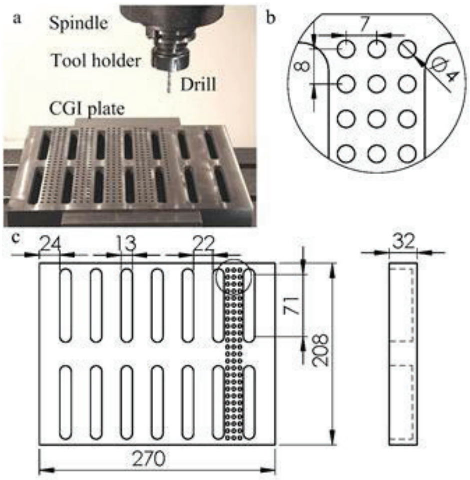

Fig. 2. (a) Drilling experiment setup; (b) hole layout on the CGI plate; and (c) dimensions of CGI plate.

Machine: The drilling experiments were conducted in a vertical machining center (Model 4020 by Fadal) with the drilling experiment setup shown in Fig. 2a. The machine has a single channel MQL system (Coolubricator by UNIST, Grand Rapids, MI) and 690 kPa compressed air applied in dry drilling and the MQL system. For MQL, the MWF was Coolube 2210EP by UNIST.

Tool Wear Measurement: An optical toolmaker microscope at 100X magnification was used to measure the drill flank wear. Flank wear measurements carried out on the points in Figure 1. For the first 900 holes, the flank wear was measured every 150 holes (to capture rapid initial tool wear). After 900 holes, the flank wear was measured every 300 holes.

Chip Morphology and Statistical Analysis: CGI chip was collected during drilling. For each drilling test, 100 chip samples were randomly selected. These chip samples were categorized based on the shape to correlate the drill life to the