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Effect of different oil-on-water cooling conditions on tool wear in turning of compacted graphite cast iron

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ABSTRACT

Although dry cutting is the most common method used in machining of compacted graphite cast iron (CGI), it sharply reduces the durability of the cutting tool, incurring the need to change tools frequently, and has high operating costs. This work proposes the use of oil-on-water (OoW), specifically external oil-on-water (EOoW), internal oil-on-water (IOoW) and cryogenic air with oil-on-water (CAOoW) droplets, as an eco-friendly cooling method for the turning of CGI. The results show that, because of better combination of cooling and lubrication effect, $EOoW_{rf}$ (spray-to-rake and flank faces EOoW) and IOoW (with 1.2 L/h water content) had the least adhesion on both tool rake and flank faces and the lowest tool wear rate among EOoW and IOoW, respectively. Furthermore, OoW condition and coated tool should be matched in order to carry out the best cutting performance. $EOoW_{rf}$ gave the best tool wear resistance in the machining of CGI by using a CVD Al_2O_3-based coated tool (Tiger). The penetrability of the OoW conditions depends on machined material, setup conditions of OoW et al. In order to improve the tool resistance in the case of turning CGI, a newly developed OoW condition (CAOoW), was proposed. CAOoW (−50 °C cryogenic air) gave 3 times lower tool wear rate and 0.2–0.3 times lower surface roughness than that of $EOoW_{rf}$.

1. Introduction

Compacted graphite cast iron (CGI) exhibits properties typical of hard machining, in which it is easy to produce discontinuous chips. This chip formation tends to cause high-frequency periodic fluctuation of the cutting force and cutting vibration. The low thermal conductivity of CGI also results in the accumulation of heat during cutting and machining processes, which causes oxidative wear and peeling of the coating (Yuan et al., 2014). The phenomena of abrasive wear on the flank face and the adhesion of chips to the rake face are serious. Such properties of hard machining may result in very low cutting parameters: the cutting tool rapidly reaches the wear standard limit and needs to be frequently changed, which, in turn, significantly increases the processing cost and reduces process efficiency (Mohammed et al., 2012; George, 2005).

These phenomena sharply reduce tool durability in the machining of CGI, so improvements in cutting performance are important. The usual approaches to improve cutting performance are: (1) changing the phase content of CGI; (2) changing the cutting tool design; and (3) changing the cooling method.

Reasonable changes to the phase content and hardness of CGI can improve its processing performance to a certain extent, but it will also change other properties. Mocellin et al. (2004). found that a 2.5% increase in pearlite content reduced the cutting life by 55% owing to changes in the microhardness of ferrite and other microstructural variations. Reasonable selection of the cutting tool coating also improves the processing of CGI; however, different coatings also give different tool performances: alumina provides high hardness needed for abrasive resistance and excellent chemical stability; silicon nitride (SiN) has relatively high fracture toughness and high hardness at high cutting temperatures, in addition to its insensitivity to thermal shocks; TiN-coated tools are the best choice for machining austempered ductile iron because TiN reduces friction, work hardening, and built-up edges. But there is presently no detailed theoretical description explaining how to optimize the tool coating. In contrast to these two approaches,

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changing the mode of cooling can provide both economic and environmental advantages.

When using cutting fluids, it is difficult for them to reach the cutting area and they often do not achieve effective cooling. Cutting fluids are the source of several environmental and biological problems. During the rough machining of CGI, it is preferable to use dry cutting, but tool durability is poor because of the difficulties in processing this material. It is therefore necessary to conduct research on a cooling mode that will not only enhance cutting performance, but also minimize environmental pollution.

Commonly used green cooling methods include cryogenic cooling, air/gas cooling, solid lubrication, and minimal quantity lubrication (MQL) (Ghosh and Rao, 2015). Sharma et al (Sharma et al., 2009; Klocke et al., 2012; Evans and Bryan, 1991; Dhar et al., 2002). used liquid nitrogen cooling for the cutting process, and determined that it was able to penetrate to the cutting area and effectively reduced the cutting temperature. However, this is an energy-dissipating technique and the installation of the equipment is costly and complex. Liu et al. (2005). carried out machining of 45# steel with water vapor as the cooling medium, using a special vapor generator and feeder system to control associated parameters, such as pressure, temperature, flow velocity, and humidity. They found that the formation of a low-shear-strength lubrication layer by vapor on the workpiece reduced the cutting forces and surface roughness. Han Rongdi et al (Liu et al., 2005, 2007; Rongdi and Guangyi, 2003; Tai et al., 2014). also observed a significant reduction in cutting force when turning 45# steel under water vapor cooling. However, the lack of lubrication of this method limits its application because water is mainly used for cooling. Reddy and Rao (2006) conducted milling of AISI 1045 steel to compare the effectiveness of solid lubricants (MoS_2 and graphite) and soluble oil (KOOLKUT-40). It is important that the solid lubricant must firmly adhere to the cutting tool to enhance working life.

MQL technology was the least costly method in comparison with other processes. Unlike cryogenic cooling and water vapor, it can provide both cooling and lubrication effects. The use of vegetable oil can further increase the sustainability of the process. MQL has high permeability because of the use of compressed air; however, this technology has a low rate of heat conduction and high temperature of the cutting area. The high amount of cutting heat generated by the hard working material leads to lubricant evaporation, which reduces the lubrication function (Su et al., 2007; Yuan et al., 2011; Lawal et al., 2013; Sharma and Sidhu, 2014).

With respect to the issue of heat conduction rate in MQL, some researchers have proposed a new cooling method known as oil-on-water (OoW) droplets, which uses MQL for lubrication and the phase transformation of water droplets to improve heat transfer. This cooling method has better cutting performance compared with traditional MQL in the processing of aluminum alloy (Yuan et al., 2011; Lawal et al., 2013; Itoigawa et al., 2006). Lin H S et al. compared the cutting effects of several aforementioned cooling methods for cutting titanium alloy recently (Lin et al., 2015). It was found that the use of cryogenic air combined with MQL (CAMQL) gave lower surface roughness and lower flank wear rate compared with dry cutting and flooding. Considering three spray locations when using external oil-on-water (EOoW), simultaneously spraying onto both the rake and flank faces gave the lowest flank wear rate. Using of internal oil-on-water (IOoW) at a water flow rate of 1.2 L/h had a better ability to lower surface roughness and reduce flank wear than IOoW at 2.4 L/h. Lubricant oils had no influence on surface roughness or flank wear rate for the EOoW method, while it had a significant effect on IOoW. Under different cooling conditions, IOoW (1.2 L/h) gave the best performance in lowering surface roughness and reducing flank wear in turning of Ti-6Al-4V alloy.

It was considered useful to further research the application of OoW condition on other material. There is little literature on the researches of machining of CGI under OoW condition so far. This paper has studied the influence of dry cutting, EOoW, and IOoW on the turning of CGI, with the aim of finding a cooling scheme that will solve the issue of low tool durability during cutting of CGI. Lubrication mechanism of OoW in the turning of CGI was revealed. Furthermore, a newly developed OoW condition, cryogenic air mixed with OoW (CAOoW) method, was proposed in this paper in order to further improve the tool durability.

2. Experimental

Machined material CGI (RuT400) was produced by Guangxi Yuchai Machinery Group Co., Ltd. CGI bars of length 70 mm and diameter 50 mm were used. The chemical constituents of the carbon and CGI matrix, and the hardness of CGI matrix, as shown in Table 1, were measured by energy-dispersive spectroscopy (EDS) and Vickers hardness tester, respectively. The Vickers hardness of the matrix was used to present the hardness of CGI. The microstructure of the material is shown in Fig. 1. The minimum tensile strength is 400 MPa. Thermal properties of CGI are listed in Table 2.

The carbide inserts with four different coatings (in Table 3), were used to compare their cutting performance under dry cutting and OoW cooling conditions. During turning process, rake angle and flank angle were, respectively, set as 25° and 0°, which were recommended by the cutting tool companies and frequently used in industrial application. The turning experiments were carried out using a CAK3675V CNC lathe. The conditions of the turning experiment were cutting speed (v_c) of 70 mm/min; depth of cut (a_p) of 0.9 mm; and feed rate (f) of 0.15 mm/r. Cutting distance was calculated by Eq. (1).

$$L = vt = \frac{n\pi dt}{1000} \tag{1}$$

where L is the cutting distance; v is the cutting speed; t is the cutting time; n is the rotation speed; d is the diameter of the workpiece. Cutting time needs to be measured during the cutting process in order to calculate the cutting length. Cutting distance was used in this paper instead of cutting time, because its relationship with cutting performance (cutting temperature, tool wear et al.) was more intuitive.

Schematics of the EOoW, IOoW and CAOoW cooling conditions are shown in Table 4. The cutting temperature, morphology of chips, machining quality, and tool wear during the cutting process were compared and analyzed for three different injection positions for EOoW (the rake face, the flank face, and both faces simultaneously), three water flow rates (0.6 L/h, 1.2 L/h, and 1.8 L/h) for IOoW and three cryogenic air temperature (-20 °C, -35 °C and -50 °C) for CAOoW. The delivery pipe, which was used to transport the cryogenic air, was cover by thick insulation cotton in order to prevent the heat exchange with the air. However, the temperature of cryogenic air would increased, mainly because of the mixing with OoW and during the way from spray nozzle to the tool tip. The temperature of CAOoW at the tool tip was measured and presented in Table 4 (1). Table 4 (a), (b), and (c) represent the use of EOoW to spray to the rake face, the flank face, and both the rake and flank faces, respectively; (d) shows the spray angle and position of the nozzle. Under the IOoW and CAOoW conditions, OoW was sprayed onto the tool tip through the inside of the tool, as shown in (e); (f) shows the injection position of the inner-cooling cutter arbor. The equipment schematic of EOoW, IOoW and CAOoW was shown in (g), (h) and (i), respectively. Lubricant oil 2000-30 used in OoW cooling conditions is listed in Table 5.

During the experiments, thermal infrared equipment (TVS-