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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 Al₂O₃-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}.

Keywords

compacted graphite cast iron; turning; oil-on-water; minimum quantity lubrication; tool wear; coated tool

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 [1]. 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 [2,3].

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. [4] 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, 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) [5]. Sharma et al. [6-9] 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. [10] 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. [10-13] 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 [14] 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 [15-18].

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 [16, 17, 19]. Lin H S et al. compared the cutting effects of several aforementioned cooling methods for cutting titanium alloy recently [20]. 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 Figure 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).

$$L = vt = \frac{n\pi dt}{1000} \quad (1)$$

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 covered by thick insulation cotton in order to prevent the heat exchange with the air. However, the temperature of cryogenic air would increase, 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-500EX, NEC®, NEC company, Japan) were used to measure the cutting temperature. The thermal infrared equipment was calibrated by measuring the temperature of CGI workpiece, which was heated thoroughly to a set temperature by chamber electric furnace. The surface roughness was measured using a portable roughness meter (TR2000, Beijing Times Co., Ltd., China). The cutting forces were measured using an online force measurement system, which included a piezo-electric three-component dynamometer (Kistler 9129AA, Kistler Instrument®), a multi-channel charge amplifier (Kistler 5080A1030001, Kistler Instrument®), and a personal computer (PC)-based data acquisition system (Dynaware). After completing each cutting process, the flank wear value (VB), which represents the wear rate of the tool, was measured using a microscope (OLYMPUS SZ61, Japan). Chip morphology and the tool surfaces were observed using a scanning electron microscope (SEM, S-3400N-II, Hitachi, Japan) with energy-dispersive spectroscopy (EDS) functionality (Zeiss Group®) to analyze the modes of tool wear at the end of the full cut. In addition, chip formation process was recorded by a high-speed camera (Hispec, 3 million pixel at maximum) and HiSpec 2 Director software. Experimental setup of cutting process, including the cutting force and cutting temperature test systems, is shown in Fig. 2.

3. Results and discussion

3.1 EOoW cooling condition

In this section, the effects of spraying locations $EOoW_r$, $EOoW_f$ and $EOoW_{rf}$ on EOoW performance in the turning of CGI were studied. Fig. 3 displayed the chip morphology resulting from the three different injection locations. All tests show the similar discontinuous chips, suggesting that the spraying position has little influence on chip morphology. However, in the machining of Ti6Al4V [20], spraying from up to down ($EOoW_f$) broke the chips more easily and produced shorter chips. This difference between CGI and Ti6Al4V is mainly because of the difference of the material toughness. In fact, material properties of CGI and Ti6Al4V have significant influence to the cutting performance when OoW cooling conditions were applied.

Cutting performance of CGI under $EOoW_r$, $EOoW_f$, and $EOoW_{rf}$ conditions was shown in Fig. 4. When the cutting distance was 45 m, cutting temperatures of $EOoW_r$ and $EOoW_{rf}$ were similar, which were 10 °C lower than that of $EOoW_f$. With the increasing cutting distance, the rise in temperature of $EOoW_r$ was obvious, while those of $EOoW_f$ and $EOoW_{rf}$ remained stable, as shown in Fig. 4(a). This was attributed to the lack of OoW on the flank face and the highest flank wear rate of $EOoW_r$.

As shown in Figure 4(b), the $EOoW_{rf}$ condition gave the lowest flank wear rate among the three different injection locations: when injecting the rake and flank faces simultaneously, the flank face was well lubricated and the rake face would have good heat conduction. The wear rate of $EOoW_f$ was slightly lower than that of $EOoW_r$, because the flank face could effectively restrain the wear under direct lubrication in the cutting process. When using the $EOoW_r$ condition, the flank face only received lubrication by penetration. The $EOoW_f$ condition therefore restrained the wear more effectively than $EOoW_r$.

Figure 4(c) shows that $EOoW_{rf}$ gave the lowest cutting temperature and flank wear rate, but highest roughness; $EOoW_r$ gave the highest flank wear rate and lowest roughness. The roughness of the machined surface under $EOoW$ conditions was not only determined by the flank wear, cutting temperature, and shear properties of the material, but also by the injecting location. $EOoW_r$ gave the lowest roughness, which may have resulted from the discontinuous chip flow being directed away from the workpiece. Under $EOoW_r$ and $EOoW_{rf}$ conditions, the chip flow easily formed scratches on the machined surface, which could increase the surface roughness.

The wear morphology of the rake and flank when using $EOoW$ at the three injection locations was shown in Fig. 5. The main wear mechanism under $EOoW$ conditions was adhesive and abrasive wear. $EOoW_{rf}$ gave the lowest adhesion on both faces. This phenomenon is due to insufficient cooling and lubrication when only one face was injected by OoW for $EOoW_r$ and $EOoW_f$. The higher of the cutting temperature led to lower thermal conductivity, lower thermal diffusion and higher specific heat capacity of CGI (Table2), which, in turn, accumulated more heat on the tool face, leading to more serious adhesion. $EOoW_r$ had less adhesion chip on rake face compared with $EOoW_f$, even though the cutting temperature of $EOoW_r$ became higher than $EOoW_f$ after cutting distance 90 m. This was because of better lubrication and less heat accumulation on rake face with OoW spraying directly to it. Adhesion phenomenon depended not only on cutting temperature, but also stress, friction, et al. Better lubrication on rake face under $EOoW_r$ reduced the stress and friction, then reduced the adhesion chip.

3.2 IOoW cooling condition

In this section, the effects of water contents on $IOoW$ cutting performance in the machining of CGI were studied. The cutting temperature was reduced as the consumption of water increased from 0.6 L/h to 1.8 L/h, indicating that the higher of the water content, the better of the cooling ability (Figure 6(b)), $IOoW$ (1.2 L/h) gave the lowest flank wear rate and $IOoW$ (1.8 L/h) gave the highest one. It suggested that $IOoW$ (1.2 L/h) had the best lubrication ability among these three water contents used. This result is consistent with the turning of Ti6Al4V under $IOoW$ [20]. $IOoW$ (1.8 L/h) gave the best surface quality due to its best cooling effect, as shown in Figure 6(c). The expansion of CGI during machining process led to the fact that the lower of the cutting temperature the lower of the surface roughness.

The wear morphologies of the coated tool under $IOoW$ were shown in Fig. 7. Adhesion was the main wear mechanism of cutting tool under $IOoW$ condition, as well as $EOoW$ condition. Even though the lowest cutting temperature of $IOoW$ (1.8 L/h) condition, large amount of chip on the rake face and serious flank wear could be observed. This is because of higher friction and stress attributing to poor lubrication. This phenomenon was similar to the adhesion of $EOoW_r$. Only small chip could be found on rake face under $IOoW$ (1.2 L/h) condition, which had the least adhesion among three water contents used because of the best combination of cooling and lubricating effect.

Thermal cracks, which were absent from $EOoW$ condition, appeared on the flank face of cutting tools under all the $IOoW$ conditions, regardless of the water contents. High cutting temperature of $IOoW$ conditions, which was higher than that of $EOoW$ conditions (Fig. 10 (a)), led to the decrease of thermal diffusion and increase of heat accumulation, which increased the temperature gradient on cutting tool. The temperature gradient would lead to serious heat shock, thus thermal cracks occurred.

3.3 Comparison of different cutting conditions

3.3.1 Comparison of different coated tools

Section 3.1 and 3.2 shows that $EOoW_{rf}$ and $IOoW$ (1.2 L/h) had the best tool wear resistance in $EOoW$ and $IOoW$, respectively. Therefore, cutting performance of four coated tools under dry cutting and these two conditions was compared. Compared to dry cutting, both $EOoW_{rf}$ and $IOoW$ (1.2 L/h) were able to reduce the tool wear of all the coated tools used. Tiger tool gave the lowest tool wear rate under all the cooling conditions.

CVD Al_2O_3 -based coated tools TK2001 had higher tool wear than PVD TiAlN-based coated tools (TH1000 and TS2000) under dry cutting, as shown in Fig. 8(a). However, TK2001 showed higher tool wear reduction under EOoW_{rf} and IOoW (1.2 L/h), as shown in Fig. 8(b)(c), tool wear rate of TK2001 was closed to TH1000 and lower than TS2000.

CVD Al_2O_3 -based coated tools (Tiger and TK2001) gave higher surface roughness than that of PVD TiAlN-based coated tools (TH1000 and TS2000) under dry cutting and EOoW_{rf} condition, as Fig. 9(a)(b) shown. However, Tiger and TK2001 showed larger surface quality improvement than PVD TiAlN-based coated tools under IOoW (1.2L/h), as shown in Fig. 9(c), surface roughness of Tiger was closed to TH1000, and surface roughness of TS2000 was the highest.

In fact, cutting performance, both tool wear and surface roughness, of TiAlN-based TS2000 had not improvement under IOoW (1.2 L/h) condition compared to dry cutting and EOoW_{rf} conditions. Therefore, an interesting and valuable result, which is opposed to traditional viewpoint, can be drawn that cooling and lubricating applied during the machining has its special preference to cutting tool in improving the cutting performance. Coated tools need to be matched with cooling conditions during the machining of CGI. The relationship of cooling condition and cutting tool should be explained by thermodynamic coupling during machining and intrinsic properties of the coatings, which will be explored in future study.

For the machining of CGI, EOoW_{rf} and IOoW (1.2 L/h) cooling conditions could help CVD Al_2O_3 -based coated tool (Tiger and TK2001 tools) better carry out their tool wear resistance compared to PVD TiAlN-based coated tools (TH1000 and TS2000).

3.3.2 Comparison of Cutting performance under dry cutting, EOoW and IOoW

Figure 10 shows that the temperature of dry cutting was 230 °C, which was 30 to 70 °C higher than that of EOoW and IOoW conditions by using CVD Al_2O_3 -based coated tool Tiger. Surface roughness of EOoW and IOoW conditions also had great improvement compared to dry cutting. EOoW_r and IOoW (1.8 L/h) gave 0.7 and 0.8 times lower surface roughness respectively in comparison with dry cutting. As the wear morphology in Fig. 11 shown, the main tool wear mechanism of coated tool in the machining of CGI under dry cutting was adhesion because of high cutting temperature. However, only IOoW (1.2 L/h) and EOoW gave improved tool wear resistance (Fig. 10(b)). This was because of the improper water and oil ratio of IOoW (1.8 L/h) and IOoW (0.6 L/h). Compared to IOoW cooling conditions, EOoW had greater improvement in tool wear resistance and surface roughness during the cutting of CGI, because the absence of thermal crack on cutting tool improved the tool life, lower cutting temperature increased the thermal conductivity of CGI, et al.

3.4 Lubrication mechanism and a newly developed OoW cooling condition: CAOoW

3.4.1 Lubrication mechanism

The lubrication in the cutting zone mainly causes by the kinetic action of capillary network existing in the tool–chip interface [21, 22]. Lubricating action requires that the time for lubrication oil penetrated to the capillaries of cutting zone is less than the capillary lifetime. A storing time (deviation of capillary lifetime and penetration time) was proposed to describe the penetration performance [23]. The penetrability of the OoW conditions depends on the many factors, mainly including machined material, setup conditions of OoW, et al.

3.4.1.1 Machined material: CGI

The orthogonal cutting process of CGI under dry cutting was shot by high-speed photography, as Fig. 12 shown. Two spray nozzles were drawn in Fig. 12 in order to show the spraying position and direction when OoW cooling conditions were used. Because of the short contact length of the chip, spray nozzle installed near the rake face sprays water and lubrication oil directly to the rake face and the back of chip, which was being removed.

Water and lubrication oil from spray nozzle in the side of flank face sprays directly to the flank face and the newly machined surface of the material.

Similar to orthogonal cutting, the chip morphology by turning was also discontinuous and saw-teeth (Fig. 13). The chip bottom was rough, uneven and flaky. There were large amount of cracks, scratch and craters. The harden particles (such as TiC, TiN, et al) inside the CGI materials led to the abrasive wear of the cutting tool. The adhesive chip on the cutting tool also had these harden particles. The abrasive wear and adhesive wear would, in turn, lead to scratches on the chip bottom during the chip flowing on tool rake face. Point A in the crater (Fig. 14(b)) was detected to be graphite because of lots of carbon element and small amount of iron and silicon (Fig. 14(c)). Because of the lack of tensile strength, the extrusion and friction cause by rake face during cutting led to deformation and peeling off of the graphite, thus lots of craters were formed in the bottom of chips. This kind of chip morphology tended to cause high-frequency of cutting vibration, rough surface and serious tool wear.

In the case of the machining of CGI, there were large amount of cracks and scratches on the chip bottom acted as capillary, which could increase the penetrating rate. Furthermore, craters formed by the peeling of graphic were able to store the lubrication media, which was helpful in forming firmer boundary lubrication layer and strengthening lubrication action. Similar to the craters on chip bottom, the un-smoothness of the surface of CVD-coated tools also can improve the lubrication by storing more lubrication media. Some researchers [24] even created textures on the surface of coated tools in order to achieve this goal. Therefore, lubricating and cooling conditions applied during the machining of CGI has great influence in improving the cutting performance.

3.4.1.2 Setup conditions of OoW

For EOoW cooling conditions, as shown in Fig. 5, EOoW_{rf} had less adhesion on tool rake face than that of EOoW_f because of its higher strength of lubrication layer on rake face. The OoW depends on penetrating capillary of tool-chip interface and forming lubrication film for reducing the friction between tool rake face and chip during cutting. The friction force follows Eq. (2) [8].

$$F_f = \tau_s A_s + \tau_m A_m \quad (2)$$

Where F_f is the friction force between rake face and chip; τ_s is the shearing strength of machined material; A_s is the adhesion area between rake face and chip; τ_m is the shearing strength of boundary lubrication layer; A_m is the action area of lubrication film; $A = A_s + A_m$, where A is the contact area between rake face and chip.

The lower of shearing strength τ_m , the higher strength of the lubrication layer. Meanwhile, the friction force F_f will reduce with lower shearing strength τ_m . Therefore, the strength of the lubrication layer can be quantified by friction force F_f .

The friction force F_f can also be calculated by the Eq. (3).

$$F_f = F_y \sin \alpha + F_z \cos \alpha \quad (3)$$

Where F_y is the radial feed force; F_z is the tangential feed force; α is the tool rake angle. F_y and F_z are measured by Kistler Dynamometer and $\alpha = 25^\circ$.

From the friction force of dry cutting, EOoW_f and EOoW_{rf} in Fig.15, it could be drawn that the friction force could be reduced by adopting EOoW_f and EOoW_{rf}. EOoW_{rf} had the higher strength of the lubrication layer than that of EOoW_f. These conclusions were consistent with rake face wear morphologies and tool wear resistance of dry cutting, EOoW_f and EOoW_{rf}.

For IOoW cooling conditions, only IOoW (1.2 L/h) could improve the tool wear resistance of CGI compared to that of dry cutting. For IOoW (0.6 L/h), it was because of the relatively weak cooling effect compared to IOoW (1.2 L/h), making lubricating layer evaporating more quickly. What is more, lower temperature can increase thermal conductivity, increase thermal diffusion and decrease specific heat capacity (Table 2), thus reduce heat accumulation during cutting. For IOoW (1.8 L/h), it was mainly because that the amount of water was too much, which diluted the percentage of lubrication oil per unit of lubrication liquid, leading to the decrease of lubrication

effect [20].

Therefore, in the case of turning CGI, spraying to rake and flank faces simultaneously, the proper oil and water ratio, and as low as possible cooling temperature should be used in order to improve the strength of lubrication layer, improve the lubrication effect and reduce heat accumulation. Accordingly, a newly OoW cooling condition, in which OoW was delivered by cryogenic air (in order to reduce the cooling temperature) to spray onto rake and flank faces, was developed, as shown in section 3.4.2.

3.4.2 Newly developed OoW cooling condition: CAOoW

In this section, a newly developed OoW cooling condition CAOoW was applied in the machining of CGI by using cryogenic air (-20°C , -35°C and -50°C) to deliver OoW, in order to improve the cutting performance.

With the decrease of the cryogenic air temperature, the cutting temperature became lower, indicating the improvement of cooling effect, as shown in Fig. 16(a). Cutting temperature of CAOoW was 50°C – 90°C and 95°C – 135°C lower than EOoW_{rf} and IOoW (1.2 L/h), respectively. At the cutting distance of 225 m, flank tool wear of CAOoW(-50°C) was two and three times lower than that of CAOoW(-20°C) and EOoW_{rf}, respectively. The tool wear rate of CAOoW(-35°C) was slightly lower than CAOoW(-20°C). CAOoW also gave the low surface roughness (Fig. 16(c)), which was 0.2–0.3 times lower than EOoW_{rf}. CAOoW, especially CAOoW (-50°C), had the best comprehensive performance in terms of tool wear and surface roughness in the machining of CGI among all the OoW cooling conditions used. This is because that sufficient cooling and lubrication effect provide by CAOoW is of much help in protecting the cutting tool and strengthening the oil film, as discussed in section 3.4.1.

4. Conclusions

This work compared the cooling methods of dry cutting, EOoW, IOoW and CAOoW with respect to cutting performance and tool wear for the turning of CGI. A cooling scheme is proposed for improving tool durability when processing CGI. Conclusions are as follows:

1. In EOoW conditions, EOoW_{rf} gave the lowest tool wear rate and less adhesion on both rake and flank faces because of sufficient lubrication and cooling. EOoW_r and EOoW_f had less adhesion on the tool face with OoW spraying directly because of better lubrication and less heat accumulation on it.
2. The larger of the water content in IOoW conditions, the lower of the cutting temperature, as well as the surface roughness. However, IOoW (1.2 L/h) had the lowest tool wear rate and the least adhesion because of better cooling effect than that of IOoW (0.6 L/h) to maintain the lubrication layer and reduce heat accumulation, and better oil/water composition than that of IOoW (1.8 L/h) to ensure the lubrication ability and penetrability. Thermal crack, which was absent from EOoW, occurred on flank face under IOoW conditions due to relatively higher cutting temperature and heat shock.
3. EOoW_{rf} and IOoW (1.2 L/h) cooling conditions could help CVD Al_2O_3 -based coated tool (Tiger and TK2001) better carry out their tool wear resistance than that of PVD TiAlN-based coated tools (TH1000 and TS2000) in the machining of CGI. Tiger tool had the highest tool wear resistance than the other coated tool under all the cooling conditions used. By using Tiger tool, IOoW (0.6 L/h) and IOoW (1.8 L/h) failed to improve the tool wear resistance because of insufficient cooling effect and insufficient lubrication respectively. EOoW_{rf} with lowest cutting temperature and high lubrication effect gave the lowest tool wear rate.
4. The penetrability of the OoW conditions depends on machined material, setup conditions of OoW, et al. In the case of turning CGI, spraying to rake and flank faces simultaneously, proper oil and water ratio and low cooling temperature could improve the strength of lubrication layer, improve the lubrication effect and reduce heat accumulation. CAOoW, a newly developed OoW condition, was proposed accordingly. CAOoW

(−50°C) gave 3 times and 0.2–0.3 times lower tool wear rate and surface roughness, respectively, than that of EOoW_{rf} in the machining of CGI. It is valuable to conduct further researches on the application of CAOoW.

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Figure captions

Fig. 1. Microstructure of CGI after corrosion by picric acid.

Fig. 2. Experimental setup of cutting process.

Fig. 3. Chip morphology obtained under (a) EOoW_r, (b) EOoW_f, and (c) EOoW_{rf} conditions. ($v_c = 70$ m/min; $f = 0.15$ mm/r; $a_p = 0.9$ mm; cutting tool: Tiger)

Fig. 4. Comparison of cutting performance of CGI under EOoW_r, EOoW_f, and EOoW_{rf} conditions. (a) Cutting temperature, (b) flank wear and (c) surface roughness.

Fig. 5. Tool wear morphology under (a) EOoW_r, (b)EOoW_f and (c)EOoW_{rf} conditions. ($v_c = 70$ m/min; $f = 0.15$ mm/r; $a_p = 0.9$ mm; cutting tool: Tiger; cutting distance: 225 m)

Fig. 6. Comparison of CGI cutting performance under IOoW (0.6 L/h water), IOoW (1.2 L/h water), and IOoW (1.8 L/h water) conditions. (a) Cutting temperature, (b) flank wear and (c) surface roughness.

Fig. 7. Tool wear morphology under (a) IOoW (0.6 L/h), (b)IOoW (1.2 L/h) and (c)IOoW (1.8 L/h) conditions. ($v_c = 70$ m/min; $f = 0.15$ mm/r; $a_p = 0.9$ mm; cutting tool: Tiger; cutting distance: 225 m)

Fig. 8. Comparison of tool wear of four coated tools under (a) dry cutting, (b) EOoW_{rf}, and (c) IOoW (1.2 L/h).

Fig. 9. Comparison of surface roughness of four coated tools under (a) dry cutting, (b) EOoW_{rf}, and (c) IOoW (1.2 L/h).

Fig. 10. Comparison of CGI cutting performance under dry cutting, EOoW, and IOoW conditions. (a) Cutting temperature, (b) flank wear and (c) surface roughness.

Fig. 11. Tool wear morphology under dry cutting. ($v_c = 70$ m/min; $f = 0.15$ mm/r; $a_p = 0.9$ mm; cutting tool: Tiger; cutting distance: 225 m)

Fig. 12. Orthogonal cutting process of CGI shot by high-speed photography. ($v = 120$ m/min, $a_p = 0.2$ mm, $a_e = 3$ mm; YG8 solid cemented carbide plane cutter; rake angle $\gamma = 10^\circ$, flank angle $\alpha = 10^\circ$; dry cutting)

Fig. 13 The micro morphology of CGI chip. ($v = 70$ m/min, $f = 0.15$ mm/r, $a_p = 0.9$ mm; turning; cutting tool: Tiger; dry cutting)

Fig. 14 The bottom surface of CGI chip. ($v = 70$ m/min, $f = 0.15$ mm/r, $a_p = 0.9$ mm; turning; cutting tool: Tiger; dry cutting)

Fig. 15 Friction force of tool rake face under dry cutting, EOoW_f and EOoW_{rf}.

Fig. 16 Comparisons of cutting performance of CGI under CAOoW. (a) Cutting temperature, (b) flank wear and (c) surface roughness.

Figure 1-Microstructure of CGI after corrosion by picric acid

Figure 2-experimental setup of cutting process

Figure 3-chip of EOoW

Figure 4- cutting performance of EOoW

Figure 5-tool wear of EOoW

Figure 6-cutting performance of IOoW

Figure 7-tool wear of IOoW

Figure 8-tool wear of four coated tools

Figure 9-surface roughness of four coated tools

Figure 10-all cooling conditions comparison

Figure 11-tool wear of dry cutting

dry cutting

workpiece

Rake face

Flank face

Figure 12-high-speed photography

Figure 13-chip micro morphology

Figure 14-chip bottom

Figure15-friction force of tool rake face

Figure 16-cutting performance of CAOoW

Table 1. Chemical compositions and hardness of CGI (RuT400).

Material	O	C	Ti	Si	Fe	Cu	Mn	Hardness
carbon	9.4-11.2	73.2-75	≤0.2	1.2-1.5	12.6-15.7	2.5-3.0	0.3-0.4	/
matrix	10.6-13.1	0.7-1.5	1-1.5	3.1-3.9	74.2-89.1	6.8-8.2	0.6-0.8	330-370HV

Table 2. Thermal properties of CGI (RuT400).

Temperature (°C)	Thermal conductivity (W/m.K)	Specific heat capacity (J/g.K)	Thermal diffusion (mm ² /s)	Density (g/cm ³)
room temperature	36.264	0.536	9.323	7.257
200	35.603	0.571	8.592	
400	33.704	0.635	7.314	

Table 3. Cutting inserts with four different coatings.

cutter bar type: CNMG120404

Walter tool: Tiger.tec Silver CVD coating $\text{Al}_2\text{O}_3/\text{Ti}(\text{C},\text{N})$
Seco tool: TK2001 CVD coating $\text{Al}_2\text{O}_3/\text{TiC}$
Seco tool: TS2000 PVD coating TiN/TiAlN
Seco tool: TH1000 PVD coating TiAlSiN

Table 4. Cooling conditions of traditional cooling liquid, EOoW, IOoW and CAOoW.

Cooling mode	Conditions	Diagrammatic sketch	Equipment schematic
(1) External oils on water (EOoW)	Water: 150ml/h Oil: 20ml/h Temperature at the exit of nozzle: 18°C Air pressure: 0.35MPa Injection location: rake face, flank face, rake and flank face		
(2) Internal oils on water (IOoW)	Oil: 20ml/h Temperature at the exit of nozzle: 25°C Air pressure: 0.1MPa Water content: 0.6L/h, 1.2L/h and 1.8L/h	(e) IOoW and CAOoW 	
(3) Cryogenic air mixed with oils on water (CAOoW)	Water: 1.2 L/h Oil: 20ml/h Air pressure: 0.24MPa Initial air temperature: -20°C, -35°C, -50°C (corresponding temperature at the cutting tip: -5°C, -12°C, -17°C)		

Table 5. Properties of lubricating oil.

Type	Main ingredient	Viscosity (40 °C)	Flash point [°C]	pH	Corrosion resistance	Lubricity *	Cooling ability *	Producer
2000-30	synthetic ester lubricant	30	290	7	Moderate	High	Moderate	DG Armoline Energe-efficient and Eco-friendly Tech Co., Ltd, China

* : Compared with fatty alcohol (2000-10 type lubrication oil produced by the same producer).