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Assessment on abrasiveness of high chromium cast iron material on the wear performance of PCBN cutting tools in dry machining

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ABSTRACT

Polycrystalline Cubic Boron Nitride (PCBN) has been considered as the main cutting tool material for hard turning, which has the comparable surface finish quality as grinding, and high efficiency, economical technology in production. It is well known that the abrasiveness of the workpiece have the very important role of the machinability of the materials. Therefore, the tool wear of the PCBN insert correlates with abrasiveness of the materials very much. In the presented paper, the influence of the micro hardness distribution is used to explain the wear mechanism in machining of the high abrasive materials and proposed a model to predict the abrasiveness. The work material is high chromium cast iron and cutting tool material is PCBN. Abrasiveness are evaluated from the micro hardness distribution by nanoindentation for the distinguish microstructure with hardness. The mapping image of the micro hardness showed the matched features with microstructure images from the scanning electron microscope (SEM). The different chemical composition groups are presented as three heat treatment conditions in experiments, which are as-cast, annealed and hardened. Based on the hardness distribution, this paper presented a model to evaluate the abrasiveness index of the material. The high performance machining is done on six material. The wear mechanism is abrasion in tool wear dominantly and flank wear showed the linear relationship with abrasiveness index. The abrasive wear on the cutting edge suggests that sliding and chipping are the main wear modes which is caused by the combination effect of carbides and matrix. The four mechanisms of diffusion, chemical, abrasive and micro chipping are happening in the tool wear of hard turning. In the dry machining by PCBN insert, abrasiveness is correlated with abrasive and chipping very much and accelerated the crater wear in machining. Abrasiveness index of the material has ability to predict wear performance in dry machining of HCWCI materials by PCBN inserts. The application of the abrasiveness is a potential parameter of machinability to improve the machining efficiency and reduce the cost of machining.

1. Introduction

The PCBN (Polycrystalline Cubic Boron Nitride) inserts are widely used as cutting tools for extremely hard and thermally stable tools materials. According to Patel and Gandhi (2016) and Sobiyi and Sigalas (2016), almost all PCBN inserts are used for the high hardness (> 50HRC) materials and offering the high finished surface quality, high manufacturing efficiency and low cost to conventional grinding process. Due to the high performance with using of the PCBN insert in manufacturing, the rapid growth of PCBN inserts application is in machining of high abrasive materials, such as the Ezugwu et al. (2003) listed application of PCBN inserts for super alloy and its high performance; Zhou and Andersson (2008) applied the PCBN inserts for high chromium alloy and improved machining efficiency significantly; Silva et al. (2016) has showed that the PCBN inserts are good for the ductility material of titanium alloy. In spite of the PCBN inserts are considered as a suitable choice for machining of the high performance materials, enhancement of the machining performance by suppressing the tool wear, improve surface finishing and predicting the tool life are still challenges in the research. De Godoy and Diniz (2011) studied the continuous turning of hardened steel by CBN insert, and found the improvement of tool life by the proper cutting speed; Jafarian et al. (2013) studied the optimization in machining operations, and improved the machining performance of surface roughness, tool life, cutting force in turning; Yucel and Gunay (2013) studied optimization in the machining of high chromium cast iron, and found that the of cutting parameters are the most significant factors to cutting force and surface roughness; Scandiffio et al. (2017) found that the quality of the cutting inserts has significant effect on tool life and surface roughness and proposed the suggestion of surface quality checking of cutting inserts.

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Moreover, it is well known that the behaviour of the work materials plays important roles in the tool wear and tool life in high performance machining of high abrasive materials, such as the hardness, microstructure of the material. According to the literature work of machining of aero alloys by Ulutan and Ozel (2011), the higher hardness of the work material will be caused the higher tool wear rate in machining. However, the hardness of the material has been reported in several investigations, such as Ånmark et al., (2015) studied the machining of non-metallic inclusions of steel; Dosbaeva et al. (2015) studied the machining of D2 tool steel; Mia et al. (2016) studied the machining of different workpieces with different hardness; which will not generate the high cutting force and tool wear in hard turning by PCBN inserts. It is important to clarify that in hard turning a negative rake angle, high speed and absence of coolant will generate the high temperature of 900 °C and high pressure on the cutting edge. According to Zhu et al. (2013), the four mechanisms of diffusion, chemical, abrasive and micro chipping are happening in the tool wear of hard turning. Under the high pressure and temperature in the cutting, the cutting edge and workpiece turned to soft, and the phases in the high abrasive are transformed to the soft phases. These transformations cannot be only explained by the macro hardness of the work piece. According to the literature work by Ezugwu et al. (2003), it has reviewed the machining of aero alloys; Ng and Aspinwall (2002) studied the machining of AISI H13 hot work die steel; Coronado and Sinatora (2009) studied the machining of white cast iron; Tang et al. (2011) studied the machining of white chromium cast iron. The common interest result is that the low macro hardness workpiece showed the higher abrasion wear than the high macro hardness material, the high abrasive particles (for example: eutectic carbides) in the workpiece wear off the binder materials of the tool inserts and influenced the strength of the cutting edge. Moreover, the high temperature and pressure are also accelerating the chemical and diffusion wear in the machining. The combination model of multiple wear mechanism cased the fast tool wear in the cutting of the high abrasive materials. For the better understand of the abrasiveness of the materials in the specific application, there are plenty of directly methods are employed to obtain the relative index, such pin-test, scratch test, standard machining, and so on. However, there is lack of general instruction into the specific manufacturing of parts of high abrasion resistance materials. The study of the tool wear in machining with PCBN inserts are still a hot topic in academic research.

The abrasion resistance of materials is related to the microstructure of the materials, especially the formed of the very hard carbides by the multiple alloying element in the materials. According to Badisch and Mitterer (2003), the abrasive wear of high speed steel is related with the abrasive particles and primary carbides in the material. Acker et al. (2005) found that the wear is related with carbides' particle size and its distribution. Xu et al. (2016) studied the wear resistance of ferrite-martensite dual phases steel, the volume fraction and its distribution are affected the wear performance significantly. Summary, the volume fraction and morphology of carbides are the main criteria of the abrasiveness of the material. But the ignoring of the hardness distribution of the matrix and the combined effect with carbides limited the application of these criteria of wear resistance in the machining of these materials. In the presented work, the wear resistance of the abrasive material is illustrated by the hardness distribution of carbides and matrix. Although the wear in high performance machining is widely studied by the macro hardness and microstructure analysis, but there is little study on the micro hardness, especially the intrinsic hardness of the phases in the materials.

The objective of this paper is to find out the wear mechanism of the PCBN inserts in high performance machining of the high abrasive materials and abrasiveness model to evaluate the wear performance in machining. It aims at studying the correlation between abrasiveness and tool wear. The selected material for workpiece is high chromium cast iron, and the cutting tool is selected the proper PCBN inserts (CBN500) from the SECO Tools.

2. High chromium white cast iron

Due to the superior abrasion and corrosion resistance, high chromium white cast irons (HCWCI) are widely applied in industrial products, especially in mining, crushing, drilling and so on. The high abrasion resistance of HCWCI is related to chromium content in the material. According to Tabrett et al. (1996), the material is alloyed with 12–35% of chromium for achieving a good balance of material performance. The chromium carbides in the matrix have the discontinuous distribution, and the high hardness of these carbides is providing the protection of materials. However, with the improvement of the abrasion resistance of the material, the machinability of HCWCI is decreasing. Shalaby et al. (2014) studied different cutting tool materials in the machining of high carbon chromium tool materials. The cutting tools show the fast tool wear and instability in the machining process, and the cost of the machining is very high. The application of the CBN cutting tool is the potential approach to improve the machining efficiency and reduce the cost of machining.

In general, the HCWCI has the microstructure of eutectic carbides (M_7C_3) in a ferrous matrix. The retained austenite and tempered martensite is always included in the as-cast condition. After heat treatment and composition adjustment, the austenite and martensite in the matrix are transformed to bainite, pearlite, or bainite; and carbides in the material are also transformed to primary carbides (M_3C), secondary carbides. Moreover, the grain size, content of phases are changed with different conditions too. According to nanoindentation characterization by Chen et al. (2015a,b), the difference of the materials is their micro hardness and micro hardness distribution of the phases. The amount, grain size, and morphology showed the typical pattern of hardness distribution, and the micro hardness distribution is shown as the effective way to characterize the materials of HCWCI.

The test samples of the HCWCI are prepared as the bar shape, and supplied by Xylem water solution AB in Sweden. There are the typical materials for the slurry pump manufacturing. The selection of chemical composition and heat treatment is applied to obtain different microstructure of matrix and carbides in the materials. Due to the C-Si content is very sensitive in the casting process, and it always applied to the chemical composition adjustment method to improve the material performance. There are two groups of HCWCI in this investigation. The chemical composition of the two groups is presented in Table 1. The effect of C-Si changed the hypoeutectic microstructure in Gr.1 to hypereutectic microstructure in Gr.2. The SEM microscope images in Fig. 1a,b revealed the features of primary austenite dendrite and brittle faceted M_7C_3 eutectic carbides in Gr.1 and big primary carbides in Gr.2. The materials is also heat treated to the softened condition and hardened condition. Fig. 1 showed the six samples of two groups with different heat treatment respectly.

Samples with different heat treatments and compositions show differences in microstructure. The Gr.1 has the lower C-Si content than

Table 1
Chemical composition of two groups of material.

	Fe	C	Si	Mn	S	P	Cr	Ni	Ti	Mo	Cu
Mat. Gr 1 (Lower C-Si)	70.55	2.71	0.8	0.34	0.012	0.019	25.3	0.11	0.004	0.02	0.047
Mat. Gr. 2 (Higher C-Si)	69.2	2.95	1.47	0.35	0.015	0.022	25.7	0.12	0.004	0.02	0.056