HIGH PERFORMANCE MACHINING OF HIGH CHROMIUM WEAR RESISTANCE MATERIALS WITH pcBN AND bcBN TOOLS

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Abstract: The presented paper is to experimentally evaluate the performance of the cBN tools in the machining of high chromium white cast iron. The performance in terms of the level of cutting forces, tool wear, surface roughness and process stability were evaluated during and after the cutting test. Two types of cBN tool material are evaluated in the tests, which include polycrystalline boron nitride (pcBN) and binder-less crystalline boron nitride (bcBN). The work materials used in the cutting tests have two groups of chemical composition with different levels of carbon silicon (C-Si) content in as-cast, annealed and hardened state respectively. Test results indicated that cutting tool materials, levels of C-Si contents and heat-treatment of the work materials have significant influence on the cutting performance. The study also reveals the mechanism of interaction between cBN tool and high chromium white cast iron under the range of machining parameters. Cutting tool materials exhibit clear differences in the wear rate and wear mechanisms during the machining test.

Keywords: Machinability, White cast iron, cBN, Machining, Tool wear,

1. INTRODUCTION

Wear resistant materials are an important group of alloys accounting for large industrial application (Sapate etc, 2004). High chromium white cast irons are among the typical wear-resistant materials in which the white cast iron alloyed with 12 – 35 % chromium for achieving superior wear resistance and corrosion resistance (Pearce,1983; Tabrett,1996). The materials offer good corrosion resistance and high abrasion resistance as the result of high concentration of chromium in the matrix and the presence of eutectic carbides (M_7C_3) (Janssen, M. etc. 1985). However, the material is well known as difficult-to-machining material due to the short tool life, unstable machining process and poor surface finishing created during the machining. Low cutting speed for conventional cutting tool materials, such as cemented carbide and ceramic, often results in low productivity of this material. Shapovalova and Bashkin (1985) reported a pre-heating approach to machine high chromium white cast iron with high speed steel cutting tool (VK6M) under the cutting speed of 15-60 m/min and feed rate of 0.05-0.15 mm/rev. They claimed that the productivity was increased by a factor of three to five due to reduced hardness of the workpiece under the pre-heating temperature up to 300°C. Ravi etc. (2013) made an experimental study on optimal cutting parameters for machining the high chromium white cast iron with multi coated hard carbide tool in terms of performance, quality and cost. By using Taguchi's parameter design, they reported that the optimal cutting speed was in the range of 40 – 110 m/min with coated carbide tools. Recent trend of high performance machining of wear resistance materials generally relies on cBN cutting tools in which much higher material removal rate and better product quality can be achieved (Zhou etc, 2010) due to high hot hardness, fracture toughness and better chemical stability provided by the cBN tools. Gunay etc (2013) studied on optimizing the cutting conditions for the average surface roughness (Ra) obtained in machining of high-alloy white cast iron (Ni-Hard) at two different hardness levels (50 HRC and 62 HRC) with cBN tools. Ren etc. (2001) studied the deformation behavior of the hardfacing material and the wear of pcBN tools. The main mode of tool wear was identified as edge chipping and flank wear in this report. In addition, mechanical loading and the abrasiveness of the carbide particle were the main cause of wear. Although use of cBN tools significantly increases the tool life compared with cemented carbide and ceramic tool materials, and results in the low frequency of tool change and high rate of productivity accordingly in the best process condition, the use of cBN tools is still constrained by large scatter of tool life, especially premature tool failure in the rough machining and intermittent machining these materials in the scenario of industrial production. The large scatter of tool life often introduces instability and disturbances to the machining processes and will lead to high production cost due to their unpredictability according to interviewing with machine operators in the workshop. Nevertheless, cBN tools are by far the most effective cutting tools in the high performance machining this material. The properties of the cBN tools vary significantly and primarily depend on its grain size and binder materials. Compared with conventional cBN tools, newly developed binder-less cBN has higher hardness and fracture toughness (Petrusha, 2011). The presented paper is to experimentally evaluate the performance of the conventional cBN and binder-less cBN tools in the machining of high chromium white cast iron and thereby optimize tool/work material combination in high performance machining this material. The performance in terms of the level of cutting forces, tool wear, surface quality and process stability were evaluated during and after the cutting test. Meanwhile, the mechanism of tool wear caused by interaction between work material and tool material are also being the focus in the study for optimum the machining condition and tool design.

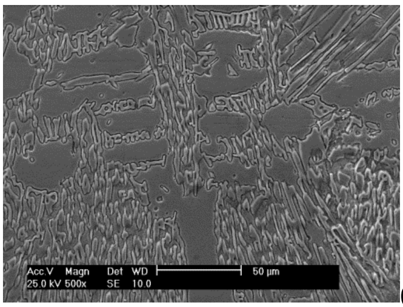
2. EXPERIMENT

Materials

The materials used in the investigation are high chromium white cast irons (Cr>25% vol.) with two groups of carbon-silicon contents: higher carbon-silicon (higher C-Si) (2.95% and1.47% vol.) content and lower carbon-silicon (lower C-Si) (2.71% and 0.8% vol.) content. Table 1 summarizes the approximate chemical composition of the two groups of material. The composition represents both hypoeutectic and hypereutectic alloys. The materials with the lower C-Si have the typical hypoeutectic microstructure, in which the matrix includes the primary austenite dendrites with needle like slide martensite and the martensite is surrounds the interconnecting network of brittle faceted M_7C_3 eutectic carbides. The materials with higher C-Si have hypereutectic microstructure, in which the austenite is almost transformed to bainite in the matrix, and the primary eutectic carbides are distributed in the middle of the interconnecting of eutectic carbides. The materials were cast into a bar shape with diameter of 66 mm and length of 370 mm. Three samples were prepared for each group of chemical composition and two of them were heat-treated in annealed and hardened respectively. Total six samples were prepared for the test. In general, the microstructure of high Cr white cast iron consists of hard eutectic carbides (M_7C_3) and primary carbides (M_3C) in a ferrous matrix of martensite with some retained austenite. The differences among the six materials are their matrix hardness, the amount of chromium carbides and morphology of eutectic carbides. Fig. 1 represents the SEM microscopes of the typical microstructure of the high Cr white cast iron (as-cast) with lower and higher C-Si contents restively. The difference between higher and lower C-Si contents in white cast iron is their microstructure and mechanical properties. Grain size of carbide and hardness are both dependent on C-Si content of the melt (Atanda etc, 2011). The materials with higher C-Si contents was observed to increase grain size and reduce free graphite but with resultant decrease in hardness.

Table 1. Chemical composition.

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


(a)

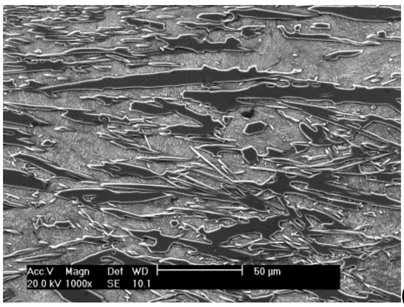

(b)

Fig. 1. Microstructure of high Cr white cast iron (as-cast): (a) lower C-Si contents and (b) higher C-Si contents.

Cutting tools (pcBN and bcBN)
Two types of cBN tool materials, named pcBN (or cBN500) and bcBN, were used in the cutting test. The pcBN is a high-cBN grade with 90% cBN content, AlN/addition (WB2) binder, 15 micro grain size and solid format. The material has the hardness of HK=32 (HV≈39) GPa. Thermal conductivity was not tested but for all pcBN materials with this type of binder it is in the range of 80-110 W/(m·K). Its hardness and fracture toughness are often largely influenced by the mechanical properties of binder materials, which is lower than pure cBN (Petrusha etc. 2011). The bcBN is a binder-less cBN grade with single phase of cBN, resulting higher hardness and fracture toughness than pcBN. In binder-less cBN, the binding of cBN grains is completed through diffusion sintering which is enabled by very high temperatures during sintering 2400°C. Pressure of 8 GPa is maintained during the HP=HT treatment to avoid a reverse cBN → hBN transformation. Absence of binder on the cBN grain boundaries leads to the increased thermal conductivity of 160-200 W/(m·K) (Bushlya etc. 2014). Higher hardness of the bcBN as compared to pcBN indicates the potential in machining materials with higher abrasiveness. At the same time high thermal conductivity is expected to lead to a lower cutting temperature and therefore facilitate longer tool life in machining. Chamfered round inserts, RNMN120400, were used in the cutting tests. The tool hold is CRSNR3225 with rake and flank angle of -6° respectively.

Machining conditions
Table 2 summaries the cutting parameters used in the test. The selection of cutting parameters covers the range of industrial production and the recommendation from cutting tool manufacturer. Dry machining tests were conducted throughout the tests. Pre-cut was made on each workpiece before the tests in order to remove the rough out-layer from prior casting process. Tool flank wear was measured by means of Alicona InfiniteFocus optical microscope. The cutting forces were measured by means of quartz piezoelectric type dynamometers (Kistler 9129A). Registration of vibration signals was performed with three accelerometers Bruel&Kjær type 8309 with following characteristics: reference sensitivity ∼0.05 pC/g, upper frequency limit 54 kHz (+10 %), max. operational shock ±1000 km·s^{-2}, temperature range from -74 to +180 ºC. The force and acceleration spectra were recorded with sample rate 1 kHz and 120 kHz, respectively.

Table 2. Machining conditions.

Cutting tool materials	pcBN, bcBN
Cutting speed, v_c (m min^{-1})	120, 140, 160
Feed, f (mm per revolution)	0.4
Depth of cut, a_p (mm)	1.5
Work materials	High Cr white cast iron
Cutting fluid	dry
Tool geometry	-6°, -6°

3. RESULTS AND DISCUSSION

Cutting forces
Fig. 2 and 3 demonstrate the fluctuation of the force values produced by pcBN and bcBN cutting tools in the machining two groups of high chromium white cast irons under different machining conditions. In the figures, F_c, F_f and F_r represent the average cutting force, feed force and radial force respectively when fresh cutting edge was used. The results demonstrated in Fig2 &3 suggest that both types of cutting tools generated approximately same level of force values in the machining of as-cast and annealed materials under the same cutting parameters. However, when hardened materials were machined, the forces produced by bcBN tools tend to be higher than the force level generated by pcBN tools although the same tool geometry and cutting condition were used during the tests. This may attributes to the different type of tool wear which result in alteration on the edge geometry of tools. The force values were also increased faster when bcBN cutting tool was used due to the higher wear rate introduced on the cutting tool.

The force measurements from cutting tests, as shown in Fig.2 and 3, also reveal the minor influences on cutting force values from the materials with two groups of chemical composition when as-cast and annealed materials were used in the test. The materials with lower C-Si content produce slightly higher force values than the materials with higher C-Si content during the machining of as-cast materials when both pcBN and bcBN tools were used, which may associate with the difference of their hardness. The material with higher C-Si content has hardness of 54 HRc in as-cast, while the material with lower C-Si content has hardness of 40 HRc in as-cast. The cutting forces show different trend when the materials were hardened. After the hardened, comparable hardness are received for the materials with both groups of chemical composites with hardness of 57 ~ 58HRc. All three components of forces were slightly higher for the material with lower C-Si content than the material with higher C-Si content. In addition, the small influence of cutting speed on the cutting force values were observed in the test of all types of materials. The force values tend to be smaller when higher cutting speed (160 m/min) was applied in the test due to the higher cutting temperature.

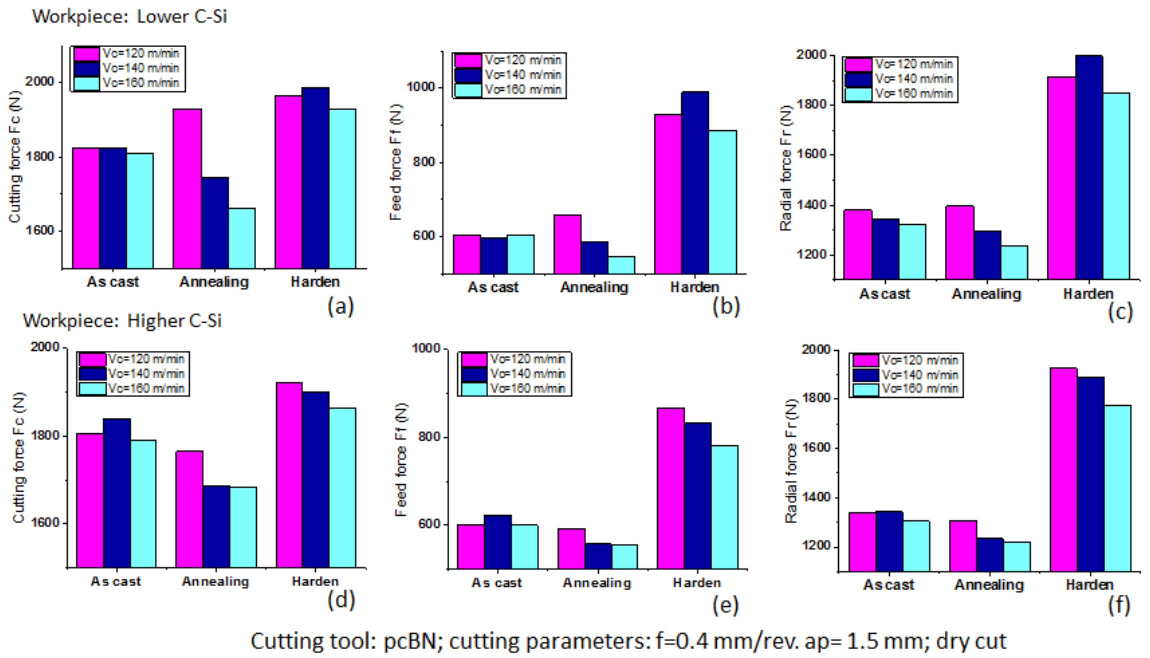


Fig. 2. Cutting forces produced by pcBN tools when cut two groups of materials under three cutting speeds.

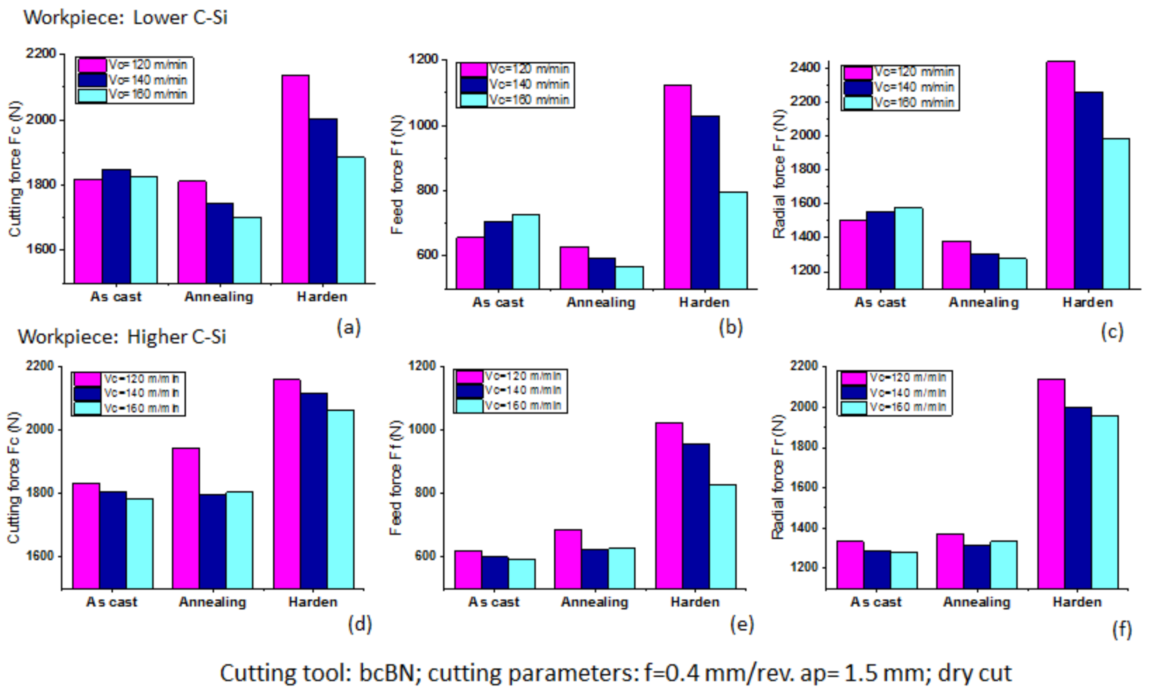
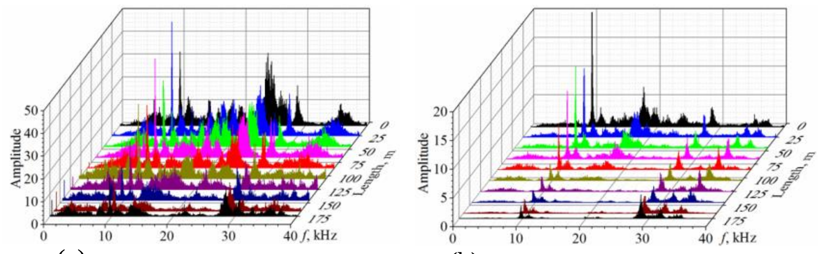


Fig. 3. Cutting forces produced by bcBN tools when cut two groups of materials under three cutting speeds.

Vibration

Results from analysis of acceleration signals demonstrate that the cutting process is characterized by the set of strong harmonics. The strongest harmonics appeared at the same frequency for both tool grades. Fig. 4(a) and (b) reveal the power spectrum of the acceleration signals measured during the tests of as-cast work material when pcBN and bcBN tools were employed respectively. The spectral amplitude generated by pcBN tools is much higher than the one by bcBN tools, which indicate the higher vibration amplitude was induced when pcBN tools were used during machining the materials. Similar phenomena were observed in the machining hardened workpieces. A possible reason to explain the difference in the vibration amplitude between the two types of grades could attribute to the damping behavior of the bcBN tool caused by its fast tool wear at the beginning of machining. Continuous Wavelet Transformation (CWT) analysis of vibration signals (Fig. 5) clearly demonstrates the vibration at the beginning of the machining and the amplitude of the vibration decreases to a stable level after one second of cut. The absolute values of signals energy, when machining as-cast materials, have comparable character independent on cutting speeds for both bcBN and pcBN tools. In all considered cases the signal energy (squared wavelet coefficients) increases with increase of cutting speed, approximately 2 times, when cutting speed increases from 120 to 160 m/sec, and decreases dramatically with cutting length during the pass. It is obviously the decrease of C(a, b) value is related to a tool wear development along with increase of cutting length.



(a) (b)

Fig. 4. Spectra of acceleration signals change in the cutting length for pcBN (a) and bcBN (b) tool grades.

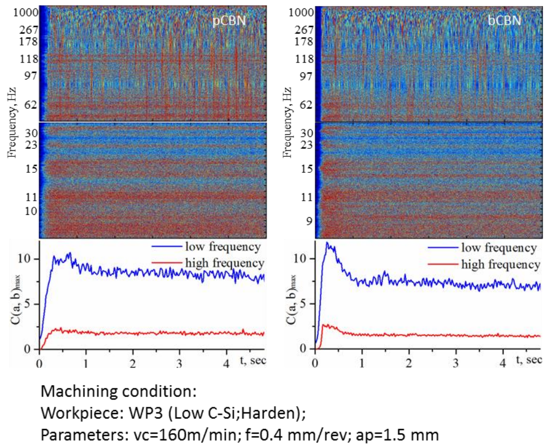


Fig. 5. Wavelet analysis of vibration signals measured when machining with pcBN and bcBN tools.

A distinctive feature of process of hardened high Cr white cast iron, as compared to as-cast material, is the absence of strong vibrations at frequency range around 300 Hz. The higher hardness of material promote the vibrations to be distributed in a higher frequency diapason (> 60 Hz) as a noise, intermittent and transient processes staying stable at lower frequency range as yet. The high frequency intensity is shifted to the frequency range higher than 1 kHz. The intermittence of signal on the spectrograms is typical for high frequency range at low cutting speed and at the end of pass in case of machining as-cast materials and always presents on the spectrograms of the hardened materials. The presence of such intermittence usually shows that the process tends to be unstable what results in a transition to chaotic behavior of process.

Surface roughness

3D surface profiles were measured by Alicona InfiniteFocus optical microscope after the tests and surface roughness, R_a, were measured between the tests with a stylus profiler. Fig. 6 (a) and (b) reveals the progression of average roughness (R_a) produced by pcBN and bcBN cutting tools respectively over 350 mm of cutting length when materials in higher C-Si contents were machined. Fig. 6 (c) and (d) represent the 3D surface roughness profile produced by pcBN and bcBN cutting tools respectively for the same group of material in as-cast. The average roughness (Ra), shown in Fig 6(a) and (b), demonstrates the trend of increase in roughness with progression of cutting length when cutting with both types of cutting tool. This may primarily attribute to the increase of tool flank wear. However, small decrease of roughness level was also observed during the test with bcBN tool for as-cast and annealed materials as result of tool wear. Sometimes, the small level of tool flank wear may benefit the surface roughness due to the better damping behavior between tool and workpiece (Fallöhmer and Scurlock, 1996). Fig. 6(a) shows that the roughness on the workpiece produced by pcBN tool has noticeably higher values than the one produced by bcBN tools. Side flow and debris of built-up-edge (BUE) left over the machined surface are the contribution of the higher roughness of the surface produced by pcBN tool, as shown in Fig. 6 (c). Compared with bcBN tools, rougher surface generated by pcBN tool may attribute to two reasons. Dull cutting edge caused by severe chipping, which generate squeeze rather cut between tool and workpiece, could be one reason. Another reason could be formation of BUE and side-flow due to the higher cutting temperature during the machining when pcBN tool was used. The pcBN material has lower thermal conductivity (80-110 W/(m·K)) than bcBN material (160-200 W/(m·K)) due to its binder materials (10 % of AlN/addition (W2B5) contained in pcBN. The thermal conductivity of binder material is much lower than cBN. In addition to the higher temperature in the tool/workpiece interface, existence of minor vibration during the process is another reason for the higher roughness on the surface. Fig. 4 and 5 suggest that the amplitudes of vibration induced by pcBN tool were clearly higher than the one produced by bcBN tool during the machining.

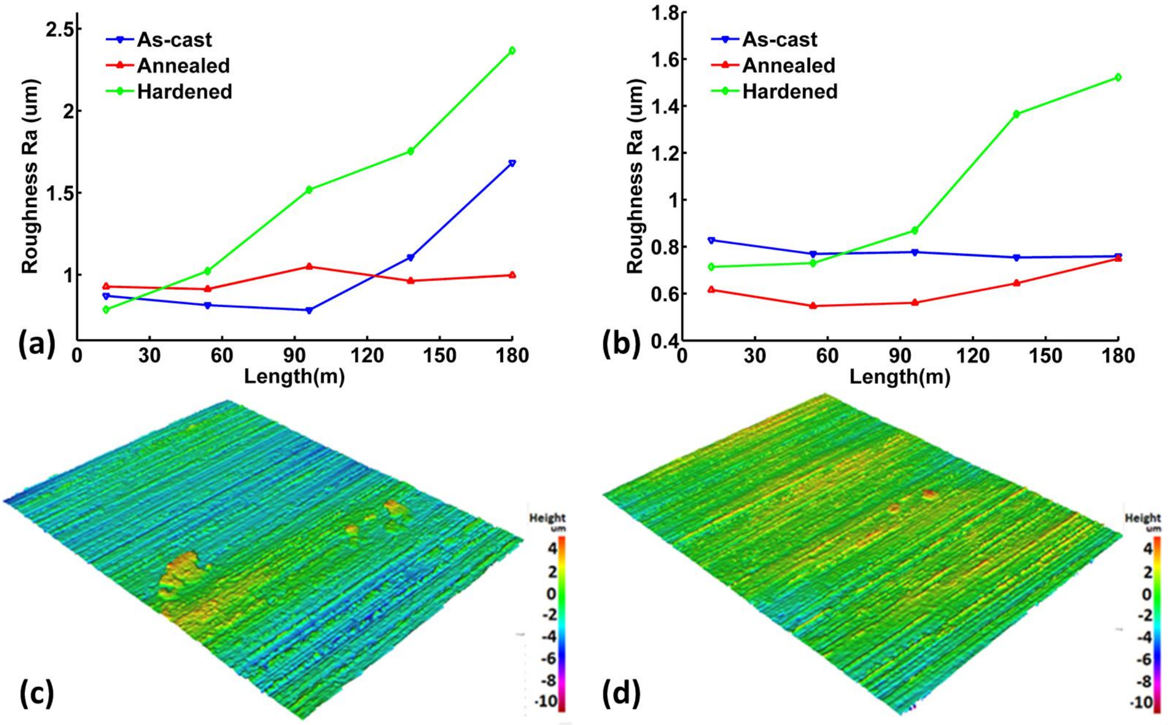


Fig. 6. Surface roughness R_a and 3D surface profile produced by pcBN and bcBN cutting tools on as-cast materials in higher C-Si.

Tool wear

Fig.7 presents the tool wear for both pcBN and bcBN cutting tools after six different materials were machined at a certain cutting length (180 m). The worn appearances on both cutting tools exhibit noticeably difference in the machining high Cr white cast iron (Fig.7 (a) and (b)). Severe edge chipping was found on the cutting edge of pcBN tool during machining as-cast and hardened workpieces, which makes the primary cutting edge to be dull. Both flank wear and crater wear on bcBN was larger than pcBN tool for all the tests carried out in this investigation. Fig.7 (c) and (d) reveals the influence of work materials on the tool wear. For both types of cutting tool, the materials with lower C-Si contents induce higher tool flank wear than the materials with high C-Si contents although the differences are not significant for the annealed materials. Hardness of the materials introduced by contents of C-Si has contribution to the level of the tool wear. The difference tends to be more significant when bcBN cutting tool was applied in the tests. The flank wear produced by the materials with lower C-Si contents is almost double as much as the flank wears produced by the materials with higher C-Si in as-cast workpiece and 30% more in hardened workpiece.

Different wear mechanisms were found for pcBN and bcBN tools in the machining of high chromium cast irons although abrasion, adhesion and chemical wear were found in machining of high Cr white cast iron with CBN tools. Fig. 8(a) and (b) shows the closed view of SEM observation of the cBN tools after turning of high Cr white cast iron for 1.4 min or 180 m cutting length at cutting speed of 160 m/min. The grooves on the flank face show typical abrasion wear appearance. The cause of this appearance may be that the tool material severely abraded by hard carbide particles of the workpiece material, which leads to cBN grains to be detached from the bond and left shallow grooves on the tool flank face. Fig. 8 also shows an adhesion layer formed on the cutting edges. The adhesion layer covers most the cutting area in the pcBN tool (Fig. 8(a)) while only little adhesion layer was observed on the crater area of the bcBN tool. The adhesion layer could be the mixture of solution from binder materials on pcBN and from work material (Luo etc, 1999), which is associated with the cutting temperature between the workpiece and the cutting tools. For bcBN tool, however, the adhesion materials are the solution of work materials. Since the thermal conductivity of pcBN is much lower compared with bcBN (Bushlya etc, 2014), the cutting temperature generated in the interface between the workpiece and cutting tool are much higher when pcBN was used. This may explain the reason of the more adhesion material covered on wear region on pcBN tools than on bcBN tools. In addition, larger crater wear was found in bcBN tools after the machining and chemical wear is believed to be the major reason for this type of wear (Bushlya etc, 2014). The boron element in cBN tools is prone to react with chromium in workpiece under proper temperature and pressure. Unlike the pcBN tools, litter adhesion layer covered on the rake face of bcBN tool makes the chemical wear easier during the machining when bcBN tool was used. Absence of a binder in the bcBN grade may lead to a more intensive chemical wear if alloying of the material being machined facilitates such chemical reactions. The results from EDX analysis of composition in the adhesion layer deposited on the tool face, as shown in Fig.8(d), reveal that the elements from both cutting tool and workpiece. In addition, the intensity of Al on the layer is much stronger than that of high level of aluminum was found in EDX analysis although no aluminum was claimed to contain in the material and in bcBN tool material.

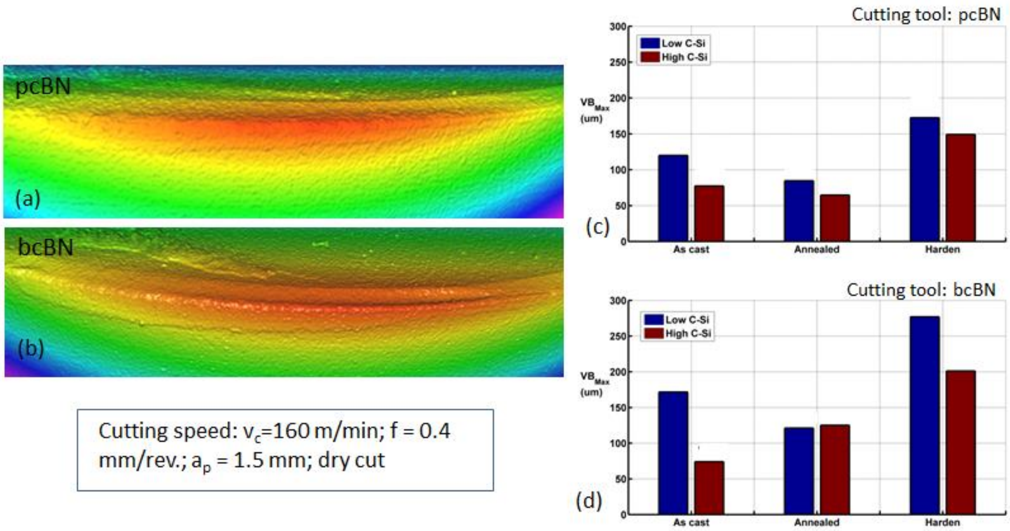


Fig. 7. Flank wear and crater wear on pcBN and bcBN cutting tools in (a) and (b); wear rate generated on pcBN and bcBN tools when machining six different materials in (c) and (d).

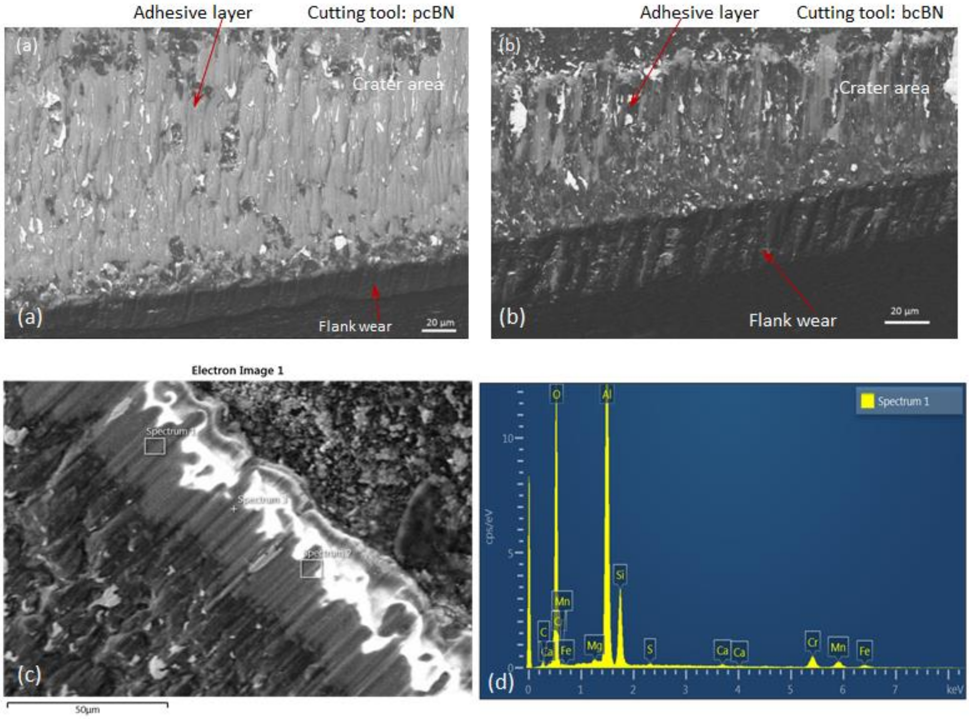


Fig. 8. Adhesion layer generated on pcBN tool (a) and bcBN tool (b) during machining high Cr white casting iron; EDX analysis of adhesion layer on tool wear region (a) and (d).

4. CONCLUSIONS

The pcBN and bcBN cutting tools demonstrate different performance in the machining high chromium white cast irons in terms surface quality, tool wear rate and process stability. Lower tool wear rate and almost no crater wear were received when machining with pcBN tools. Chipping along the cutting edge was major type of tool deterioration. The higher surface roughness (R_a) is obtained caused by BUE and smear induced during the machining as result of squeezing between the cutting edge and workpiece, and higher cutting temperature. Lower surface roughness (R_a) was measured when bcBN tools were used while the larger tool flank wear and crater wear were generated during the machining. Large crater wear generated on bcBN tools during the test could attribute to the chemical wear induced under the contact between chip and tool rake face causing higher local temperature. Absence of a binder in the bcBN grade may lead to a more intensive chemical wear if alloying of the material being machined facilitates such chemical reactions. The pcBN tool material exhibits lower wear rate and longer tool life while bcBN tool material demonstrates better surface finish and process stability. Carbon and silicon (C-Si) content in high Cr white cast iron materials has also noticeable effect on both cutting force and wear rate. Lower C-Si content in as-cast workpiece results in higher cutting force and higher wear rate for both types of cBN tool than higher C-Si content materials. After hardening treatment, the same trend on the cutting force and wear rate was observed for both lower and higher C-Si content materials although both types of materials show roughly the same hardness. This can be associated with the differences in the volume fraction of martensite structure in the high Cr white cast iron materials.

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