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Characterization and performance evaluation of mono-grain and bi-modal PCD grade in machining of MMC

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Abstract

The aim of this investigation is to study the influence of different parameters such as grain size and cobalt content on the tool performance in the machining of metal matrix composite (MMC) using different polycrystalline diamond (PCD) tools. The experimental tests were conducted with four different PCD grades in dry the milling of Aluminium-Silicon carbide (Al-SiC) composite containing 20% wt of SiC as a workpiece material. The SEM study shows that PCD grades I and II have a bimodal grain size distribution. Rietveld refinement of the XRD spectra for these grades indicates that grade I contains larger amount of Co compared to grade II. The difference in performance between these grades can be explained by the Co content. PCD grade III is a coarse grain grade while grade IV is a fine grain grade. An XRD analysis shows that the main difference between the mono-grain and bimodal grain PCD is the presence of WC in the mono-grain grades which is believed to be added to the raw material of PCD as a grain growth inhibitor. In the XRD pattern for the bimodal grades the peaks in the WC phase are completely absent. The results indicate that the tool performance in terms of wear development is influenced by grain size distribution, cobalt content and the presence of WC; where the abrasive wear is the main wear mechanism which determines the tool life of the diamond grades in milling MMC. The results also indicates that the MMC can be machined with any diamond grade at the low range of cutting speed (≤ 400 m/min) while at a higher range of cutting speed (> 400 m/min) the selection of the diamond grade should be based on the chemical composition and grain size distribution. The presence of grain growth inhibitor also has a significant effect on the tool performance in machining MMC at cutting speeds above 400 m/min.

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1. Introduction

Metal matrix composite (MMC) provides a combination of excellent mechanical properties and low weight. This combination gives the MMC good potential for expanding as a “new” product generation in automotive and aerospace industries. The main obstacle to expanding the MMC materials in these industries is the poor machinability in terms of rapid development of severe wear of the cutting tool [1- 3]. The machinability which describes the operational characteristics of the cutting edge is normally judged in terms

of tool life, surface finish, cutting forces and material removal rate [4]. Factors that directly influence the machinability depend on the tool performance which is in turn dependent on the wear resistance of the tool material. Published research work [5, 6] show that either high speed steel or cemented carbide can be used as cutting tool material due to the fact that these tool materials can sustain significant levels of wear after a very short cutting time. Few studies on the wear mechanisms in machining MMC material with 10 -20 vol. % silicon carbide have been published [6-8]. However, these works were carried out in the “low” range of cutting data with

respect to the machinability of the material.

Tools with different thickness of diamond coating have been used to increase the tool life and reduce machining cost [9, 10]. However, poly crystalline diamond (PCD) tools are still superior for the MMC's and nonferrous materials compared to coated carbide, uncoated carbide and Poly Crystalline boron nitride (PCBN). Poly Crystalline diamond (PCD) tools are used extensively in different cutting processes (turning, milling and drilling) of aluminates and composites. The research work of [11, 12] show that the selection of cutting tool should be based on the volume fraction and the nature of the reinforcement in combination with cutting data and cutting operation. Also the combination of diamond grain size and cobalt (Co) content is significant in the selection of the appropriate grade for a specific composite in a specific cutting operation. Cobalt acts in two different ways in the sintering process of PCD. Graphite that has been formed in an earlier step is dissolved in the cobalt which in turn deposits on the large diamond particles. Cobalt also reduces the sharpness of diamond particle grains which results in a decrease in the stress of the material [13]. Hence, it is important to know the amount of Co present in the material.

Literature reviews show that there is no reported research which relates the diamond performance to the chemical composition in machining of MMC. This research work attempts to study the influence of the grain size distribution and the chemical composition of the diamond on the tool performance in machining MMC. Four different, PCD grades available commercially were chosen. Grade I and II have a bimodal grain size distribution and are rather similar; while grade III is a coarse grade (~25 μ m) and grade IV is a fine grade (~5 μ m).

2. Experimental set-up

2.1. Machining

The workpiece material is an aluminum alloy reinforced with silicon carbide (SiC) particles having a diameter of 12 – 25 micrometer and the volume fraction of SiC in this MMC material is 20 wt-%. The workpiece was squeeze-casted to form discs of 350 mm diameter and 20 mm thickness. Table 1 below describes the chemical composition of this MMC material while the microstructure is shown in Figure 1.

Table 1. Chemical composition of the trace elements in workpiece material.

Element	Weight%
Si	9.3
Fe	0.12
Bi	0.0002
Mn	0.003
Mg	0.6
Zn	0.65
Ti	0.09
Cr	0.07
Ca	0.001
P	0.0006
Sn	0.1
Ni	0.8

The different sets of experiments were performed by a dry face milling operation on a MORI SEIKI NV6000 DCG milling machine with different cutting speeds ($V_c = 400 - 700$

m/min), constant feed ($f_z = 0.3$ mm/tooth) and depth of cut ($a_p = 0.5$ mm).

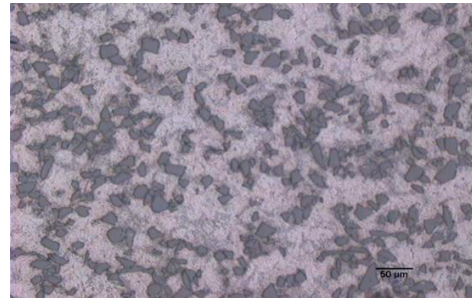



Figure 1. Microstructure of the MMC material used in investigation.

The PCD variants used in this investigation were of identical geometry which is a standard product of Sandvik Coromant for general milling applications (see Table 2). The criteria for evaluation of the tool life are: flank wear ($VB = 0.3$ mm), notch ($VB_n = 0.4$ mm), edge destruction or maximum cutting time 60 minutes.

Table 2. Cutting tools variants used in investigation.

Variant	Grain size	Geometry
Grade I	2 and 30 μ m	 R590-1105H-PR2-NL
Grade II	4 and 25 μ m	
Grade III	25 μ m	
Grade IV	5 μ m	

2.2 Analysis

The XRD data was collected using two different diffractometers. At the first stage a Bruker D8 Discover diffractometer equipped with a Vântec 500 area detector and a microfocus X-ray source were used. The samples were mounted on a centric Eulerian cradle (axis: Chi, Phi, x, y, z) in which accurate positioning and alignment of the sample was achieved by a laser-video microscope. Cu-K α radiation were used for the measurements. The mirrors attached to the microfocus X-ray source focused the beam to about 0.8 x 0.8 mm without pinhole collimator. Measurements were done with a voltage of 50 kV and a current of 1 mA, resulting in a maximum power of 50W. A pinhole collimator of 0.1 mm was used in order to avoid any diffraction from underlying cemented carbide. The diffracted intensity from the sample was measured with one single frame, with a θ angle of 20° and a 2 θ angle of 40°, resulting in diffraction information between 26 and 58° in 2 θ . The images were thereafter imported into Bruker's EVA (V3.0) software and converted to 1D diffraction patterns by integrating in what in the Bruker software is defined as Gamma direction.

Since the collected data was of limited range for Rietveld refinement, the data for the two bimodal grades were recollected using a PANalytical XPERT-PRO diffractometer equipped with a X'Celerator RTMS detector and a X-ray tube (PW3373/10 Cu LFF DK184159). The measurements were done with a voltage of 45kV and a current of 40mA, resulting in a maximum powder of 1.8kW. The data was collected with a step size of 0.0084° in the 2 θ range of 35-80°. Phase identification and Rietveld refinement was carried out using

PANalytical High score plus (V 3.0.4).

The SEM micrographs were collected with a FEG-SEM of type Zeiss SUPRA 40 equipment. All micrographs were recorded using 7kV accelerating voltage and with a backscatter detector with a working distances between 9-10 mm. In order to facilitate the comparison, all micrographs were collected with a magnification of 3000.

3. Results and discussion

3.1. Tool performance

Figure 2 describes the tool performance in terms of tool life as a function of cutting speed. The figure shows that the difference in performance appears when the cutting speed exceeds 400 m/min. At a cutting speed of 500 m/min grade III shows the lowest performance, at 600 m/min both grade III and IV show the lowest performance and finally at 700 m/min all the grades II, III and IV show very low performance compare to grade I. According to the results there are different relationships between the tool performance and the composition of the diamond grade. The results clearly indicate that the PCD grades with mono grain size distribution provide low performance compared to the grades with bimodal grades. A comparison between the grades which have mono grain size distribution (grade III and IV) shows that the influence of the grain size on the tool performance is not obvious. A comparison between the grades which have bimodal grain size distribution (grade I and II) shows that the best performance can be achieved by grade I which has a higher cobalt content.

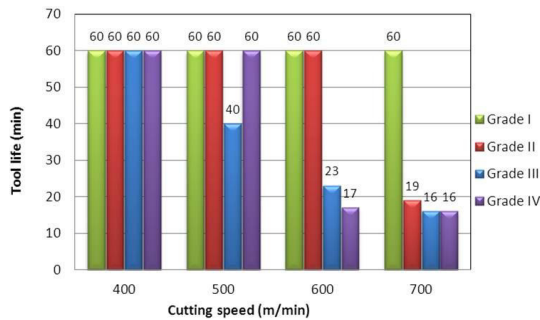


Figure 2. The performance of different PCD grade in milling of MMC.

3.2. Wear development

Figures 3-6 below shows the rate of wear development as a function of grade composition and cutting speed for all PCD grades in this study, the feed and the depth of cut have been kept constant at 0.3 mm/rev and 0.5 mm respectively. The results describe two different rates of wear development. The grades which have mono grain size distribution and WC-phase (grade III and IV) exhibit rapid wear development especially when the cutting speed exceeds 400 m/min. On the other hand the grades which have a bimodal grain size distribution and no WC-phase exhibit very good abrasive wear resistance where the flank wear development is slow, even and predictable over the whole range of cutting speed (400 – 600 m/min).

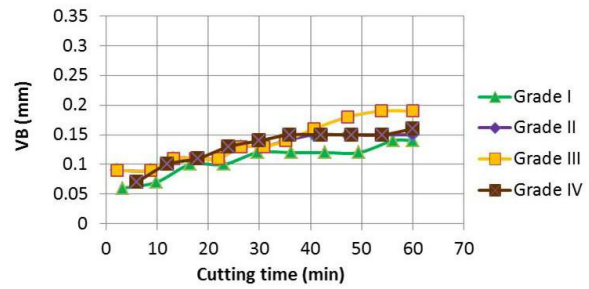


Figure 3. Wear development at Vc=400 m/min.

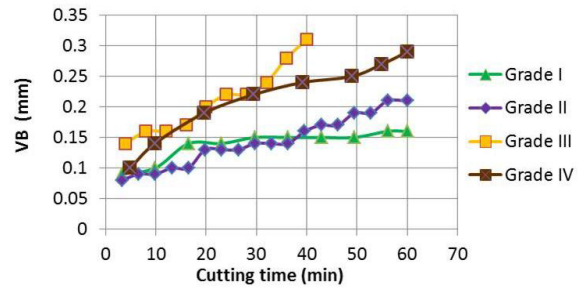


Figure 4. Wear development at Vc=500 m/min.

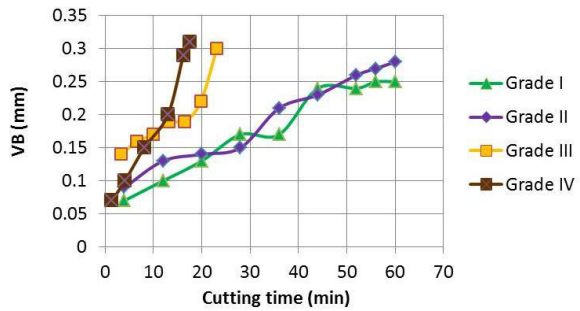


Figure 5. Wear development at Vc=600 m/min.

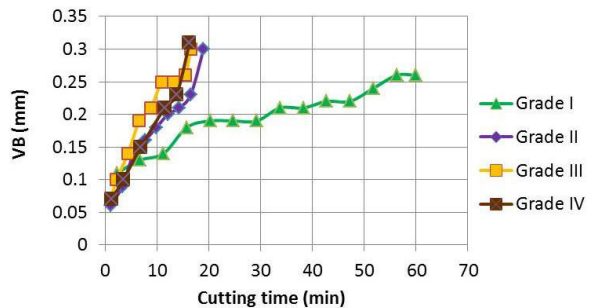


Figure 6. Wear development at Vc=700 m/min.

A comparison between the grades which have mono grain size distribution (grade III and IV) shows that the grade with small grain size (grade IV) provides better wear resistance at 400 and 500 m/min. The difference in wear resistance between these grades (I & IV) becomes insignificant when the cutting speed increased. A comparison between the grades with bimodal grain size distribution (grade I and II) shows that the grade with high cobalt content (grade I) provide the

best abrasive wear resistance over the whole range of cutting speed. However it is well known that the cobalt content influences the strength [13], which in turn could influence the wear development. Figures 7-9 describe the typical flank wear for grades I-III at the same cutting data in dry condition ($V_c=600$ m/min, $f=0.3$ mm/tooth, $a_p=0.5$ mm), all these micrographs have been collected with an accelerating voltage of 10kV and with 60 times magnification. The figures clearly show the difference in performance between these grades. Figure 7 shows the status of the grade I after cutting time of 60 minutes where $VB=0.24$ mm. Figure 8 shows the wear development on the grade II after cutting time of 45 minutes where $VB=0.3$ mm. Finally figure 9 shows the wear development on the grade III after a cutting time of 23 minutes where the $VB=0.32$ mm.

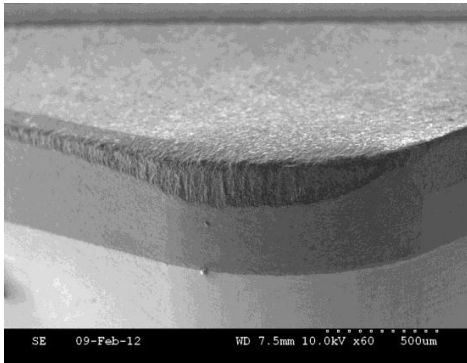


Figure 7. Wear development on grade I.

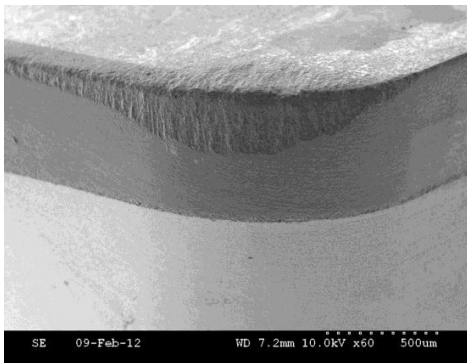


Figure 8. Wear development on grade II.

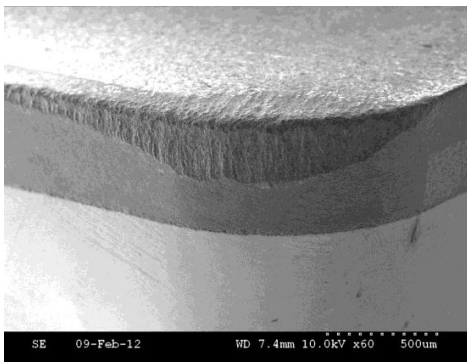


Figure 9. Wear development on grade III.

3.3. PCD characterization

In order to understand the difference in performance between these grades and relate the wear resistance to the materials properties, all four grades were studied with SEM and XRD. The SEM micrographs illustrate the grain size distribution in all four grades (see Figure 10 & 11).

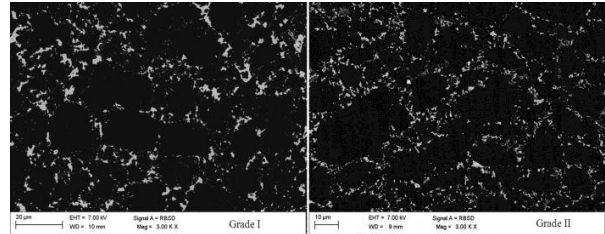


Figure 10. BSE-SEM micrograph of the grade I and II. The diamond grains are dark while the Co region is light. Both these grades are containing a bimodal grain size distribution.

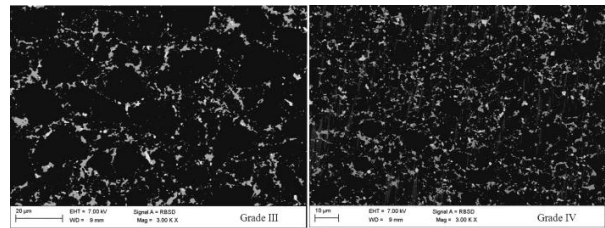


Figure 11. BSE-SEM micrograph of the grade III and IV. As it is clearly seen grade III is a coarse grain grade while IV is a fine grain grade. The light grey region than can be observed corresponds to the WC phase.

All micrographs are recorded in the backscatter mode that illustrates different phases with different contrasts where the heavier phase is presented with darker grey. In the SEM micrographs presented here the diamond particles are black while the cobalt is grey. In Figure 11 a heavier phase (light grey) is visualized, that corresponds to the WC phase. The latter mentioned phase is also illustrated in the XRD pattern for grade III and IV.

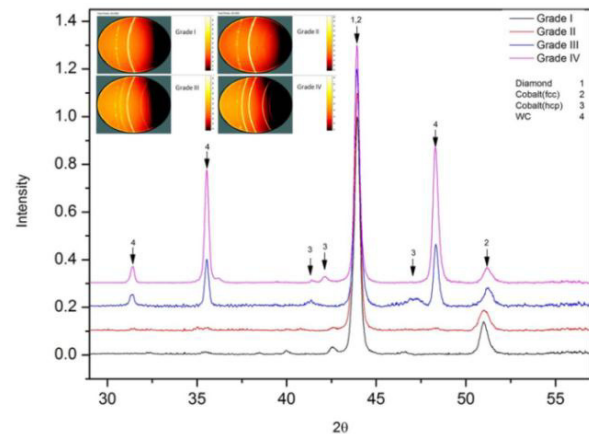


Figure 12. Combined and normalized XRD pattern with phase identification for all PCD grades in the current study. In the upper left corner the 2D measured frames for each spectrum is presented.

The WC is believed to be acting as a grain growth inhibitor and is only added to the mono grain grades. Except for the grain size, the presence of the WC phase is the difference between the bimodal and the mono grain grades. This has also been verified by the XRD data (see Figure 12). The effect that the WC addition will have on the performance of the tool is not very clear, and literature review showed no earlier report regarding the effect of the addition of WC to PCD. However, it can be assumed that the hardness of the material is influenced since a softer phase has been added. That in turn reduced the abrasive resistance of the tool, which has been presented above in section 3.2 (see Figures 3-6).

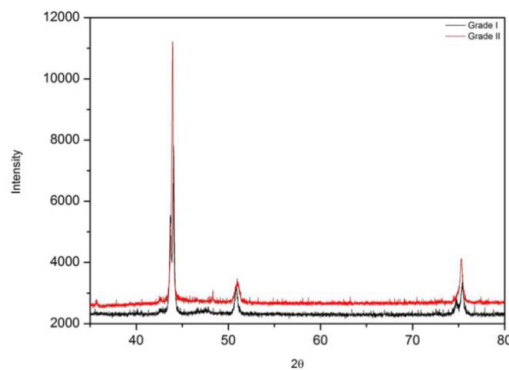


Figure 13. Recollected XRD pattern for grade I and II used for Rietveld refinement.

For further understanding of the difference between the bimodal grades the recollected XRD data (Figure 13) was subjected to Rietveld refinement [14]. It generates the contribution of each phase to the XRD pattern in terms of weight percentage. The latter is calculated from the scaling factor in combination with the formula weight and the unit cell volume of each phase. In Rietveld method a model is constructed to model the observed data and refines according to eq. 1; where w_i = suitable weight, y_{ic} = sum of the contribution of all neighboring Bragg reflection, y_{io} = observed reflections.

$$R = \left(\sum_{i=1}^n w_i (y_{io} - y_{ic})^2 \right) \left(\sum_{i=1}^n w_i y_{io}^2 \right)^{-1} \quad (1)$$

The crystallographic data used as a starting model for the Rietveld refinement has been extracted from the Crystallography Open Database (COD) [15] and are presented in Table 3.

Table 3. The crystallographic parameters used in the Rietveld refinement of the bimodal grades extracted from COD.

	Diamond	Cobalt
Ref Code	96-901-1998	96-901-2935
Crystal system	Cubic	Cubic
Space group	$Fd\bar{3}m$	$Fm\bar{3}m$
a [Å]	3.5600	3.5860

The results of the Rietveld refinement (Table 4) shows that grade I contains larger amount of Co compare to grade II. An addition of Co in PCD usually benefits the toughness property since the Co phase can handle mechanical impact much better than the PCD skeleton. So this higher Co content

can explain the reason why grade I has better resistibility to mechanical impact in the milling of MMC.

Table 4. Rietveld results for PCD grade I and II in the current study.

	Diamond w%	Cobalt w%	GOF	R profile [%]	R Bragg (C) [%]	R Bragg (Co) [%]
Grade I	93.5	6.5	0.88	1.78	4.02	2.67
Grade II	98.2	1.8	0.84	1.87	0.48	0.47

Conclusions

According to the results the main wear mechanism that determines the tool life of the diamond grades in milling MMC is the abrasive wear, irrespective of cutting speed. The MMC can be machined with any diamond grade at the low range of cutting speed (≤ 400 m/min) while at a higher range of cutting speed (> 400 m/min) the selection of diamond grade should be based on the chemical composition and grain size distribution. It must be emphasized that the influence of the cobalt content on the wear resistance is still not clear and should be further studied. However the results show that the bimodal grade which has higher cobalt content exhibit the best abrasive wear resistant among the tested grades. It is possible to assume that the grain growth inhibitor (WC-phase) influences the performance in machining MMC at cutting speeds above 400 m/min. The key to provide a good abrasive wear resistance and toughness is a combination of bimodal grain size distribution and relatively high Co content.

References

- [1] Muthukrishnan N, Murugan M, Prahlada Rao K. An investigation on the machinability of Al-SiC metal matrix composite using PCD inserts. *Int. J. Adv. Manuf Technol* 2008; 38:447-454.
- [2] Ding X, Liew W.Y.H, Liu X.D. Evaluation of machining performance of MMC with PCBN and PCD tools. *Wear* 2005; 259: 125-1234.
- [3] Karthikeyan R, Ganesan G, Nagarazan R. S, Pai B. C. A critical study on machining of Al/SiC composite. *Materials and manufacturing processes*. 2001; 16(1): 47-60.
- [4] Shaw M.C. *Metal cutting principles*, Clarendon, Oxford Series on advanced manufacturing 3; 1984.
- [5] Lin J.T., Bhattacharyya D, Lane C. Machinability of a silicon carbide reinforced aluminium metal matrix composite. *Wear* 1995; 181-183: 883-888.
- [6] Muthukrishnan N, Murugan M, Prahlada Rao K. Machinability issues in turning of Al-SiC (10p) metal matrix composites. *Int. J Adv. Manuf Technol* 2008; 39:211-218.
- [7] Manna A, Bhattacharyya B. A study on machinability of Al-SiC MMC. *J Mater Process Technol* 2003;40:711-716.
- [8] Heath Peter J. Developments in applications of PCD tooling. *Journal of Material Processing Technology* 2001;116: 31-38.
- [9] Durante S, Rutelli G, Rabezzana F. Aluminum-based MMC machining with diamond-coated cutting tools. *Surface and coating technology* 1997; 94-95: 632-640.
- [10] Hu J, Chou Y. Nanocrystalline diamond coated cutting tools. *Material science and technology (MS&T) 2007*; September: 16-20, Detroit, Michigan
- [11] Cronjäger L, Meister D. Machining of fiber and particle – reinforced Aluminium 1992 *Annals of the CIRP* 41:1.
- [12] Rosenberger M.R., Schvezov C.E, Forlerer E. Wear of different aluminium matrix composites under conditions that generate a mechanically mixed layer. *Wear* 2005; 259: 590-601.
- [13] Lammer, A., Mechanical properties of polycrystalline diamonds, *Materials Science and Technology* 1988; 4: 949-955.
- [14] Rietveld, H.M. A profile refinement method for nuclear and magnetic structures, *Journal of Applied Crystallography* 1969; 2: 65.
- [15] Grazulis, S., Chateigner, D., Downs, R.T., Yokochi, A.F.T., Quiros, M., Lutterotti, L., Manakova, E., Butkus, J., Moeck, P., Le Bail, A. Crystallography Open Database- an open-access collection of crystal structures, *Journal of Applied Crystallography* 2009; 42: 726-729.