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Performance and wear mechanisms of novel superhard diamond and boron nitride based tools in machining Al-SiCp metal matrix composite

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ABSTRACT

Metal matrix composites are the desired materials in aerospace and automotive industries since they possess high specific strength. However addition of reinforcement to the matrix material brings the adverse effects of high wear rate of tool materials used in their machining. The current study addresses the issues of wear and performance of superhard tools when high speed machining cast Al-Si alloy reinforced with particulate SiC (20% vol.). A wide range of developed superhard materials was compared to the commercial PCD tools. Nano grain sized wBN-cBN, binderless cBN; B_6O-cBN, nano-diamond with WC binder; diamond/MAX-phase; and diamond/SiC tool materials were employed. Use of nano-diamond/WC and diamond/MAX-phase composites resulted in their rapid deterioration due to primarily adhesive pluck-out of diamond and binder phase. Diamond/SiC material exhibited slightly lower performance than the PCD, with the primary wear being the abrasive on the SiC binder phase. Machining with cBN-based tooling at lower speed lead to formation of stable build-up layer, frequently accompanied by severe seizure of tool and workpiece material. However at speed of 400 m/min the absence of such build-up layer caused rapid tool wear. Presence of chemical and diffusional wear mechanisms for diamond tooling has been confirmed through scanning and transmission electron microscopy. Archard-type model of abrasive tool wear was developed for modelling of tool deterioration for all studied tool materials.

1. Introduction

Metal matrix composites (MMC) are a relatively new class of materials that have a variety of advantageous properties like high specific strength, wear resistance, hardness, etc. They have found application in aerospace, automotive and other advanced industries. The most widespread, due to the cost benefits, class of MMC has aluminum alloy matrix strengthened by ceramic (eg. Al_2O_3, SiC, B_4C, etc.) reinforcement [1]. It is the reinforcement that brings favorable properties but introduces the main problem in machining the MMC materials related to rapid wear of cutting tools and poor machinability.

Conventional tooling like high speed steel, cemented carbides and ceramics, hardness of which is lower than the reinforcement, suffer from severe abrasion [2]. Polycrystalline cubic boron nitride (PCBN) tools with low cBN content and polycrystalline diamond (PCD) tools were found to be roughly one and two orders of magnitude better in wear resistance than cemented carbide [2]. That is why superhard diamond or cubic boron nitride (cBN) tooling pose scientific and industrial interest. This is explained by the high hardness of such tooling which can be ranked as follows: for PCD the hardness is $HV=70\text{–}85$ GPa; for PCBN with high cBN content it equals $HV=36\text{–}40$ GPa; and for PCBN with low cBN content the hardness is $HV=28\text{–}32$ GPa [3]. The hardness for all these materials exceeds the value for SiC reinforcement thus allowing for reduced wear rate.

PCBN grades with binders that are softer than the wear resistant cBN phase, mainly AlN [2] or TiC [4,5], have been tested. The tool wear is characterized mainly by abrasion or abrasion combined with adhesion of workpiece material [4]. MMC machining with PCBN having low cBN content additionally exhibited edge chipping and nose fracture [5]. The use of binderless cBN with ultra-fine grain microstructure, which gives improved hardness, has shown only 20–30% improvement in wear resistance, when compared to PCBN with ceramic binders [5]. However, tooling with coarse grain microstructure is known to have better

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wear resistance and generate finer surface roughness [6,7]. Therefore binderless cBN with coarser grain-size might have improved wear resistance.

Machining of MMC is frequently accompanied by adhesion of workpiece material and formation of build-up edge (BUE) that introduces protective action against abrasion by SiC reinforcement. Muthukrishnan et al. [7] have shown that PCD machining at low cutting speed was accompanied by significant formation of build-up edge which was attributed to increased tool life at this cutting speed. BUE acted as a protective cap on the cutting edge. Similar effect was found when machining Al-SiCp MMC with PCBN tools. Ciftci et al. [4] have shown that PCBN machining with cutting speed of $v_c = 150$ m/min results in large and strongly attached BUE. The dimensions of BUE reduced at increased cutting speed and lead to accelerated tool wear. Adhesion of the MMC and formation of BUE varies with the tool material. PCBN tools have a stronger tendency to adhesion than PCD tools [5]. In general, superhard tool materials of different composition show individual sensitivity to abrasive and adhesive wear mechanisms and therefore different wear resistance when machining MMC. Therefore evaluation of performance for any novel superhard materials is of scientific and practical interest.

The aim of this study is to evaluate the performance and obtain in-depth understanding of wear mechanisms of several novel diamond- and cBN-based superhard tooling in comparison to commercial PCD. Binderless cBN, wBN-cBN, B_6O-cBN, nano-diamond with WC binder, diamond with MAX-phase binder, and diamond-SiC tool materials were tested. Wear characteristics of the tooling were examined via 3D optical, scanning electron, transmission electron microscopy, and energy dispersive X-ray analysis. Archard-type model of abrasive tool wear is developed for modelling of tool deterioration.

2. Experimental setup

The following metal matrix composite (MMC) material was used in experiments – AlSi9Mg0.3 aluminum alloy reinforced with SiC particles (20 % vol.) having the grain-size of 10–30 μm. The molten Al-SiC_p MMC material was gravity cast (directly from the industrial furnace, Amtek Components Sweden AB) into tubular stainless steel moulds. The moulds were allowed to cool for 30 s on air and then rapidly cooled in a water basin. This sequence was found to minimize the sinking of SiC particles and provide the MMC microstructure identical to the industrial one (see Fig. 1). Cast MMC ingots were pre-machined to bars of 56 mm in diameter and 400 mm in length prior to the actual machining tests.

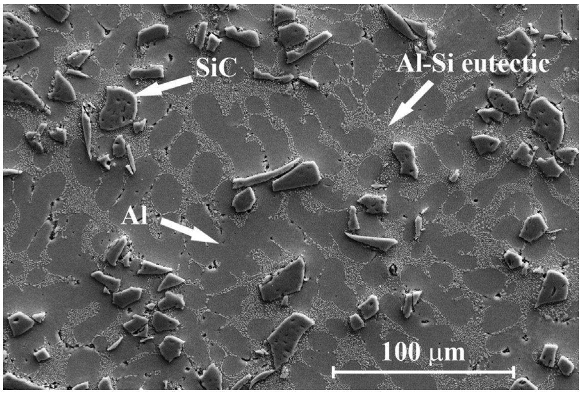

Fig. 1. Scanning electron microscope (SEM) image of the microstructure of Al-SiC_p MMC workpiece material.

The machining test involved longitudinal turning operation where the commercial PCD reference tool material was compared to several experimental superhard tool materials. Some of the materials structurally are also polycrystalline diamond (PCD) compacts and therefore binder type is used in material designation to avoid confusion between various PCD materials. The description of all tooling materials, their properties, microstructure and phase content is listed below.

1. D-Co – commercial polycrystalline diamond material which forms a solid diamond matrix as a result of intergrowth of diamond grains. The formation of strong diamond-to-diamond bonding is a result of dissolution-precipitation sintering mechanism when molten cobalt dissolves part of the diamond grain to the solubility limit of carbon in the Co-C solution and precipitates it as diamond on the diamond grains (Fig. 2a). The material possesses high hardness of $HV = 89$ GPa (Fig. 3), high fracture toughness ($K_{IC} = 9.8$ MPa m$^{1/2}$) and thermal conductivity of $k = 760$ W/(m K) [3].
2. D-SiC – thermostable polycrystalline composite which forms as a result of infiltration of molten silicon into the diamond preform and subsequent reaction of both phases with formation of silicon carbide matrix (Fig. 2b). The material has hardness of $HV = 84$ GPa (Fig. 3), lower fracture toughness of $K_{IC} = 7.6$ MPa m$^{1/2}$ and lower thermal conductivity of $k \approx 200$ W/(m K) [8].
3. D-MAX_{95} – experimental polycrystalline diamond material where the bonding of diamond is realized via decomposition of Ti_3SiC_2 MAX-phase during the sintering, release of TiC, elemental silicon and titanium and their subsequent reaction with the diamond [9]. Mixture of 95 vol.% diamond and 5 vol.% Ti_3SiC_2 was subjected to the sintering process (Fig. 2c). The sintering resulted in a material with hardness of $HV = 71$ GPa (Fig. 3).
4. D-MAX_{60} – similar experimental polycrystalline diamond material which contained 60 vol.% diamond and 40 vol.% Ti_3SiC_2 prior to the sintering (Fig. 2d). Reduced diamond contents, compared to D-MAX_{95}, resulted in a lower hardness of $HV = 62$ GPa (Fig. 3).
5. nD-nWC – experimental material for which the nano-diamond (3–15 nm) is subjected to sintering with tungsten [10], the reaction products creating a nano-grained WC matrix (Fig. 2e). Residual surface oxygen introduces an undesired by-product of WO_2. Softer WC matrix and presence of WO_2 cause a reduced hardness of $HV = 52$ GPa (Fig. 3).
6. bcBN – experimental binderless cubic boron nitride material which possesses a solid cBN matrix as a result of diffusional bonding of cBN grains during the high temperature – high pressure sintering (2300 °C and 8 GPa). Additive of 3 vol.% of silicon nitride (Fig. 2f) is introduced to the cBN matrix for enhancement of fracture toughness ($K_{IC} = 12.6$ MPa m$^{1/2}$) [11]. The material has highest hardness of $HV = 54$ GPa and thermal conductivity of $k = 180$ W/(m K) [12] among the boron nitride based tooling.
7. wBN-cBN – experimental superhard material which forms as a result of controlled partial transformation (50 vol%) of ultra-fine grain wurtzite boron nitride to a cubic one in the region of thermodynamic stability of cBN at pressure 8 GPa and temperature of 1700 °C (Fig. 2g). While the hardness of the material $HV = 48$ GPa is rather high (Fig. 3), its thermal conductivity is only $k = 26$ W/(m K) [13].
8. B_6O-cBN – experimental superhard material which combines superhard cBN grains bound in a superhard matrix of boron suboxide B_6O. The mixture of 40 vol% B_6O and 60 vol% cBN were sintered at pressure 8 GPa and temperature of 2000 °C (Fig. 2h) [14]. High hardness of the material $HV = 41$ GPa is combined with