Wear performance of the diamond coated cutting tools by machining Al-SiC metal matrix composites

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Abstract- *In the present experimental study, wear performance of the diamond coated cutting tools with various coating architectures was studied by turning Alm–30%SiCp metal matrix composite material. Chemical vapor deposited (CVD) diamond can be classified into nanocrystalline diamond (NCD) and microcrystalline diamond (MCD) that are known for their distinct characteristics. Diamond coatings with three different coating architectures were deposited for the machining study. Wear performance of the diamond coated (3 architectures), uncoated and commercial TiN coated tools was evaluated and compared by conducting high speed machining tests. Superior wear performance of the diamond coated tools was clearly evident from the tool wear measurements. The poor tool life (t b1 min) of the uncoated and TiN coated tools was attributed to the abrasive action of the hard SiC reinforcement particles. Dual-layer graded composite diamond coated (t = 14.7 min) and mono-layer MCD coated (t =13.5 min) tools showed superior machining performance in comparison to that of the dual-layer composite diamond coated tool (t =9.8 min). Dual-layer graded composite diamond coatings deposited with the concept of transition-layer are the prospective tool coatings for high performance machining applications due to their top-layer nanocrystallinity and enhanced interfacial integrity.*

Keywords- Al-SiC metal matrix composites, Carbon fiber reinforced plastics, Diamond Coating, Chemical vapor deposition

I. INTRODUCTION

Al–SiC metal matrix composites (MMC) and carbon fiber reinforced plastics (CFRP) are widely used engineering materials in the aerospace and automobile industries due to their high strength to weight ratio.

These materials are considered as difficult-to-machine because of the hard and abrasive reinforced particles or fibers [1, 2]. The most commonly used tools and tool coatings fail to perform due to the aggressive machining conditions [3, 4]. The stringent machining applications demand high performance super hard coatings with a designed coating-substrate system for better performance and durability [5, 6].

In general, the coating-substrate system can be divided into three different entities such as coating, interface and substrate. The functional and basic requirements of these three entities for mechanical and tribological applications are considered as follows; (i) coating: surface coating is expected to have high wear resistance, low friction coefficient, good surface finish, high oxidation resistance, high fracture toughness, high thermal conductivity and enough thickness for load-bearing applications,(ii) interface: good adhesion and shear strength represent a good interface quality and (iii) substrate: high elastic modulus, high temperature strength and high thermal conductivity are the most important properties that a substrate should possess[7]. For high performance applications, all the design considerations and requirements of the coatings may not be possible to realize with a single layer coating architecture. Design and utilization of different layers of the coatings are important particularly for high performance machining applications [8].

CVD diamond coatings are known for their unique characteristics such as high hardness (N40 GPa) and low friction coefficient (<0.1). The mechanical characteristics such as wear resistance, friction coefficient and interfacial adhesion integrity of the diamond coatings are greatly influenced by the surface pre-treatment and grain size of the coated layers [9]. Hence the microstructure and coating-substrate architecture of the CVD diamond coatings need to be tailored to achieve the basic functional requirements such as high wear resistance, features, reduced grain size and the presence of non-diamond carbon phases at the grain boundaries. On the other hand, microcrystalline diamond (MCD, grain size N 500 nm) coatings exhibit high hardness and good adhesion characteristics [9].Hence the microstructure and coating-substrate architecture of the CVD diamond coatings need to be tailored to achieve the basic functional requirements such as high wear resistance, low friction coefficient and good interfacial adhesion integrity [10].

Nanocrystalline diamond (NCD, grain size b 100 nm) coatings are known for their tribological properties due to the smooth surface features, reduced grain size and the presence of non-diamond carbon phases at the grain boundaries. On the other hand, microcrystalline diamond (MCD, grain size N 500 nm) coatings exhibit high hardness and good adhesion characteristics [9]. However, NCD and MCD coatings have their own merits which can be exploited by developing the multi-layer coating architectures [11].

Several studies have been reported on dual- and multi-layer composite diamond coatings by depositing a combination of NCD and MCD layers with different coating architectures [12–19]. Dual-layer composite diamond coating (NCD/MCD/WC–Co) is the commonly used architecture to realize thick diamond coatings with top-layer nanocrystallinity for mechanical applications [20]. The integrity of the dual- or multi-layer composite diamond coatings was found to be compromised due to the sharp interface between the constitute NCD and MCD layers. In our earlier studies, dual-layer graded composite diamond coatings with the architecture of NCD/transition-layer/MCD/ WC–Cowere developed to enhance the interfacial integrity by eliminating the sharp interface between the NCD and MCD layers [10, 21]. In the present study, wear performance of these dual-layers graded composite diamond coated cutting tools was studied by machining Alm–30%SiCp MMC material. Flank wear and nose wear on the cutting tools were measured to estimate and compare the tool life.

II.EXPERIMENTAL DETAILS

Five variants of the coated and uncoated cutting tools (geometry: SPUN120308) were used for the tool wear studies. Three diamond coating Variants, (i) mono-layer MCD coating (MCD/WC-Co), (ii) dual-layer composite diamond coating (NCD/MCD/WC-Co) and (iii) dual-layer graded composite diamond coating (NCD/transition layer/MCD/WC–Co) are deposited with the coating thickness of ~10 μm. MCD monolayer coating was deposited for 12 h. Dual-layer composite diamond coating was deposited for 14 h with the coating architecture of NCD-8 h/ MCD-6 h/WC–Co. Dual-layer graded composite diamond coating (dual-layer composite diamond coating with graded diamond transition-layer between NCD and MCD layers) was deposited for 14h with the coating architecture, NCD-6 h/transition-layer-2 h/MCD-6 h/WC–Co. Gradient diamond transition-layer of ~1 μm thickness (transition from MCD grains to NCD grains) has been obtained by changing the process parameters linearly from MCD to NCD within the duration of 2 h. Complete experimental details including the substrate pretreatment and deposition process were discussed elsewhere [10,21]. Commercially available uncoated and TiN coated inserts were the other two variants used for the performance comparison.

Alm–30%SiCp MMC material is the work material for machining experiments and the ingot of size Ø100 × 300 mm was fabricated using sand mold casting method and the fabrication process is as follows. The matrix material (Alm), Al–12%Si alloy ingot was cut into small pieces and melted using an electric arc furnace and the temperature of the molten metal was maintained at around 725 °C. Degassing process was carried out by adding hexachloroethane tablets to the molten metal, which removed nitrogen, carbon-dioxide and other gases absorbed by the melt in the furnace. The molten base alloy was stirred for about 5 min at ~450 rpm. The silicon carbide particles (30% by volume) of the size ranging from8 to 10 μm were heated to a temperature of 650 °C and added to the molten base metal with simultaneous stirring under argon atmosphere. During stirring, a mixture of magnesium and aluminum powder was also added to the molten metal mixture to enhance the wettability. The stirring process was continued for 15 min and then the molten mixture was poured into the sand mold. Fig. 1(a) shows the HRSEM image of the microstructure of the etched Al–12%Si matrix material; Fig. 1(b) shows the HRSEM image of the raw SiC particle sand Fig. 1(c) shows the photograph of the casted Alm 30%SiCp ingot.

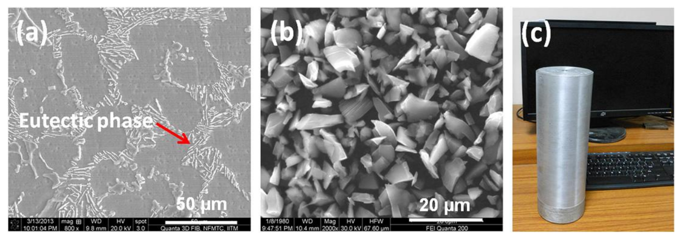

Fig.1. (a) Microstructure of the etched Alm (Al–12%Si alloy), (b) HRSEM image of the raw SiC particles and (c) photograph of the casted Alm–30%SiCp ingot.

Surface topography and cross-sectional characteristics of the diamond coatings were studied using a high resolution scanning electron microscope (HRSEM, Quanta 3D, FEI). Cross-sections of the diamond coatings were prepared using a low speed diamond saw cutter (ALLIED TechCut). Confocal Raman microscope (Alpha 300R,WITec)was used to confirm the structural characteristics and distribution of the SiC particles in the Alm–30%SiCp MMC material.

MAZAK NEXUS 200-II model turning center facility and the tool holder (270 SCP 2525 75°) were used for the high speed turning tests. Turning experiments were carried out under dry conditions using the following cutting parameters: Cutting speed = 380 m/min, feed =0.1 mm/rev and depth of cut = 1 mm. The assessment of the tool wear was by direct measurement as described in the ANSI/ASMEB94.55M-1985 standard. Intermittently, flank wear and nose wear of the cutting tools were measured using NIKON measuring microscope. The tool is considered to be failed, if either of the maximum flank wear (VB_Bmax) or of the maximum nose wear (VBc) reaches 0.3 mm. Fig. 2(a) shows the isometric view of the turning insert cutting edge and directions to measure the flank and nose wear. Fig. 2(b) and (c) shows the views of the flank face and nose of the uncoated WC–Co cutting insert.

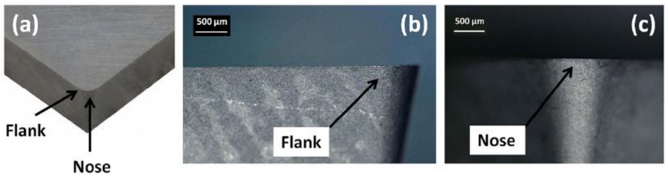

Fig.2. Views of the tool cutting edge. (a) Isometric view, (b) flank face and (c) nose.

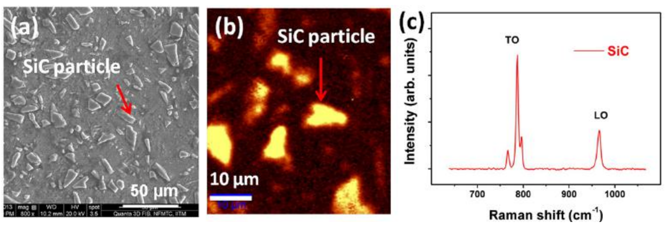

Fig.3. (a) Microstructure of the Alm–30%SiCp MMC obtained using HRSEM, (b) Raman mapping of the Alm–30%SiCp MMC and (c) Raman spectrum of the SiC

III. RESULTS AND DISCUSSION

Characterization of Alm–30%SiCp MMC work material:

Fig. 3(a) shows the microstructure of the polished Alm–30%SiCp MMC material obtained using HRSEM, which also shows the distribution of the SiC particles. Fig. 3(b) shows the Raman mapping of the polished Alm–30%SiCp MMC material. The regions with high intensity correspond to SiC particles and Fig. 3(c) shows the respective Raman spectrum, which confirms theα-SiC phase with hexagonal crystal structure (6-H). Transverse optical (TO, 760 to 800 cm−1) and longitudinal optical (LO, 965 to 975 cm−1) regions were indicated accordingly. With regard to the TO region, α-SiC shows weak Raman peaks at 768 and 796 cm−1 and the strongest at 789 cm−1 and with regard to the LO region, α-SiC shows a Raman peak at 967 cm−1 [22].

Surface topography and cross-sectional characteristics:

Fig. 4(a), (b) and (c) shows the surface morphology of the, (i) monolayer MCD coating (MCD/WC–Co), (ii) dual-layer composite diamond coating (NCD/MCD/WC–Co) and (iii) dual-layer graded composite diamond coating (NCD/transition-layer/MCD/WC–Co) respectively. Well faceted microcrystalline diamond grains of the mono-layer MCD coating are evident from Fig. 4a and the average grain size is around 2 μm. Insets of Fig. 4(b) and (c) show the magnified HRSEM images of the respective coatings with top-layer nanocrystallinity, the average grain size is around 40 nm. This top-layer nanocrystallinity of the coating enhances the tribological and anti-sticking characteristics of the cutting insets. Fig. 5(a),(b) and(c) shows the cross-sectional morphology of the coatings (i), (ii) and (iii) respectively. Sharp interface of the NCD and MCD layers of the dual-layer composite diamond coating is evident from the cross-sectional morphology (Fig. 5b). In order to enhance the interfacial integrity between NCD and MCD layers, this sharp interface was completely eliminated in the case of dual-layer graded composite diamond coating by incorporating transition-layer between NCD and MCD layers (Fig. 5c). Details of structural characteristics, interfacial integrity and influence of the transition-layer on the cross-sectional morphology and residual stresses of the dual-layer graded composite diamond coatings (NCD/transition-layer/MCD/WC–Co) were studied and have been described in our earlier reports [10,21].

Fig. 6(a) shows the surface morphology of the uncoated WC–Co cutting tool and the average grain size of the WC grain is around 1 μm. Fig. 6 (b) and (c) shows the surface topography and cross-sectional morphology of the commercial TiN coated cutting tool. The rough morphology of the TiN coating was evident from the surface topography image (Fig.6b).

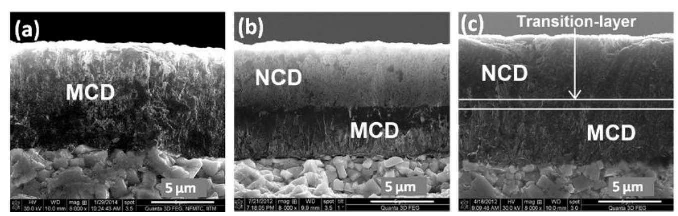

Fig.5. Cross-sectional morphology of the (a) mono-layer MCD coated, (b) dual-layer composite diamond coated and (c) dual-layer graded composite diamond coated cutting tools.

High speed machining experiments and chip formation:

Selection of cutting parameters is crucial for tool wear studies and the parameters in this study were so chosen to realize accelerated wear. Cutting parameters were selected based upon the existing literature and by considering the stability of the turning center that used for the experiments [23, 24]. Machining experiments were carried out under dry conditions using the following cutting parameters: cutting speed=380 m/min, feed=0.1 mm/rev and depth of cut=1mm. Discontinuous and uniform chip formation was observed while machining Alm–30%SiCp material using the above mentioned cutting parameters. Discontinuous chip formation was attributed to the brittleness of the Alm–30%SiCp material induced by SiC reinforcement particles. Fig. 7(a) and (b) shows the typical chip formation that was observed from the randomly selected chips and Fig. 7(c) shows the shear deformations on the chip surface. SiCp particles that are embedded in the Alm matrix cause severe wear to the cutting tools during machining because of their high hardness (~24 GPa) and abrasive action. The hardness of the SiC is higher than that of the regular carbide tools (WC–Co,~18 GPa) and closer to the general tool coatings (TiN, ~22 GPa). Diamond coatings on WC–Co substrates with good interfacial adhesion integrity are expected to perform well while machining Alm–SiCp material because of the high coating hardness (N40 GPa) [9].

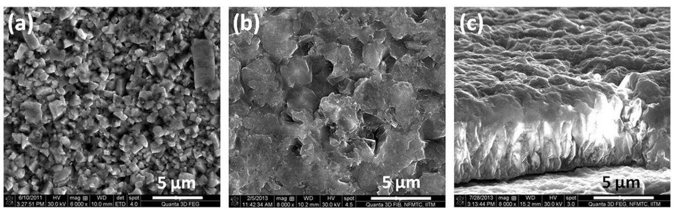

Fig.6.Surface morphology of the (a) uncoated and (b) TiN coated cutting tools (c) Cross-sectional morphology of the TiN coated cutting tool

Coating performance evaluation by tool wear measurement:

During the machining, maximum flank wear (VBBmax) and maximum nose wear (VBc) of the cutting tools were measured intermittently at the certain intervals of 1, 2, 4, 8, 12 and 16 min. However, if the tool wear exceeded the tool failure criterion of 0.3 mm, the respective cutting insert was considered to have failed. Machining experiments were continued with the other set of cutting tool variants, till they reach the tool failure criterion. After 1 min of machining, VB_Bmax of the uncoated and TiN coated inserts was observed to exceed the tool failure criterion (N0.3mm). The life of uncoated and TiN coated cutting tools is less than 1 min and the rapid wear of these two cutting tool variants is attributed to the hard and abrasive action of the SiC reinforcement particles that were embedded in the work material. Also low anti-sticking characteristics of the uncoated and TiN coatings in comparison to that of the diamond coatings may cause plaster effect on the flank face due to the soft and tough aluminum (Al) matrix during machining. This plaster effect could be one of the reasons for the rapid flank wear of the uncoated and TiN coated cutting tools.

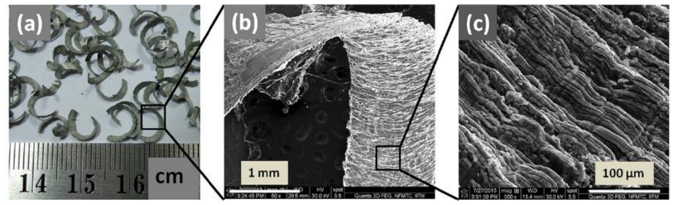

Fig.7. (a) Typical chip formation observed during the turning of Alm–30%SiCp MMC, (b) magnified image of the chip and (c) shear deformations on the chip surface

Fig. 8(a) and (b) shows the maximum flank wear (VBBmax) and maximum nose wear (VBc) data plotted against machining time for all the five cutting tool variants. The tool failure criterion limit of 0.3 mm wear is represented by the dotted line. The intersection of the wear plot with this dotted line gives the tool life of that particular cutting tool variant.

Fig. 9(a) and (b) shows the flank faces of the uncoated and TiN coated inserts obtained after 1 min of machining time using measuring microscope. Built-up edge (BUE) formation was evident in both the cases. The measured VBBmax of the uncoated and TiN coated inserts was 0.36 mm and 0.63 mm, respectively. However, VBBmax of 0.3 mm is the tool failure criterion and hence the calculated tool life of uncoated cutting insert is ~0.8 min and that of the TiN coated cutting insert is ~0.5mm. The poor performance of the TiN coated cutting insert in comparison to uncoated insert is attributed to the blunt cutting edge of the former. The pristine WC–Co cutting insert has sharp cutting edge, whereas the commercial TiN coated insert has honed cutting edge (increased edge radius) leading to increased cutting load. Moreover, one more reason is that the criterion for measuring VBBmax on uncoated insert is the area of WC–Co material wear, whereas, in the case of TiN coated insert, the area of coating delamination is considered as the tool wear.

Diamond coatings (mono-layer MCD, dual-layer composite and dual-layer graded composite diamond coatings) have shown excellent performance and no considerable wear (b0.15 mm) was observed till 8 min of machining time and also there is no considerable BUE formation because of their anti-sticking properties and high thermal conductivity. However, the dual-layer composite diamond coating (deposited without graded transition-layer) is found to have failed after a machining time of 12 min. Fig. 10(a) shows the image of the flank face after the machining time of 12 min and the measured VBBmax is ~0.57 mm. The tool failure criterion or limit is 0.3 mm. Hence the calculated tool life of the dual-layer composite diamond coated cutting tool was around 9.8 min.

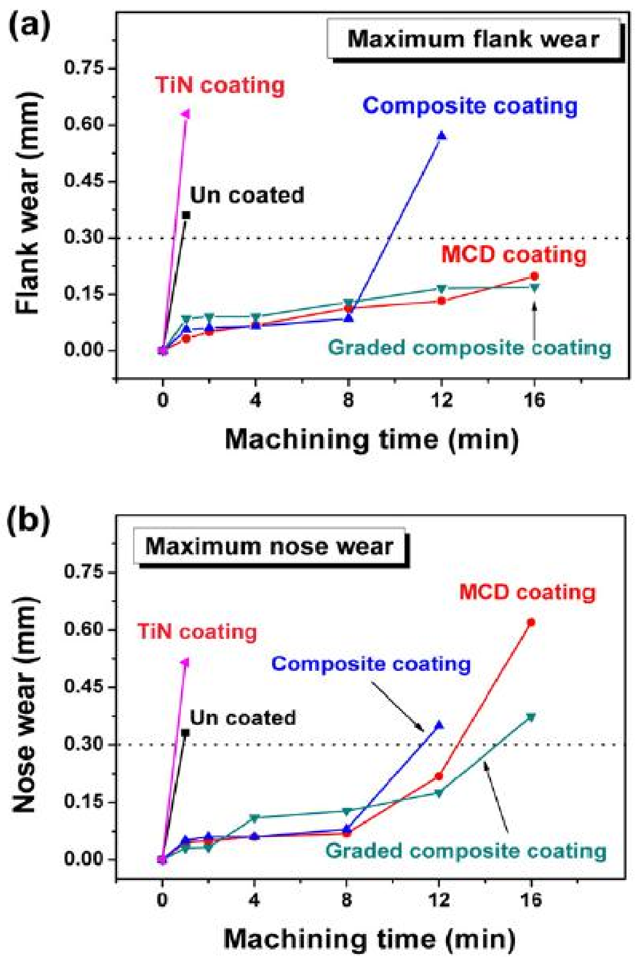

Fig. 8.Wear measurements on the coated and uncoated cutting tools plotted against the machining time, (a) maximum flank wear (VBBmax) and (b) maximum nose wear (VBc).

The mono-layer MCD and dual-layer graded composite diamond coatings are found to have failed after a machining time of 16 min. Fig. 10(b) shows the nose wear and the small region of the flank face images of the mono-layer MCD coating. The measured flank wear was 0.2 mm, which was found to be below the tool failure criterion of 0.3 mm. However, the measured maximum nose wear was observed to be 0.62 mm. This maximum nose wear value of 0.62 mm exceeds the tool failure criterion and the calculated tool life of the mono-layer MCD coating was found to be ~13.5 min. Fig. 10(c) shows the nose wear image of the dual-layer graded composite diamond coating. The measured maximum nose wear ~0.37 mm was found to exceed the tool failure criteria. The calculated tool life of the graded composite diamond coated insert was around 14.7 min.

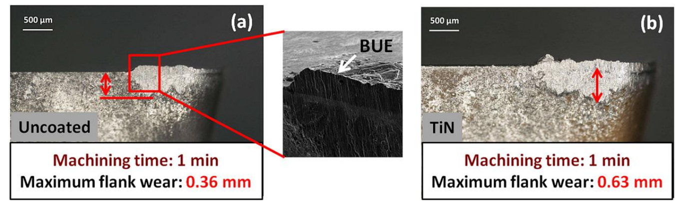

Fig.9. Flank wear images of the (a) uncoated and (b) TiN coated cutting tools.

Gomez et al. conducted the machining tests under dry conditions using diamond coated cutting tools and no significant adhesion was achieved, as revealed by the sudden coating delaminations that occurred [25]. Whereas in the present study no such large area diamond coating delaminations were observed on the cutting tools during the machining (Fig. 10), which shows the excellent coating substrate adhesion. Fig. 11 shows the bar chart representing the tool life of all the five cutting tool variants. Uncoated and TiN coated cutting tools have shown poor performance and the tool life of these cutting tools was found to be 0.8 and 0.5 min respectively, which is obvious due to their low hardness in comparison to that of SiC reinforcement particles. On the other hand diamond coatings have shown excellent performance due to their high hardness (N40 GPa). However, the variation in the tool life among the mono-layer MCD, dual-layer composite diamond and dual-layer graded composite diamond coatings was attributed to their microstructure, coating architecture and interfacial integrity. Dual-layer graded composite diamond coated tool has exhibited superior tool life (14.7 min) followed by mono-layer MCD coating (13.5 min) and composite diamond coating (9.8 min).

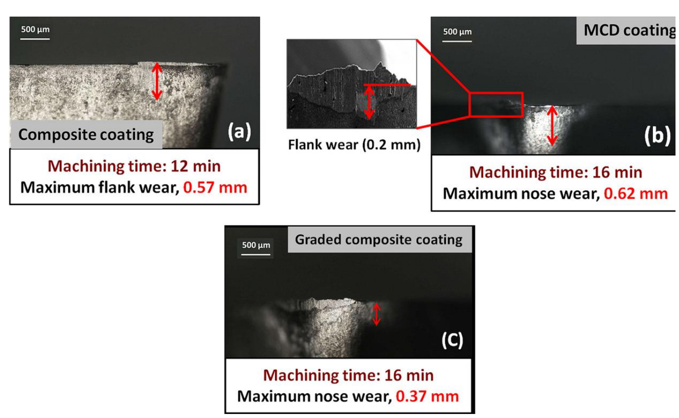

Fig.10. (a) Flank wear image of the dual-layer composite diamond coated cutting tool. Nose wear images of the (b)mono-layer MCD coated and (c) dual-layer graded composite diamond coated cutting tools.

The poor performance of the dual-layer composite diamond coating (NCD/MCD/WC–Co) could be due to the existence of a sharp interface between the NCD and MCD layers. Takeuchi et al. found that the integrity of the multilayer composite diamond coatings was compromised due to the non-diamond graphitic phases present at the interfaces of the constitute layers [15]. Kremer and El Mansori conducted extensive machining studies on Alm–SiCp MMC material using similar multilayer composite diamond coatings and found frequent notch wear or coating peel off due to their poor interfacial integrity [26]. In the case of dual layer graded composite diamond coating (NCD/transition-layer/MCD/WC–Co), the sharp interface between the NCD and MCD layers could be eliminated and the integrity of the coating was enhanced by the concept of graded diamond transition-layer. Voevodin et al. discussed the need and significance of the graded layers in order to enhance the interfacial integrity of the coatings [27]. Tools coated with dual-laer graded composite diamond and mono-layer MCD coatings have shown better tool life in comparison to the dual-layer composite diamond coated tools deposited without diamond transition-layer between NCD and MCD layers. Superior performance of the dual-layer graded composite diamond coating over the other coating variants can be attributed to its top-layer nanocrystallinity and enhanced interfacial integrity (by diamond transition-layer) of the NCD and MCD layers. The top-layer nanocrystallinity of the tool coatings reduces the contact friction and thereby causes less heat generation at the tool chip-interface and also the smooth contact minimizes the impact of reinforcement particles during machining [26].

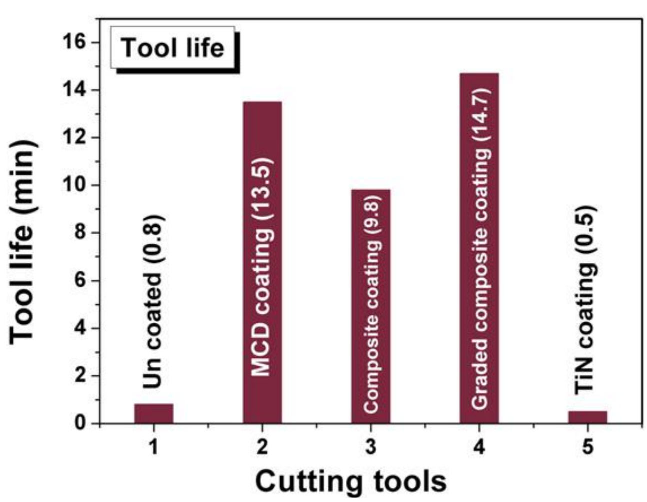

Fig.11. Tool life of the uncoated, diamond coated (3 variants) and TiN coated cutting tools.

IV. CONCLUSIONS

Uncoated and TiN coated inserts were found to have failed after machining for a duration of 1 min and the tool life was estimated 0.8 and 0.5 min, respectively. This rapid wear of uncoated and TiN coated cutting inserts could be attributed to the abrasive action of the harder SiC particles.

On the other hand, diamond coated tools have exhibited significant improvement in machining performance as no considerable wear was observed until 8 min of machining. The observed tool life durations of the mono-layer MCD, dual-layer composite diamond and dual-layer graded composite diamond coatings were found to be 13.5, 9.8 and14.7min, respectively. The dual-layer graded composite diamond (NCD/transition-layer/MCD/WC–Co) and mono-layer MCD coated cutting tools have shown superior performance over composite diamond (NCD/MCD/WC–Co) coated cutting tools. Graded composite diamond coated cutting inserts have exhibited clear tool life improvement of about 18.5 times in comparison to that of the uncoated cutting insert.

The poor performance of the dual-layer composite diamond coating (deposited without diamond transition-layer) could be due to the sharp interface between the NCD and MCD layers. The enhanced tool life of the dual-layer graded composite diamond coated cutting tool is due to its top-layer nanocrystallinity and improved interfacial integrity of the constitute NCD and MCD layers which has been realized by the integration of the dual-layer architecture and graded diamond transition-layer concept.

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