CIRP Annals - Manufacturing Technology 00 (2024) 1–4

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

Machining SiC fibre reinforced metal matrix composites – How do different matrix materials affect the cutting performance?

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A R T I C L E I N F O

Article history:
Available online xxx

Keywords:
Metal matrix composite
Machining
Surface integrity

A B S T R A C T

SiC fibre reinforced metal matrix composites find widespread application but show major machining difficulties due to significant variations in constituents' properties. In this sense, while the SiC fibre plays significant strengthening effects, the properties mismatch between the brittle fibre and ductile matrix materials becomes important in their machining performance. Through machining tests, SiC fibre reinforced MMCs with Al (soft) and Ti (hard) matrix alloys are evaluated, showing the variation of interaction between inserts and fibres in cutting due to the different matrix properties. This leads to less tool wear but compromised surface integrity in Al-based composite than in Ti-based one.

1. Introduction

Metal matrix composites (MMCs) with long fibre reinforcement show significantly improved strength along the fibre axial direction while keeping light weight [1]. The excellent properties (e.g. high strength, stiffness, creep and fatigue resistance) inherent in these materials have propelled their escalating application for high-value industries such as aerospace and automotive (e.g. turbomachinery blades, brake disks, etc.) [2]. However, despite the compositional resemblance to the normal particle reinforced MMCs, where Ti or Al alloys function as the matrix and silicon carbide (SiC) serves as the reinforcement, the machining of these highly anisotropic materials is considerably intricate due to catastrophic tool wear [3] and compromised surface integrity [4]. Furthermore, the scarcity of research on the machining of these *Fibre reinforced MMCs* (FrMMCs) hinders progress in improving their machinability. While extensive research has been conducted on machining particle reinforced MMCs [5,6], the discontinuous form of the reinforcement makes the cutting mechanism of those materials, somehow, similar to the metal cutting process, except for the particle push-in, pull-out, and fracture during cutting [2]. Besides, the relatively uniform distribution of particles in the material ensures minimal alteration in the surface integrity of the machined workpiece across various directions. However, the regular distribution of SiC fibres in the FrMMC and their fracture in the cutting process not only makes the tool material suffer large abrasive wear (less on PCD cutting edges compared to carbide cutting edges) [3] but also highly degrades the surface integrity through the interaction between the matrix and reinforcement, which is affected by the properties of constituents [4].

It can be imagined that SiC fibres, as hard and brittle material, interact aggressively with the cutting tool, while the matrix material, which supports the fibres but is ductile, can be heavily deformed under the high cutting force generated during the cutting of SiC fibres. As such, the following open questions could be posed: How can the matrix material support the fibres when the cutting engages with the intermittent distributed fibre/matrix and how can this influence the tool wear and surface formation?

In this sense, this work selected two SiC FrMMCs with different matrix materials, i.e. Al-based/SiC FrMMC and Ti-based/SiC FrMMC fabricated by hot isostatic pressing, and conducted face milling tests (see schematics in Fig. 1) and in-depth machinability and surface integrity analysis. It is revealed that the differences in matrix mechanical/thermal properties influence not only the overall machining response of the SiC FrMMC, but more interestingly, at microscopic level, the depth and number of the fibre fracture under the machined surface and even the grain deformation mechanism of the matrix itself.

2. Experimental details

Face milling tests were conducted on a Hermle C32U machine tool equipped with a Kistler 9257BA dynamometer under the clamped workpiece. The feed direction is selected to achieve the regular interacting of fibre and matrix along the feed path. The reinforced region was in the middle with 35 vol% SiC, surrounded by pure matrix

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https://doi.org/10.1016/j.cirp.2024.04.060

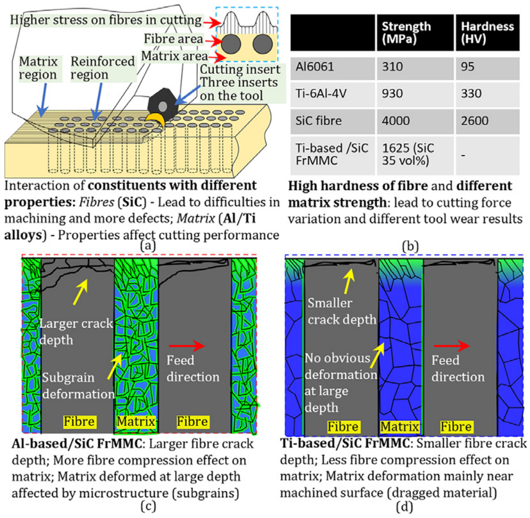

Fig. 1. Schematic of face milling results of FrMMCs (a), Different properties of FrMMC constituents and Ti-based/SiC FrMMC (b); Potential surface integrity (misorientation showed with green colour) when machining Al-based/SiC (c) and Ti-based/SiC FrMMC (d).

regions (Fig. 1a). Both workpiece materials have the same 140 μm diameter SiC fibres as reinforcement embedded in "hard" (Ti-6Al-4V) or "soft" (Al6061) matrix. To investigate the cutting tool performance of different materials, PVD coated carbide (SEEX09T3AFNM-05-F40M: rake angle γ=0°, clearance angle α=20°, standard edge honing), PCBN (SEEX09T3AFTND09-LF-CBN200: γ=0°, α=20°, chamfer and standard edge honing) and PCD (SEEX09T3AFFNL1-PCD20: γ=12°, α=26°, no edge preparation) indexable inserts with fresh edges were used. The cutting parameters employed for particle reinforced MMCs were considered as a starting point (cutting speed, v_c=25-100 m/min; axial depth of cut, a_p=0.2-0.5 mm; feed speed, f_z=0.05-0.15 mm/tooth) from which the following parameters were finally selected due to the smallest tool wear when machining Ti-based/SiC FrMMC (v_c=100 m/min, a_p=0.2 mm, f_z=0.05 mm/tooth). The results from this condition for two materials are analysed in this research. The tool wear was checked after a single milling pass (cutting length: 200 mm for Ti-based/SiC FrMMC, 150 mm for Al-based/SiC FrMMC based on the workpiece dimension left by fabrication; Width and height of workpiece were both 10 mm). Three repetitions were done for the selected condition on both materials. The tool wear showed good consistency and average values were used to evaluate the forces and surface roughness.

3. Results and discussion

As SiC fibres bring particular mechanical and thermal properties to this unique composite structure, when machining Al and Ti-based/SiC FrMMCs, their effects are highly changed by the matrix properties by varying intensity of the interaction between inserts and fibres, ultimately leading to different cutting mechanisms.

3.1. Stepping-up the cutting edge specifications for machining SiC FrMMCs with different matrix materials

While cutting edge specifications (material, edge preparation) of machining conventional (i.e. particle reinforced) MMCs are well documented and can be dealt with conventional carbide inserts, for SiC FrMMCs, considering the high anisotropy of the structure, there is a need to move the specifications more towards ultra-hard materials (e.g. PCBN and PCD) (see tool wear results in Fig. 2).

Although carbide inserts are widely used in machining particle reinforced MMCs, for FrMMCs they showed catastrophic failure (Fig. 2a,d), which could be attributed to their interaction with the ultra-hard/abrasive SiC fibres. When cutting particle reinforced MMC, only part of the particles will engage with the cutting tool, while other particles are removed within the matrix [5]. However, when it comes to FrMMCs, all the fibres need to be cut through in the

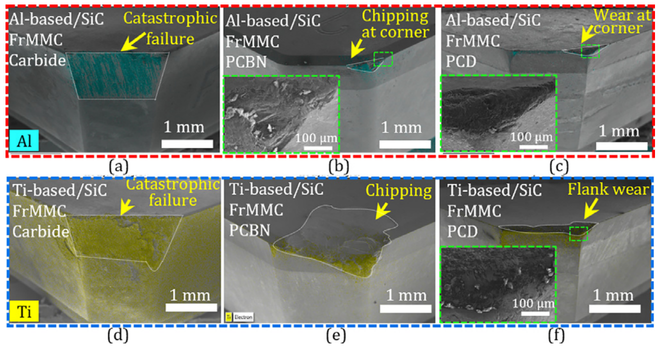

Fig. 2. Tool wear after a single pass on MMCs with different matrix materials: (a)-(c) Al-based/SiC FrMMC, (d)-(f) Ti-based/SiC FrMMC. (Tool wear regions marked by white dotted lines. Other inserts used in tests showed good repeatability as the representative results here.)

selected feed direction during machining (Fig. 1a). Since the SiC fibres are harder than the carbide insert material, the inserts got worn out quickly and rubbed severely with the workpieces, leaving the matrix and broken fibres smeared on the tool surface (Fig. 2a,d). Based on this, the insert materials with higher hardness were tested (Fig. 2b,c, e,f). While PCBN inserts effectively avoided the catastrophic failure in the cutting process, the chipping on the cutting edge still showed their limitations (Fig. 2b,e). It could be noticed that chipping only happened on the side when cutting Al-based/SiC FrMMC (Fig. 2b), while large material was removed from tool surface after machining Ti-based/SiC FrMMC (Fig. 2e). Apart from the matrix properties, the large tool wear when machining Ti-based/SiC FrMMC could also affected by the high temperature in milling due to low thermal conductivity of Ti-6Al-4V. The tool wear shows that the fracture toughness of PCBN inserts is still not high enough to withstand the impact brought by the mechanical property mismatch between the matrix and fibre material during milling process. Although the PCBN inserts chipping in Al-based/SiC FrMMC machining seems smaller compared to Ti-based/SiC FrMMC, it is still unstable and could lead to stuck material on the broken edge (Fig. 2b,e) and even fracture of the tool [7]. While inserts with carbide and PCBN materials failed fast, the PCD inserts showed uniformly distributed flank wear after cutting (Fig. 2c,f), which revealed their outstanding capability in this application. As the hardest material, the PCD inserts showed much less tool wear in the milling process, on which abrasive wear was found with no obvious sharp edges (Fig. 2c,f), i.e. no apparent chipping. While the PCD inserts for Al-based/SiC FrMMC cutting showed wear mainly near the right edge, tools milled Ti-based/SiC FrMMC exhibited uniform wear along the whole edge, which experienced more rubbing with the machined surface. It can be seen that although SiC fibres lead to the high tool wear when machining FrMMC, the different properties of matrix highly affected the tool wear due to varying support to fibres that are loaded. These results shows that not only high hardness, but also good stiffness are key factors when developing the tooling solutions for these FrMMCs, while the matrix supporting needs to be considered for their different wear forms.

3.2. Cutting forces revealing varied interaction with SiC fibres when cutting Al and Ti-based/SiC FrMMCs

Based on the tool wear results, PCD inserts can perform stable milling of these two FrMMCs and their results are further analysed (see force results in Fig. 3). As mentioned before, the workpieces included regions with no fibre at the start and the end of the milling process, which led to the variation of the cutting forces. Although FrMMCs showed similar variation trends in different regions, the evolution of cutting forces is different due to the matrix. While the passive force (F_p) and resultant of F_x, F_y (F_a, active force) were stable in each region when cutting Al-based/SiC FrMMC, the higher strength of Ti-6Al-4V in Ti-based/SiC FrMMC could provide better support to the fibres and made the material removal much more difficult, as could be seen from the fast increasing cutting force in the reinforced region (Fig. 3b,d) due to tool wear. As a result, the worn tool and smeared material on the inserts contributed to the high cutting force even after exiting the reinforced region when milling Ti-based/SiC FrMMC, which didn't show in Al-based/SiC FrMMC case. An interesting phenomenon is that F_a decreased a bit when entering reinforced region, which is more obvious when milling Al-based/SiC FrMMC. This can be attributed to the brittle fracture of SiC, which needs less force for crack propagation once the crack is generated. Then the force increased with the tool wear after entering this region. When cutting these MMCs with different matrix, not only was the tool wear rate affected, but also the stability of the cutting process, which needs to be considered when designing suitable cutting tools for different MMCs.

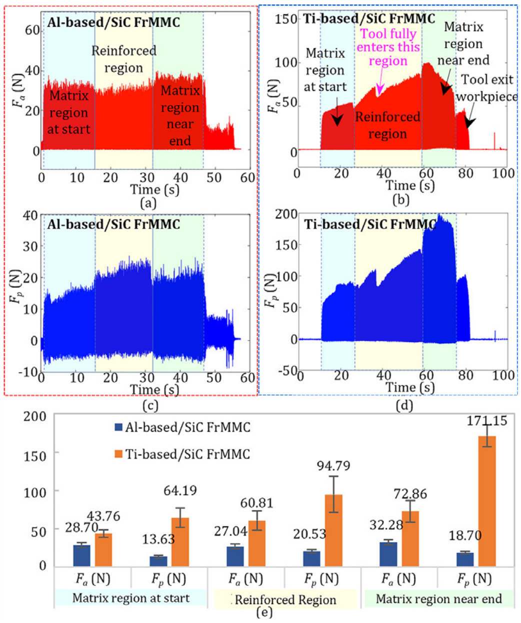

Fig. 3. Cutting force when machining FrMMCs with different matrix materials. (a), (c) F_a (resultant force of F_x, F_y) and F_p (passive force) of Al-based/SiC FrMMC. (b), (d) F_a and F_p of Ti-based/SiC FrMMC. (e) Forces of Al-based/SiC FrMMC and Ti-based/SiC FrMMC in three regions. (Force signals were filtered with low pass filter with 150 Hz cut-off frequency.)

3.3. *Surface and subsurface deformation showing different material removal mechanisms in Al/Ti-based FrMMCs*

Due to the brittle fracture of SiC fibres, the surface topography of machined workpieces showed much worse results than metal cutting (see measured results by Alicona G4 in Fig. 4).

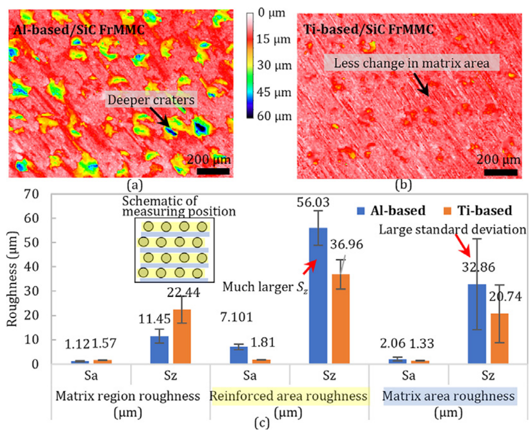

Fig. 4. Surface topography characteristics of reinforced region generated due to different matrix properties. (a), (b) Surface topography of Al-based/SiC FrMMC and Ti-based/SiC FrMMC. (c) Surface roughness results in different region and areas. Average value of 3 areas is calculated. The values of matrix region near workpiece end are presented for comparison.

Compared to machining marks and debris on pure matrix region, the obtained surfaces of reinforced region exhibited a great number of cavities which were left by the fractured fibres. The fluctuation at the fibre positions could be seen clearly (Fig. 4a,b), but the depth of the cavities varied a lot on MMCs with different matrix. For both MMCs, although the average values (S_a) were small, the maximum peak-to-valley heights (S_z) showed large height, especially in the fibre area. Despite these common phenomena, the depths of craters on the Al-based one were much deeper than the Ti-based one and the machining marks in its matrix area led to large S_z. These results showed much worse roughness when machining Al-based/SiC FrMMC compared to Ti-based/SiC FrMMC, which can be explained by the subsurface formation later. Apart from these, the tool wear in machining can also affect the surface roughness, which can be seen from the larger S_z value in matrix region near end of Ti-based/SiC FrMMC workpiece than Al-based one due to larger tool wear (Fig. 4c).

To further check the surface integrity, the surface morphology was observed by SEM (see Fig. 5). It is noticed that the machining marks on the surface did not follow the cutting direction but were aligned with the rubbing direction, i.e. generated when inserts rotate back and contact with the machined surface, which is different from machining of metal alloys. Due to the existence of SiC fibres in the machining process, much poorer surface quality was obtained. However, the impact of the same fibres can be influenced by the different matrix properties and the Al-based/SiC FrMMC showed much worse results than Ti-based one. Apart from machining marks and smeared material, some small debris could be seen in the matrix area (Fig. 5a), which could be generated from the rubbing of fractured SiC. However, in the fibre area, larger debris appears near the brittle fractured fibres, which leads to worse surface integrity. Although the machining marks in the matrix region doesn't change much, the rubbing effect on soft matrix (Al-based) FrMMC is more severe than hard matrix (Ti-based) FrMMC in the reinforced region, and a lot of matrix material is smeared on the surface of fibres, leaving unclear fibre profiles on the surface. On the other hand, when the inserts contact with the machined surface, shallow machining marks are generated in the matrix region (Fig. 5c,d). Then the inserts rub against the fractured fibres and smear the debris on the surface, leading to deeper machining marks in the reinforced regions (Fig. 5b).

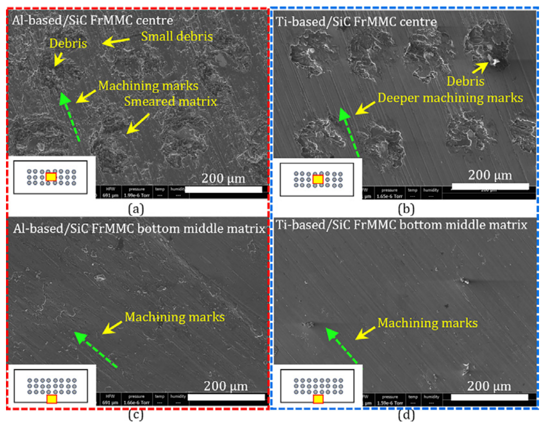

Fig. 5. Machined surface in different regions of MMCs. (a), (c) Reinforced region and pure matrix region on Al-based/SiC FrMMC. (b), (d) Reinforced region and pure matrix region in Ti-based/SiC FrMMC. (Position on the workpiece indicated in the schematic in the left corner.)

To help understand the formation of surface defects on machined workpieces, the subsurface results were checked both for the fibres (Fig. 6) and matrix (Fig. 7) after mechanical sample preparation process. (Diamond disk and suspensions were used to achieve effective grinding and polishing without damaging the fibres by applying suggested parameters from Struers.)

The machined subsurface of these FrMMCs shows mainly fibre fracture near the machined surface and their crack propagation as well as matrix deformation. Apart from the shear deformation that occurs in conventional metal cutting, the matrix deformation also

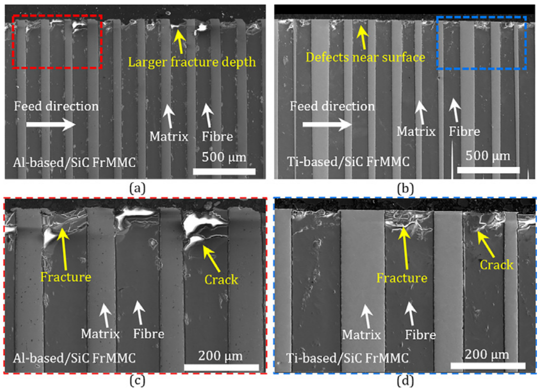

Fig. 6. Cross-section results of machined Al-based/SiC FrMMC and Ti-based/SiC FrMMC workpieces. (a), (b) SEM results of cross-section. (c), (d)Enlarged figures of local area.

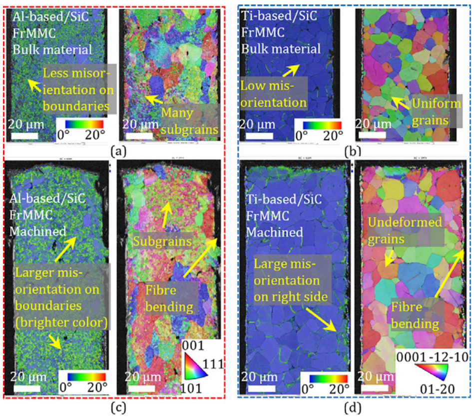

Fig. 7. EBSD results of matrix in cross section. (a), (b) Misorientation map and microstructure of Al-based/SiC FrMMC and Ti-based/SiC FrMMC in bulk material. (c), (d) Misorientation map and microstructure of Al-based/SiC FrMMC and Ti-based/SiC FrMMC under machined surface.

comes from the compression of fibres. Similar to the machining marks, the fibre crack directions were also opposite to the feed direction of milling tool, proving that surface defects generation mainly happened in rubbing process when inserts rotate back.

Compared with hard matrix (Ti-based) FrMMC, the soft matrix (Al-based) FrMMC shows more chipped fibres near the surface as well as cracks on subsurface (Fig. 6c,d), which demonstrate the larger fibre bending and fracture in cutting process. Apart from these, the matrix in Al-based FrMMC also showed much deeper deformation than Ti-based FrMMC (see EBSD results in Fig. 7). Before cutting, the material showed microstructure with many subgrains in Al-based/SiC FrMMC and undeformed uniform grains in Ti-based/SiC FrMMC (Fig. 7a,b), which affected machining performance of the materials. While Ti-based/SiC FrMMC only showed large deformation (dragged material) near the machined surface due to cutting and some strain on the right side due to the compression of the fibre bending in machining, the matrix in Al-based/SiC FrMMC showed large deformation in great depth (>180 μm) with higher strain on grain/subgrain boundaries. This large deformation could be attributed to the lower strength of Al6061 matrix and its weaker support to fibres, which led to larger bending effect instead of cutting and shearing when the insert interacted with reinforcements then in turn led to compression of the nearby matrix. Besides, the high cutting temperature in the tests could soften the Al6061 matrix more easily than the Ti-6Al-4V, which leads to the larger deformation depth in the matrix of Al-based/SiC FrMMC under both thermal and mechanical load.

4. Conclusion

This paper reports face milling results of SiC fibre reinforced MMCs with soft (Al) and hard (Ti) matrix materials. The tool wear with different insert materials were also studied. Both surface and subsurface results were checked to evaluate effect of different matrix alloys on surface integrity of the workpiece. Much severe damage was generated in the cutting process compared to machining metal alloy or particle reinforced MMC. Besides, the properties of matrix materials significantly affected their interaction with fibre, which leads to larger matrix deformation in Al-based/SiC FrMMC compared to Ti-based/SiC FrMMC, characterised by high strain on grain/subgrain boundaries in large depth. This in turn leads to larger fibre fracture near the machined surface, which generated much worse roughness and more surface defects. These results can be of help for understanding the cutting performance of these MMCs, choosing of insert material (PCD inserts needs to be used, might be improved by edge honing) and removing of the affected layer (larger depth for Al-based/SiC FrMMC) in following machining processes. And further research can be conducted to study the cutting performance of this material in different orientation and more details in the material removal process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Shusong Zan: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Zhirong Liao:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Omkar Mypati:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Dragos Axinte:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Rachid M'Saoubi:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Mark Walsh:** Investigation, Methodology, Project administration, Resources. **Jose A. Robles-Linares:** Investigation, Methodology, Writing – review & editing.

Acknowledgement

We acknowledge the THERMACH project (Innovate UK Grant No.74744, SMART Eureka Grant No.S0313) for sponsoring this research, TISICS Ltd for supplying the material, and the Nanoscale and Microscale Research Centre (nmRC) for providing access to the material analysis facilities.

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