Review Article

Mechanisms in turning of metal matrix composites: a review

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\textbf{A B S T R A C T}

Metal matrix composites have evoked a keen interest from the automobile and aerospace sectors owing to their attractive mechanical properties and applications. Over the past two decades, researchers have unearthed many secrets pertaining to these advanced materials. This paper briefly reviews the research revelations of the mechanisms that make these materials so superior. Turning of metal matrix composites is focused in particular. Mechanisms such as particle fracture, particle pullout, debonding, dislocation phenomena, thermal softening, wear modes, surface generation, cutting forces, chip formation, strains and stresses are addressed. Discussions on related phenomena such as effects of tool coatings, adhesion, friction, microstructures and strain hardening are also presented.

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1. Introduction

Metal matrix composites (MMCs) are the new age materials that are being preferred by the automotive and aerospace industries for their enhanced properties. These materials exhibit higher strength to weight ratio, hardness, stiffness, wear resistance etc. as compared to conventional metals and alloys. However, these very properties make them difficult to machine. Hence, numerous investigators have dedicated themselves to unraveling various aspects of machining these composites.

There is extensive literature available that records the precious work and contributions in this area by researchers throughout the world. In fact, the available literature is so incredible that the authors of the present work have restricted themselves to a brief discussion of turning mechanisms alone. Some of these mechanisms are very basic, like cutting forces, surface morphology, chip formation. Others are more intricate like particle pullout, particle fracture, debonding, micromechanics.

The purpose of this paper is to provide a brief overview focusing only on mechanisms in turning of MMCs. Topics like preparation, characterization, optimization, simulations have been left out. Of course, ample pointers have been included regarding MMC properties and related tool properties as well. Later, effect of mechanisms like friction, effect of coatings, built up edges (BUE), thermal softening etc. have been discussed. Tool wear has also received due attention, in sections dedicated to abrasion, flank, notch and crater wears. The paper then shifts to advanced mechanisms like tool–particle interactions, debonding, particle fracture. Sections on surface roughness, cutting forces and chip morphology also follow, to clearly understand the peculiar behaviors of the MMCs in turning. Primary results obtained by researchers have been furnished all along, and further details can be obtained from the respective papers.

2. Tool and MMC properties

2.1. Tool selection

In machining metal matrix composites, tool selection is of primary importance. Gallab and Sklad [1] have pointed out the superiority of PCD tools over Al2O3/TiC tools owing to their higher hardness and thermal conductivity, which helped heat flow away from the cutting zone. Similar results have been arrived at by other researchers [2–4], where excellent chemical affinity of the MMC with the PCD is also pointed out. In fact, Monaghan et al. [5] ranked various tool materials in the order of decreasing tool wear. Hung [6] found PCD and PCBN tools to be much better than WC tools. Tomac et al. [7] compared chemical vapor deposition insert tools (CVD) to TiN, TiCN and Al2O3 coated tools. They confirmed superior performance of CVD tools over the others. Weinert and Biermann [8] advocated PCD and CVD inserts in machining MMCs owing to their low tool wear rates. Regarding hardness, thermal and fracture properties, PCBN tools also fare well against ceramic and cemented carbides, in machining MMCs. Binders also helped improve fracture resistance of tools [9]. Looney et al. [10] reported that cubic boron nitride inserts provided the best overall machining performance in machining Al/SiC MMCs.

2.2. MMC physical properties

For investigation of MMC properties, Zhang et al. [11] developed quantitative models for steady sliding [12] and adhesive wear [13] in wear experiment of a steel disk sliding against metal matrix composite pins. They concluded that increase in particle size was more fruitful than incrementing volume fraction in delaying wear intensification from mild to adhesive modes. Ozben et al. [14] reported that greater SiCp reinforcement directly resulted in higher tool wear. Pramanik et al. [15] discovered a correlation between cutting velocity and the strength of the composite material. For example, only 0.25% of the MMC strength reduced up to a cutting velocity of 50 m/min. Similarly, some studies reported machining temperatures at specified volume fractions, speeds, feeds and depths of cut [16]. Others also determined the extent of change in MMC material properties as per cutting temperatures [17]. Material properties of the aluminum MMCs, like the initial yield stress, modulus of elasticity, tangent modulus etc. were provided by Meijer and Long [18,19]. Maximum tensile stress of silicon carbide reinforcements was determined to be 245 MPa by Muller [20].

2.3. MMC microstructures

Li et al. [21] compared microstructures of aluminum A359 alloy with those of A359/SiC composite. They found SiC particles huddled along the eutectic phase of the matrix. Vickers micro hardness measurements showed that the hardness of the matrix material is very similar to the unreinforced parent alloy (Figs. 1 and 2). According to Kannan and Kishawy [22], the micro hardness of aluminum metal matrix composites varied inversely with the volume fraction and fineness of the reinforced particles. This means that for the purpose of analytical modeling, rate-dependent properties of the matrix can be considered to be same as that of the unreinforced alloy.

2.4. MMC strain hardening

Li et al. [23–25] have determined high strain rate and quasi static properties of the Al/SiC composites in compression and tension. Related stress-strain curves, and tensile failure strains have also been reported. Researchers have pointed out that at reasonably large strains, both the unreinforced matrix and the reinforced composite show similar degree of strain hardening [26–28]. But, the particle reinforcements increase the strain rate sensitivity of the composite depending on the volume fraction, shape and aspect ratio of the reinforced par-
particles [29]. However, particle fracture under compression slows down strain hardening of the composite [25].

3. Tool wear – modes and mechanisms

3.1. Edge chipping

According to Gallab and Sklad [1], Al$_2$O$_3$/TiC tools suffered extensive damage in machining of Al/SiC MMCs due to edge chipping. Other researchers have also reported grooving and edge chipping on the flank face and cutting edge due to impact of the hard ceramic particles [9,3]. Chipping of the cutting edge increased with cutting speed [30].

3.2. Crater wear

In the study of Gallab and Sklad [1], alumina in the tool got pulled out by the abrading workpiece particles of SiC which proved to be harder. Due to abrasion, the grooves on the tool got wider, resulting in crater wear. Tools with TiN coatings provided better results, as they were harder. However, Sahoo et al. [31] did not find crater wear while turning A6061/SiC MMCs and concluded that crater wear may not be a major concern while machining metal matrix composites.

3.3. Notch wear

Ding et al. [9] observed notch wear formed on the flank face due to a series of undulating ridges formed on the machined surface. These ‘notch ridges’ had lengths equal to the feed. This notch wear was more pronounced in wet cutting in comparison to dry cutting conditions. It happened due to increased hardness of the work piece matrix due to reduced cutting temperatures, brought down by the application of coolant. Similarly, coolant application increased notch wear significantly only at lower cutting speeds, because at higher speeds the coolant was unable to efficiently absorb heat from the machined surface and thus, hardness of the work matrix did not increase. In this way, notch wear did not increase even by coolant application due to higher cutting speeds. Thus, notch wear depends on the abrasion resistance of the tool material, but it also depends on flank wear occurring during machining. This factor comes into prominence and increases notch wear even in case of high abrasion resistance tools, especially at higher cutting speeds, where notch wear cannot occur by high

![Fig. 1 – Optical micrographs of (a) A359 Aluminum alloy and (b) A359 with 20 vol.% SiC particles MMC. by Li et al. [21]](image)

![Fig. 2 – True stress–strain curves of composite and monolithic alloys at (a) quasistatic deformation rates (10$^{-3}$ s$^{-1}$) and (b) high strain rates (200 s$^{-1}$). by Li et al. [21]](image)
hardness of the work material, because it has been thermally softened. Coolant also cannot help in this situation as detailed above. At lower cutting speeds, certainly the higher abrasion resistant tools are able to withstand the higher work material hardness, helped by lower flank wear. Similar phenomenon has been observed by Cronjager et al. [32].

3.4. Flank wear

Flank wear is usually taken as the tool life criterion. Manna and Bhattacharyya [33] observed high flank wear rate at low cutting speed during machining Al SiCp MMC due to higher cutting forces and built up edge. However, Gallab and Sklad [1] observed an increasing flank wear with increasing cutting speed, due to higher kinetic energy of the chip containing abrading particles. Flank wear also increased by increasing depth of cut, due to more micro-cutting on the flank face. Feed rates improved tool life by not giving enough chance to the abrading particles of the work piece to wear down the tool. Negative rake increased flank wear due to higher cutting forces while positive rake also increased flank wear and pitting. Best results were obtained with zero rake only. Furthermore, lower tool nose radii caused higher cutting forces, resulting in greater chipping and flank wear. Li and Seah [34] reported that volume fraction increment of hard particulates in metal matrix beyond a particular threshold value proved detrimental to the tool life. Andrews et al. [35] reported higher rate of tool wear on CVD diamond inserts than PCD inserts in machining silicon carbide reinforced aluminum MMCs. PCD tools fared better than PCBN in terms of flank wear in machining of MMCs [9]. The same authors (Ding et al. [9]) also found flank wear incrementing with cutting speed directly and they explained this occurrence on the basis of thermal weakening of binder in the tool. Furthermore, there was no significant difference in flank wear at high cutting speeds under dry and wet machining conditions. This important finding is due to the inability of coolant to reach flank face during high cutting speeds, hindered by the high flow rate of the work material past the tool. Similar and more limitations of the flood coolant applications have been highlighted by Trent and Wright [36]. Li et al. [37] also corroborated the above results confirming that the tool flank wear was directly related to cutting speed and feed, owing to thermal softening of the tool, diffusion wear and higher kinetic energy of chip abrading against the tool. Similar results were obtained by Kilickap et al. [38] as well.

3.5. Abrasion wear

In machining metal matrix composites, due to the hard inclusions in the work material, abrasion is found to be the most dominant wear mechanism [39]. Gallab and Sklad [1] identified abrasion wear as the primary mechanism of tool wear in case of PCD against Al/SiC MMCs, by the parallel grooves created in the direction of the chip flow. Tetti [40] also observed rapid abrasive wear on tool due to anisotropic and non-homogeneous structure of composites. Similar observations were made by Lin et al. [37]. They attributed the phenomenon to the two-body and three-body mechanisms. Two body abrasions occurred when the hard ceramic particulate embedded in the work piece dug into the tool surface and cut grooves parallel to cutting direction. Three body mechanism included the cutting action by a dislodged ceramic particle on both – tool land and parent matrix material. Similarly, abrasion due to dislodged particles was found to be the main reason behind tool cutting edge damage by other researches [41–43] as well. Regarding machining of MMCs with diamond tools also, wear on rake face was found to be abrasive. However, this wear was lesser than that on the flank face, due to the continuous sliding phenomenon of particles on the rake face [44].

4. Coatings

Hung [45] observed marginal improvement in tool life in case of diamond tool coatings. However, other researchers [46] found thick diamond coatings (500 μm) almost matching the performance of PCD tools. Similar observations were reported by Luniano et al. [47], who studied the behavior of rake angle in uncoated and CVD diamond coated carbide tools in high speed machining of metal matrix composites. Sahoo et al. [31] observed improved machinability of Al/SiC composites due to multi-layer coated inserts of TiN, TiCN and Al2O3. The lubricating effect of the TiN coating reduced chip tool interface temperature and eliminated BUE formation as well. Thus, tool wear was subdued. Al2O3 provided thermal barrier coating, TiN gave diffusion barrier coating and TiCN endowed a wear resistant coating for longer tool hardness retention. Similar findings have been reported by other researchers [3,48,49].

5. Protective thin layer of W/P on tool/adhesion

Gallab [1] observed the formation of a protective thin layer of Al/SiC MMC on PCD tool that enhanced tool life. This protective layer was later found removed at higher cutting speeds. Ding et al. [9] also found work material adhering to the tool edges at cutting speeds of 50 m/min. They carried out dry cutting of MMCs with PCBN and PCD tools. PCD tools attracted lesser adhesion of MMC work piece in comparison to the PCBN tools, due to better thermal properties. This adhesion increased with increasing cutting speeds. The adhered work piece can be removed by sodium hydroxide solution.

6. Coefficient of friction

Friction plays a vital role in tool wear and cutting forces. Lower friction coefficients resulted in lesser wear in PCD tools in machining Al/SiC MMCs [1]. Zhang et al. [50] found that T6 heat treatment resulted in highest friction coefficient values as compared to under-aged and over-aged treatments in Al 6061 alloy reinforced with alumina and SiC particles. Pramanik et al. [51] used Coulomb friction model to consider the effect of friction at the tool–chip interface. Dabade et al. [52] also considered chip–tool interface friction to predict cutting forces in oblique cutting. This chip–tool interface friction occurs mostly due to two body rolling abrasion and/or three body rolling friction [34,53]. Sikder and Kishawy [54] utilized these two mechanisms for calculating total frictional force at tool–chip interface. Firstly, the two body rolling abrasion friction force
was determined as per Jiaren et al. [55], in which the reinforcement particles were assumed to be perfectly spherical. Hence, the normal force acting on a single abrasive particle was formulated from the multiple contact condition. Secondly, the three body rolling friction coefficient was formulated on the basis of studies by Venkatachalam and Liang [56] and Sin et al. [57]. While turning 6061 Al MMC, Sikder and Kishawy [54] reported that the frictional forces constituted about 20% of the total forces along the cutting direction. The normal force and the two body abrasion force on single reinforcement particle increased with rising particle sizes. On the other hand, a rising volume fraction reduced the normal and ploughing forces on a single particle. This was due to a corresponding increment in the Young's modulus of the reinforcements, which resulted in lesser penetration in the tool–chip interface.

7. Thermal softening

Gallab and Sklad [1] reported a decrement in cutting forces with increasing cutting speeds and depths of cut, and attributed the same to thermal softening of the workpiece, which led to lower cutting forces. Tomac et al. [7] have reported that at elevated temperatures of the cutting zone, the metal matrix softens up, enabling the reinforced particles to plough into the workpiece, thus preventing tool wear.

8. Built up edge

Muthukrishnan et al. [58] found lesser BUE at lower cutting speed in turning A356/SiC, at 10% volume fraction, using medium grade PCD inserts. Gallab and Sklad [1] attributed the phenomenon of reducing cutting forces with increasing cutting speeds to the effect of BUE. They observed the formation of BUE in turning of Al/SiC MMCs under all cutting conditions because of the material composition of these MMCs. Therefore, the effect of BUEs in such cases cannot be ignored. They define BUE as the strain hardened two phase material under high temperature and pressure. Furthermore, they observed formation of BUE at higher cutting speeds (890 m min⁻¹) as compared to lower speeds of 600–700. BUE formation also increased with augmenting depth of cut, leading to tool chipping. The grooves on rake faces due to wear were filled with workpiece material, also a kind of BUE, which helped decelerate further wear. Thus, although BUE appears to protect tool edge from abrasion, it may actually cause tool chipping if it goes unstable, and therefore cannot be relied upon as an effective tool protection measure.

9. Particle pullout and debonding

Gallab and Sklad [1] found that tool abrasive wear was caused by possible grain pullout from the PCD tool, by the micro-cutting action of the SiC particles. The authors concluded in this respect that such wear can be controlled by choosing the size of PCD grains to be more than the grain size of the SiC particles. However, this action would increase the vulnerability of the tool toward possible failure due to fracture. Similar conclusions have been arrived at by Weinert [59] that the tools with coarse grain size possess higher abrasion resistance, albeit at the risk of reducing fracture resistance. Similarly, Yuan et al. [60] and Cheung et al. [61] observed that best surface finish is obtained when reinforcement particles are clearly cut from the work piece, and not pulled out from the metal matrix. Particle pull outs and corresponding cavities were observed by other researchers too [50,62,63]. Such debonding of particles also produced cracks in front of the advancing tool, as observed by Hung et al. [64], who used a quick stop device in their experiments to observe crack propagation.

10. Chip formation

Chip formation mechanism of metal matrix composites resembles, if not replicates, the behavior of monolithic materials [65]. Flow lines [63,64] due to chips in MMCs echo those produced due to grain boundary deformation and etched patterns in steel, aluminum, titanium and brass [65]. Joshi et al. [66] emphasized that the most efficient and cheapest ways of studying the machining characteristics of any material is to study its chip formation details. They further stated that the number of circles that the chips form before breaking decreases as the volume fraction of the reinforcement particles increases. They explained this observation based on decreasing strain at failure of the chip curls. Therefore, number of chip curls is directly related to material strain at failure. It can also be understood that the increased volume fraction of the hard reinforcements reduces ductility of the composite, favoring chip breakage. Another interesting event is that the unreinforced aluminum alloy chips curl is affected by tool rake, whereas composite chip curls remain unaffected. For example, in the former, chip curl diameter increases with a decrease in tool rake angle. Basically, chip curling depends on the ratio of plastic contact length to total contact length between the chip and the tool face [67]. Flatness of chips increases with this ratio. Thus, as the rake angle decreases, chips turn out flatter, i.e. having greater diameter. Also, at lower cutting speeds, shear strength of the alloy remains high, facilitating chip breakage at smaller lengths. However, the same does not hold true in case of composites as their low ductility generates much smaller chips. Still, it was observed that chip morphology of composites did depend on the volume fraction of reinforcements. For lower volume fractions, the chips showed a tendency to stick to the tool face, thus restricting their movement, resulting in longer chips, of larger diameters. Furthermore, Joshi et al. [66] have developed a combined chip breaking criterion based on two criteria given by Nakayama [68] and Zhang [69]. According to the former, chip breaks when its strain reaches a certain limit (given as a formulation), whereas the latter expressed this limit of strain on chip based on mechanical properties and chip breaker geometry. The authors have also provided a detailed procedure and guidelines for chip characteristics evaluation like yield strength, elastic modulus, strain on chip. On comparison with obtained experimental results, the authors found better resemblance with the model given by Nakayama [68], due to inclusion of chip breaker geometry and neglect of spring back effect in chips considered by Zhang [69]. Gallab
Dislocations as based edges saw dependent conditions, in handling. At higher feed, discontinuous chips were generated. Lin et al. [37] observed that cutting with sharp tool resulted in the formation of long, helical chips. As the tool became blunt, chips turned to short, helical shapes. This phenomenon was explained by the authors as owing to lowered ductility of aluminum matrix by reinforcement of hard ceramic particles, as well as due to chip breaking action by the built up edges developed on the progressively blunt tool nose. Such short chips are more desirable as they get detached from the cutting zone faster, without causing tool/workpiece damage/recutting. Davim [70] determined chip compression ratio in radial turning of 20% Al/SiC metal matrix composites, based on Merchant’s orthogonal cutting model. He observed that the ratio decreased slightly with cutting velocity. In yet another work, Lin et al. [71] and Gallab et al. [63] machined aluminum based MMCs with 20% reinforcement volume fraction subjected to depth of cut, feed and cutting speeds up to 2.5 mm, 0.45 mm/rev and 300–700 m/min respectively. Under the above conditions, continuous chips were formed using sharp PCD tools, whereas discontinuous chips were generated with blunt tools or at higher feed and speeds. Similar findings were arrived at by Karthikeyan et al. [72], who used tungsten carbide tools at much lower speeds (up to 150 m/min). Thus, it can be concluded that chip formation mechanism is very much dependent on cutting conditions and applied tool conditions as well. Sahoo et al. [31] observed that continuous fragmented saw tooth chips were generated during turning of AA6061 Al/SiC MMC by multi-layer coated carbide inserts under high speed and dry conditions. High cutting temperatures at elevated cutting speeds, combined with low thermal conductivity of the MMC led to high strain rate in the shear plane, resulting in saw tooth chips.

11. Dislocation phenomena

Dislocations are responsible for plastic flow behavior of materials. Arsenault et al. [73,74] reported fivefold increment in yield stress on addition of discontinuous reinforcements to the matrix. They assigned this improvement to the increase in dislocation density and decrease in sub grain size of the composite. Miller and Humphreys [75] showed that quenching generated dislocations in MMCs. This happened due to large difference in thermal coefficients of expansion of matrix and reinforcements particles. Yuan et al. [60] and Gallab et al. [63] opined that abundance of dislocations in the region of the reinforcement particles contributed to eventual cracks and voids. According to Kannan et al. [76], metal matrix composites fall into the category of materials having ‘alien dislocations’ [77] before testing. The alien dislocation distributions caused an increase in flow stress due to increase in dislocation tangles [78,79]. Kannan et al. [76] found that AA7075 based MMC exhibited greater hardness and yield strength over AA6061 because of more alloying elements in AA7075 (Fig. 3). These alloying elements (Cu, Mg, Cr, Zn) formed higher density of precipitates, enabling more dislocation pinning and dislocation density. This dislocation density can be determined by a line intercept method using TEM micrograph analysis, proposed by Hale and Henderson-Brown [80].

12. Tool and particle fracture

Ding et al. [9] found extensive intergranular tool fracture in turning of Al-SiC MMCs by PCBN tools. Higher contents of TiN binder raised resistance in PCBN tools against such fracture. Other researchers also corroborated such findings [81–83]. Uesaka and Sumika [84] also emphasized that thermal cracking and fracture resistance improved with coarser grains and binding agents. They explained increase in fracture resistance due to better ductility and bond strength provided by TiN binder. Furthermore, Ding et al. [9] found better tool fracture resistance at high cutting speeds of 400 m/min, due to thermal softening of the work piece which reduced stress on tool face due to hard reinforcement particles in chips. Binderless PCBN showed best fracture resistance property. Yan and Zhang [62] determined particle fracture energy based on Griffith’s theory.
by subtracting energies of rubbing, plastic cutting and ploughing from the total energy of scratching. They conducted single point scratching (by a pyramid indenter) of four different compositions of aluminum based MMCs reinforced with SiC/Al₂O₃ particles. Li et al. [25] reported significant SiC particle fracture in A359/SiC metal matrix composite loaded in compression. However, the tensile failures of both A359 alloy and A359/SiC composite showed fracture along the inter-dendritic eutectic phase of aluminum-silicon, without any trace of silicon carbide particle fracture [85].

13. Surface roughness/morphology

With PCBN tools machining Al-SiC MMCs, surface roughness (Ra) gradually increased with cutting distance/progression at lower cutting speeds (50 m/min) [9]. The roughness increment was more rapid at higher cutting speeds (400 m/min). This behavior was explained by the dominance of adhesion in high speed cutting. At high cutting speeds, the hard work material diffused to the tool surface and then abraded against the work surface itself. Later, it again detached back from the tool to the machined surface and thus induced a myriad of surface defects such as debris, grooves etc., thus increasing Ra value. Application of coolant somewhat curbed the diffusion effect, and helped improve surface quality. At lower speeds, notch wear on the tool translated into replication of the ridges on the machined surface, imparting higher surface roughness. Tools with higher notch wear resistance due to higher abrasion hardness imparted much better surface quality to the machined surface. Overall, surface cracks were predominant. Lin et al. [37] observed that the surface finish actually improved with increasing cutting speeds at constant feed rate. Best surface finish was obtained with a slightly worn tool due to stabilization of the nose radius. And at constant speeds, surface finish deteriorated with rising feed rates. This inverse relationship of surface finish with feed was also reported by Venkatesh et al. [86], while machining A356/SiC (20p) MMCs. During turning of LM25 Al/SiC MMC, Arakiadass et al. [87] found feed to be the most significant parameter affecting surface roughness, followed by spindle speed and weight percentage of particle reinforcement. Similarly, Muthukrishnan and Davin [88] found that feed rate had maximum statistical influence on surface roughness, followed by depth of cut and cutting speed, in turning of Al/SiC (20p) MMC with coarse grade PCD insert. Sahoo et al. [31] reported that surface roughness increased with elevated feed in turning AA6061/SiC MMC with multi layered coated carbidies (TiN, TiCN etc.). They reasoned that at higher feed, tool traversed the work too quickly and left feed marks on it. Another rationale offered was the phenomenon of chatter that accompanied higher feed, and induced surface roughness. But, at higher cutting speeds, better surface finish was obtained as explained by better stability and lesser chatter of the machine tool at higher cutting speeds. Ge et al. [89] conducted ultra precision turning of powder formed Al2024/SiC and cast A1012L/SiC composites. They obtained surface roughness Ra of 20–30 nm using SDPT/PCD tools. Surface finish deteriorated with rising feed, volume fraction and dry condition. Cracks, pits and voids were formed due to particle pullout.

14. Cutting forces

Cutting force generation in metal matrix composites is a complex phenomenon because it depends on the structure and properties of the matrix, the reinforcements and their interface [43]. Davin [90], Chambers [3] and Gallab [1] determined cutting forces in machining MMCs with PCD tools under varying cutting speeds. Lin et al. [37] observed increasing cutting and feed forces with tool wear progression. Similarly, both of these forces at constant cutting speed increased with rising feed rates. At constant feed, both of these forces changed marginally with rising cutting speeds. Pramanik et al. [15,91] developed a mechanics model to predict cutting forces in machining of Al₂O₃/SiC reinforced metal matrix composites. They considered the cutting force generation mechanism to be based on chip formation, ploughing and particle fracture forces. They computed chip formation forces using Merchant’s theory applicable to orthogonal cutting [92]. Ploughing forces were determined using a slip line field model for a rigid wedge in orthogonal cutting [90]. Particle fracture force was based on the average fracture energy per unit cutting edge length in orthogonal cutting. The authors reported that the cutting and thrust forces increased almost linearly with feed. However, the rate of increase was higher in case of the cutting force. Both forces reduced with increasing cutting speeds. Kishawy et al. [93] used an energy based model for cutting force prediction. This model was founded on deformation in the primary and secondary zones as well as particle displacement and fracture. They considered the energy consumed in the secondary cutting zone to be one third of that in the primary cutting zone, akin to the monolithic materials. They also assumed that the cracking damage of the reinforced particles was dependent on stress in the particle and the statistical behavior of the particle strength. On similar lines, Sikder and Kishawy [54] also investigated the effect of particle sizes on cutting forces in turning of metal matrix composites. Their analytical force model was based on matrix shearing, ploughing and particle pullout. Chip formation force in this case was captured by matrix shearing mechanism, using the Johnson–Cook constitutive model [94]. Johnson–Cook’s model gives material flow stress under high strain rate conditions. Furthermore, Sikder and Kishawy [54] considered only half of the equivalent shear strain in their model on the basis of Oxley’s theory [95]. They also implemented the concept of equivalent cutting edge proposed by Colwell [96], in which a single straight cutting edge was considered to replace both the straight and rounded parts of the cutting edge. This was done to include the effect of the cutting tool nose radius in the force model. They too confirmed the increase of cutting forces with feed. Moreover, they noted that frictional force along the chip tool interface and debonding force were the reasons that explained why cutting forces increased with rising reinforcement volume fraction. Similar results were obtained by Dandekar and Shin [97], who modeled cutting forces and sub-surface damage in turning MMCs. They used equivalent homogeneous material (EHM) model for defining material properties toward machining simulation.
15. **Stresses and strains**

Davim [70] determined normal shear, shear strain and shear strain rate in radial turning of 20% volume fraction Al/SiC metal matrix composites. He reported that shear plane angle decreased, whereas the shear strain increased slightly with rising chip compression ratio. Opposite trends were observed with respect to cutting velocity. Normal stresses were found to be always bigger than shear stresses. Both varied directly and inversely with cutting velocity and feed, respectively. Pramanik et al. [51] explored the development of stress/strain fields for various tool–particle orientations in machining MMCs. They used Cowper–Symonds model and finite element simulations for strain rate determination. Also, the matrix at the particle–matrix interface as well as the tool–particle region was found to be highly strained. Same was observed by Monaghan [98] too, who studied the micromechanics involved with the machining of the metal matrix composites. Pramanik et al. [91] defined residual stress as an incompatibility between the surface layer and the bulk material, generated by any mechanism that creates variation in the surface geometry. They showed that longitudinal residual stress was tensile for unreinforced alloy but compressive for the composite for all values of feed and speed. Transverse residual stress exhibited similar trend, although for the composite it remained largely neutral with respect to feed and cutting speed. According to Capello [99], the residual stress generation mechanism is of three types: plastic deformation, thermal plastic flow and specific volume variation. Thermal effects cause tensile residual stresses, while mechanical deformation causes compressive residual stresses. Thus, in case of MMCs, mechanical deformations became more prominent than thermal effects due to restriction of matrix flow by particles, particle indentation on the machined surface and matrix compression between tool and particle. These factors led to compressive residual stresses in MMCs.

16. **Tool–particle interactions**

The effects of tool–particle interactions are wide ranging in machining of metal matrix composites [15,93,100]. Pramanik et al. [51] showed the influence of particle orientations on the plastic deformation of the machined surface. They showed that tool movement caused significant stress changes in particles and the surrounding matrix, leading to inhomogeneous deformation and matrix flow. Particles just below the tool path acted like indenters, whereas particles along the cutting path got debonded, left cavities and then ploughed into the newly machined surface. Particles above the tool path moved along the chip and slide along the rake face, with the matrix material experiencing very high plastic strain. In a similar work [15], they further estimated the influence of reinforcement particles based on the specific energy of debonding. Sikder and Kishawy [54] determined that debonding changed the potential energy of metal matrix composite as a function of material properties and reinforcement volume fraction. They showed that the potential debonding energy per reinforcement particle was a function of the particle diameter. Therefore, the total debonding energy increased with incrementing volume fraction as well as particle size, because of greater availability of contact surface for debonding.

17. **Future trends**

Metal matrix composite materials have a brilliant future. Researchers have explored many unchartered territories in turning of metal matrix composites. Bejjani et al. [101,102] conducted laser assisted turning of titanium metal matrix composites, building upon the pioneering work of Wang et al. [102]. Wang et al. [103] evaluated the LAM (laser assisted machining) of aluminum MMCs and showed the importance of matrix softening in particle pullout. Bejjani et al. [101] obtained optimum cutting conditions in turning of TiMMCs. Using LAM, they [101] reported a tool life improvement of 180% at high cutting speeds, explained through chip morphology and micro-structure observations. They also encountered an unexpected occurrence of high tool wear at elevated cutting speeds under all machining conditions, which needs further attention. Kremer and Mansori [104] studied the influence of nano structured CVD diamond coatings on dust emission and machinability of A2009 Al alloy/SiC MMC. Dry machining eliminates recycling costs and environmental hazards due to coolant fluids. But, it generates fine inhalable particles that pose a serious health risk. They quantified this factor of dust emission in terms of dust concentration in μg/m⁻³. Khettabi et al [105] have developed an index for dust concentration, called the dust unit, Du. Du is the ratio of dust mass to the mass of chips generated. These are just some of the frontiers of research pertaining to the nuances of turning metal matrix composites.

18. **Conclusions**

Significant research has been dedicated to the machining of metal matrix composites. This paper provides a brief overview of related investigations, focusing on turning mechanisms. Important results were also presented and discussed. Metal matrix composites promise to shape the technological advancements of the 21st century, especially in the auto and aerospace sectors. Nowadays, there is increasing focus on MMCs reinforced with nano particles like carbon nano tubes, graphene, nano-SiC. Other attempts are directed toward investigation of hybrid composites, composed of multiple matrix and/or reinforcement materials.

**Conflicts of interest**

The authors declare no conflicts of interest.

**References**


