



# A critical review on tool wear mechanism and surface integrity aspects of SiCp/Al MMCs during turning: prospects and challenges

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## Abstract

Among several kinds of metal matrix composite materials (MMCs), such as silicon-based reinforced aluminum matrix (SiCp/Al) composites have become the most valuable composite material due to their various applications in industries, sports equipment, electronics, and automotive. Due to the presence of hard ceramic reinforcements, the SiCp/Al composite is considered a difficult-to-cut material, which leads to significant hindrances in machining operations together with increased tool wear, cutting force, and degradation of machined surface quality. The present review is focused on the recent advancements in turning process of metal matrix composites. An attempt is made to comprehensively analyze and identify the influencing factors on the machinability of metal matrix composites (MMCs). The main purpose of this review is to cover the topics such as the recent trends in turning and hybrid turning processes of MMCs, tool wear and its mechanisms, tool selection, the effect of cutting parameters, surface integrity, SiCp/Al composite properties and reinforcement effect, chip formation mechanisms, and different modeling approaches used in particle-reinforced MMCs machining process. Finally, some research gaps and future directions are suggested that could lead to efficient machining of particle-reinforced MMCs.

**Keywords** SiCp/Al metal matrix composites · Turning process, Tool wear, Surface integrity · Surface roughness · Cutting force · FEM

## 1 Introduction

Nowadays worth of metal matrix composite (MMC) material is increasing due to growing demands in industries including the manufacturing of heavy-duty parts, space and locomotive industry, sports, medical equipment, electronics, and manufacturing of space aircraft parts [1–4]. Due to the existence of the reinforced particle phase in MMCs, the tool wear

is serious and it is difficult to obtain high machinability performance during the cutting process of MMCs. Metal matrix composites are the combination of two or more substances; the major alloying elements in composite materials are aluminum, titanium, magnesium, and nickel together with adding SiC and Al<sub>2</sub>O<sub>3</sub> [5, 6]. Of all these alloy elements, the combination of aluminum and SiC is the most employed

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material in various fields of heavy-duty industries due to their cost effectiveness [7–9].

Due to the ductile behavior of aluminum matrix, the addition of brittle SiC particles in such ductile matrix improves the hardness, which is advantageous in forming discontinuous short chips [10, 11]. However, the addition of these hard and brittle reinforced SiC particles (hardness is approximately 3000Hv) leads to the cutting process of the composite material becoming extremely difficult. The metal-based composite material processing is complex which leads to increased tool wear seriously which reduced the tool's durability, causing processing inaccuracy and inferior surface quality. Hence, there is a need to find solutions to such drawbacks associated with metal matrix composites [12, 13].

The machining operations of particle-reinforced MMCs have several complications due to the existence of hard particles such as  $Al_2O_3$  and SiC. Hard particles in the workpiece cause serious issues in metal-cutting machining operations such as related to the surface and dimensional accuracy of the component and wear and tear related to the cutting tools and their short tool life [14]. Machining of MMCs needs significant efforts to sort out the different operational difficulties; this can be performed by selecting suitable tool material and machining parameters for prolonged tool life [15–17].

The turning process of particle-reinforced aluminum-based composite materials has mainly focused on the selection of tool materials and their wear mechanisms, cutting forces, surface integrity of workpieces, chip formation analysis, and selection of machining parameters. However, these kinds of variables are affected by the characteristics of the cutting tool and its materials and machining conditions [18–22].

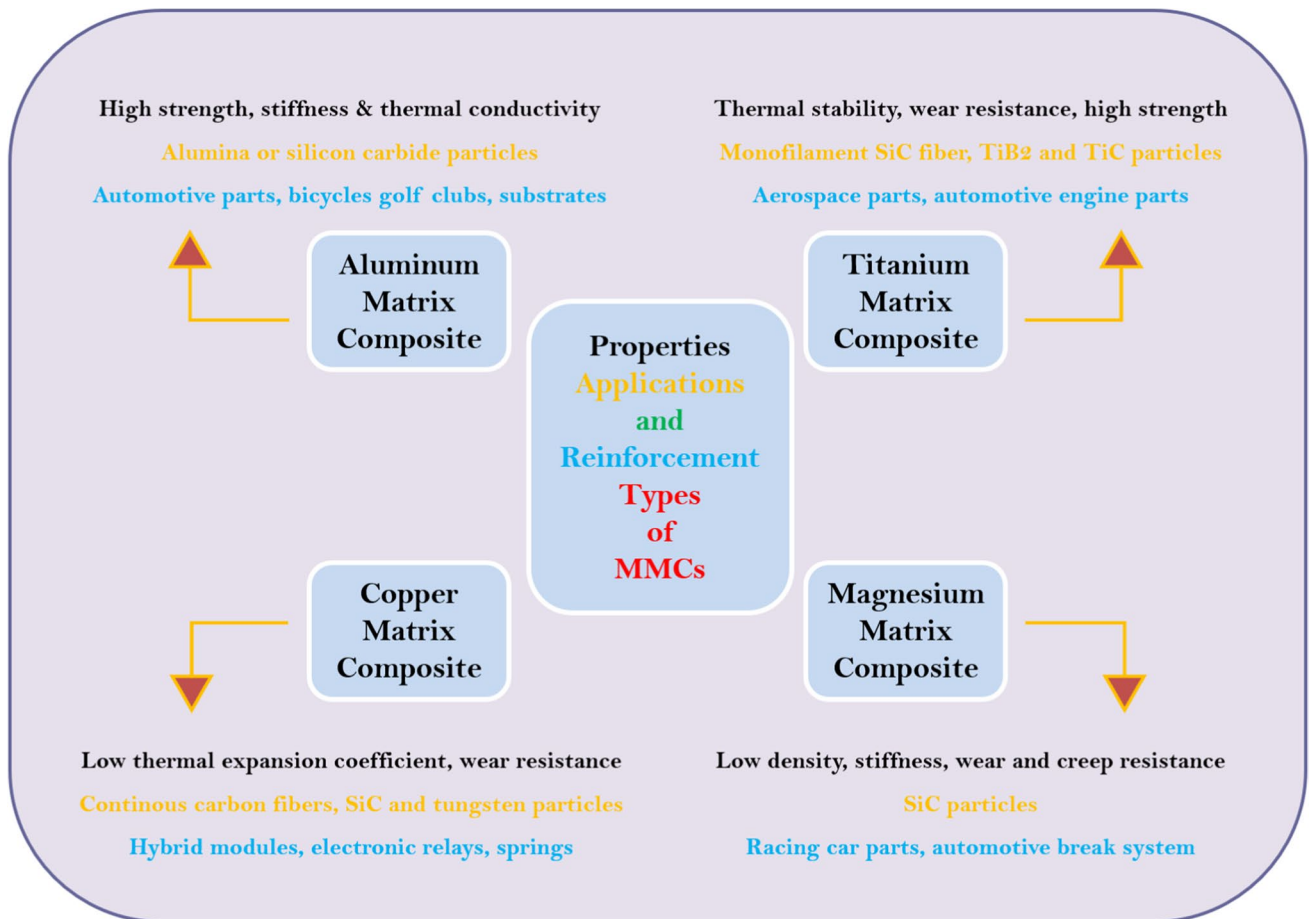
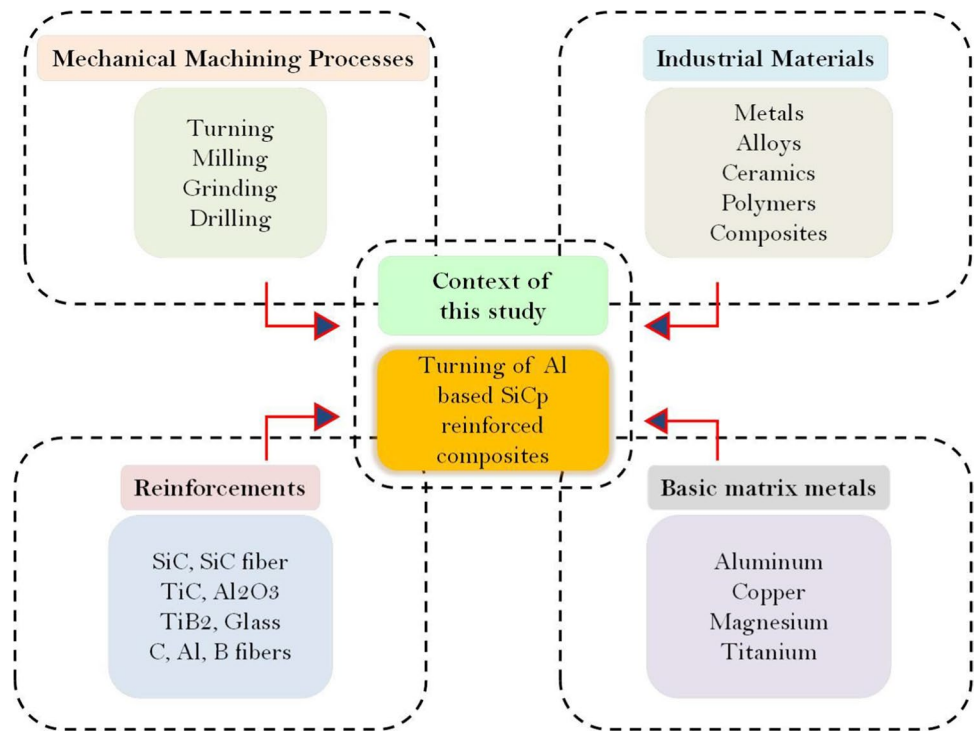
This study focuses on analyzing metal matrix composites of different volume fractions with different tools (such as PCD, PCBN, CVD diamond coating, CBN coating, and uncoated WC) [23–26]. In addition, the optimization and modeling methods of different machining processes were tried to study the processing behavior. The research will contribute to the current literature on machining particle-reinforced metal matrix composites (PMMCs). For the development of smooth operation during the machining of PMMC materials, the choice of appropriate cutting parameters, the formation of chip geometry, tool wear mechanism, surface quality, etc. provide reference theory for machinability and experimental guidance [27, 28]. The cutting performance and wear behavior for different tool materials needed deep research and analysis due to low tool performance in the cutting process [16, 29, 30]. Therefore, it is necessary to study the different cutting mechanisms of composite materials using different optimization methods and technology combined with experimental methods from the literature to thoroughly analyze and understand the cutting process of composite materials [31–35].

The present work reports the latest progress in the turning machining process and machinability characteristics of particle-reinforced metal matrix composites and their applications to fully analyze and achieve the machinability of difficult-to-machine material SiCp/Al composites. The major theme of this review is to consider the different approaches of turning and hybrid turning process of SiCp/Al composites, and to study the tool wear and its mechanism, tool selection, tool life, operation enhancement effects, chip formation mechanism, cutting parameters, surface integrity, and particle enhancement as well as different modeling methods such as FEM and other mathematical modeling techniques in the machining of MMCs. The outline and scope of this work are shown in Fig. 1.

## 2 Strengthening mechanism and influencing factors of SiCp/Al composite properties and reinforcement effect

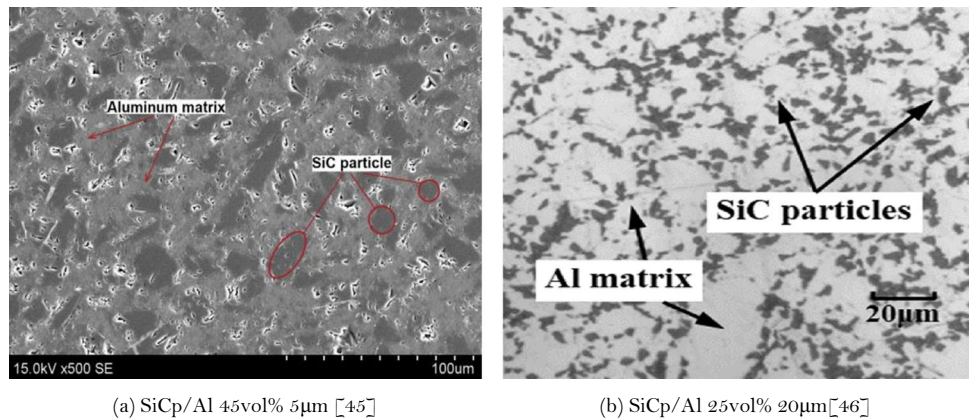
SiC-reinforced particles make the internal structure of SiCp/Al composites very complicated. These composites can attain excellent properties such as high strength-to-weight ratio, high wear and heat resistance, high modulus, and high hardness [36–39]. The existence of reinforced phase SiC particles in the SiCp/Al converts the machining process very hard to process. The interface plays a vital role in stress flow phenomena between the reinforcement and metal matrix. Increasing the thickness of the interface layer provides more strength to the interface layer which is stronger than the matrix which increases the elastic modulus of the interface as comparing the intrinsic elastic modulus of the matrix. Higher interface strength increases the flow stress in the material which can be absorbed by the matrix with a large amount of energy so that high energy can be partially released and the interface becomes strong. On the other hand, with the high strength of the interface layer, the stress gradient also increases, and the uniform distribution becomes weaker, which tends to cause the stress concentration to increase, and the matrix may experience high strain due to elastoplastic deformation [40, 41]. The interfacial bonding strength is the key to the strengthening effect of the composite material; it can maximize the load-bearing capacity due to the addition of reinforcements, which leads to the enhancement of the respective properties of the resulting composites [42, 43]. The existence of the reinforcing particles during the synthesis such as powder metallurgy of composites greatly affects the processing performance of metal matrix composites (Fig. 2). Figures 3 and 4 show the SiCp/Al composite workpieces SiCp/Al 45vol% with 10 microns particle size and a reinforcement volume fraction of 65% prepared by the vacuum infiltration method.

**Fig. 1** The outline and scope of current review



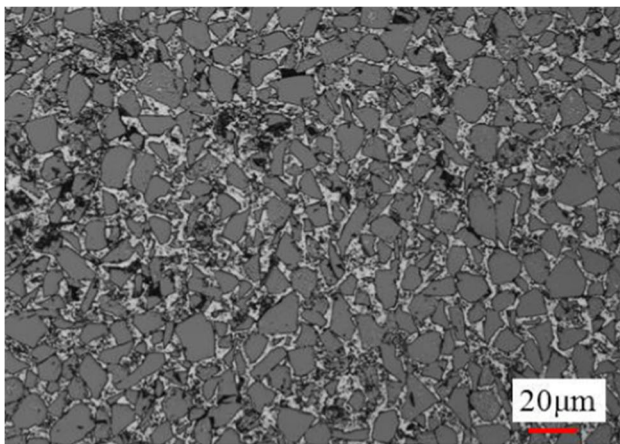
**Fig. 2** Application along with physical and mechanical properties of MMCs and their various reinforcements [44]

**Fig. 3** SiCp/Al 45vol% 10 micron. (a) SiCp/Al 45vol% 5  $\mu\text{m}$  [45], (b) SiCp/Al 25vol% 20  $\mu\text{m}$  [46]



(a) SiCp/Al 45vol% 5 $\mu\text{m}$  [45]

(b) SiCp/Al 25vol% 20 $\mu\text{m}$  [46]



**Fig. 4** The workpiece is SiCp/Al composite with 65% reinforcement volume fraction fabricated by the vacuum infiltration method, and the average size of particles is 10  $\mu\text{m}$  [47]

### 3 Applications of MMCs

Metal matrix composites (MMCs) are used in many applications particularly in automobile industries [48, 49]. Automobile industries are giving more preference to MMC material over steel parts due to their light weight as the density of these composites is about one-third of steel alloys. PMMCs possess widespread applications in heavy industries due to their operative ability at high elevated temperatures which fulfill the designers' requirements and conceptions as depicted in Fig. 2 [44, 50–52]. MMC composite materials have excellent properties which include high wear resistance, fatigue resistance, better dimensional stability improved thermal conductivity, electrical conductivity, high specific modulus, and strength. These qualities are providing an ability to withstand the demand for heavy-duty parts in modern industries [48, 53, 54].

MMC composite materials consist of numerous ranges of materials, which adopt various ranges of fabrication

such as low casting to complex reinforced alloys and metals. The method and technique of fabrication define the particulate applications with their most favorable mechanical and physical properties [55].

MMCs find numerous applications in aerospace, defense, sports, and transport industries, electronic packaging, and structural parts, advanced weapon systems, optical precision instruments, textile industries, and satellite parts. However, due to the inhomogeneous distribution of particles in the matrix, the material itself has high brittleness and low toughness [44, 56].

SiCp/Al composites are widely utilized in industrialized countries and are found one of the most advanced composite materials with wide practical value. In the USA, DWA Composites and Lockheed Martin used the SiCp-reinforced aluminum-based (6092Al) composite prepared by powder metallurgy to the rib cage of the F216 fighter, replacing the 2214 aluminum alloy. The skin structure increases its stiffness by 50%, and the service life has increased from hundreds of hours to ~8000 h, reaching the full life cycle of the aircraft design, which is equivalent to a 17-fold increase [53, 57].

SiCp/Al composites are applied in the Russian aerospace sector to develop satellite inertial navigation platforms and support members. Advanced countries such as the USA and European countries are the first to achieve large-scale applications of SiCp/Al in developing the car piston, which improves wear resistance and reduces the weight of parts as well as economical to adopt [58]. In Japan, metal-based composite reinforcement manufacturing processes possess several varieties of fabrication processes at low prices together with the support of government enterprises. Composite material research in Japan recently gained great attention which surpassed the USA in the last 20 years [59].

### 4 Turning of particle-reinforced MMC

Turning is the most common metal-cutting process in the industry, which is mainly used to give the required shape and dimension to the workpiece in metal-cutting



technology [60]. Among various machining operations used for semi-finished and finished products, the turning operation is one of the most commonly used operations which is used for machining hard-to-cut workpieces including metal matrix composites [61, 62]. The turning process is used to achieve the dimensional requirements of the respective operated part through the material removal method which involves the rotation of workpieces fed against the cutting tool [63]. Several researchers studied different aspects of the turning operation and reported important findings on the effect of cutting parameters, tool geometry, and tool materials to achieve desired surface qualities during machining PMMC composite [61–63].

The turning machining process can be defined as a machining process, which is used to remove the required material by rotating the parts fed against the tool to manufacture the required component [64, 65]. The literature shows that the factors that affect turning in the metal-cutting process are primarily influenced by the properties and type of material chosen for machining [66–68]. For example, Bai et al. [69] have performed a study on the effect of the material structure and vol% on the tool wear during the cutting of SiCp/Al. The results demonstrated that the most influencing wear mechanism found is the abrasive wear mechanism during the silicon-based aluminum metal matrix cutting process, which is the main failure mechanism for conventional cutting tools, while the main damage form of high hardness tools is a brittle fracture. However, the particle size and volume fraction have an important influence on tool wear. Davim [70] who conducted research on tool wear during A356/SiC/20p turning showed that PCD tools have good cutting performance when cutting composite materials. Under medium cutting conditions, PCD tools showed good surface finish, which reduce the machinability cost and complexities. Dabade and Jadhav [71] conducted an experimental study on the machining of Al-5052/TiC/SiC composites using a CNC lathe. It is reported in a study that the higher cutting depth and the feed rate are the major factors influencing the cutting force, which led to the rise in cutting temperature in machining operations. Higher cutting temperature is an important factor for surface integrity, which can deteriorate the workpiece surface. Das et al. [72, 73] studied the machinability of aluminum-based SiCp composite material in turning operation. They executed the cutting process with a different approach, which was performed to analyze and understand the effect of the selected cutting parameters on the wear mechanism of cutting tools as well as the variation in the cutting forces during the cutting process.

Through the development of the test bench, the monitoring of the tool status during the turning process was studied [74]. In this experiment, a variety of choices of sensors were employed such as a laser Doppler vibro-meter and

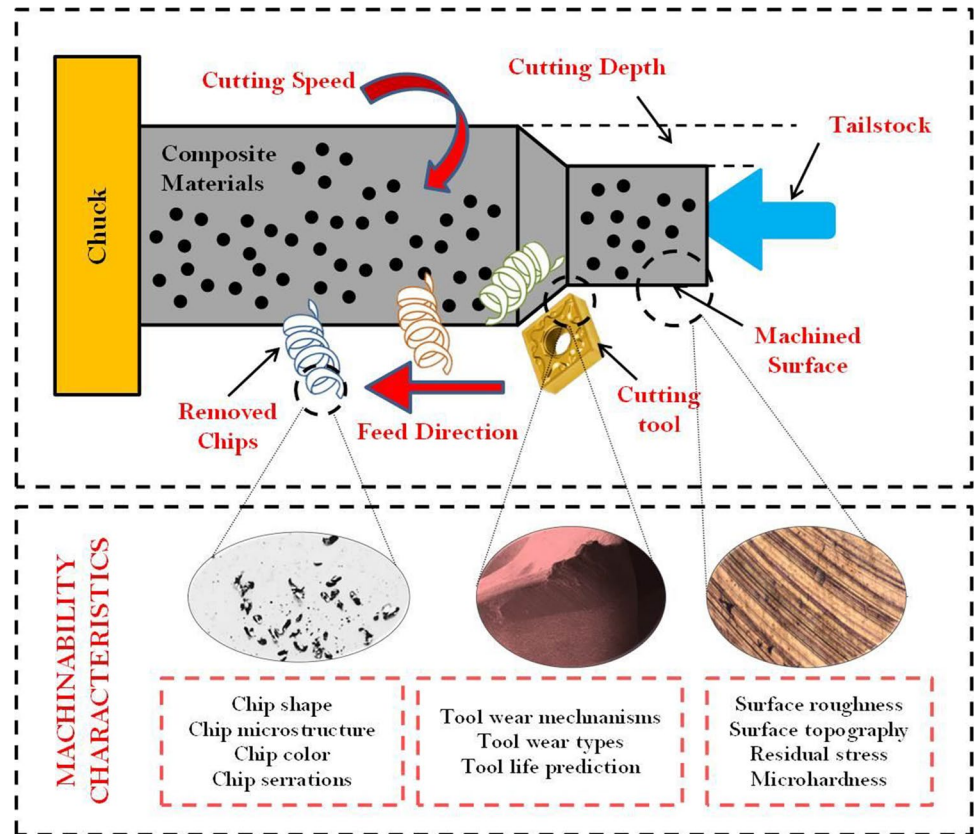
infrared thermal imager, which were used to monitor the performance of coated carbide tools with uncoated carbide tools. There may be a correlation between even and uneven forms of tool wear. The cutting parameters such as the cutting speed and moderate feed rate have a very low effect on the cutting temperature fluctuation. Furthermore, the performance of the coated carbide blades with uncoated carbide blades was also investigated at a higher depth of cut during the machining process of SiC-based reinforced ZA43 alloy, although the performance of coated carbide blades was found greater compared to uncoated carbide [52]. The force or torque signal is the number used during processing. In the manufacturing process, as the core purpose of monitoring the processing process, many sensors are used in the monitoring system, such as piezoelectric sensors, AC induction sensors, and strain gauges [75–77].

In the turning process, machinability parameters such as cutting speed, rebar weight fraction, and grain size are the main factors affecting tool wear. It has been reported that coated tools prevent tool wear better than uncoated tools. However, the uncoated tools have been reported to show better results in terms of surface finish, especially at lower cutting speeds [29]. The performance of the TiN-coated cutting tool was studied for the turning operation of SiCp/Al and the comprehensive analysis was performed by Kannan et al. [78]; the finding from the study shows that the TiN-coated cutting tools' performance increased significantly compared to the uncoated cutting tools. Swain et al. [79] also found that compared with uncoated tools, tool wear is reduced when using coated tools, and the integrity of the workpiece surface shows excellent characteristics at a relatively low amount of feed speeds and higher cutting speeds. In the context of this review paper, the effects of cutting speed, feed rate, and cutting depth are considered to monitor tool wear mechanisms, surface quality issues, and chip morphology. Figure 5 presents the approach utilized in this study which is twofold: (i) the effect of important factors on the machinability of SiCp/Al composites, (ii) the study of machining characteristics.

#### 4.1 Hybrid turning of PMMC

The hybrid turning process of metal matrix composite possesses its application in the machinability of hard-to-cut materials, as the toughness and hardness of MMCs are the major factors, which limit its usage in a wide range of manufacturing and production processes [69, 80, 81]. The tool wear and fracture mechanisms are considered important to understand for increasing and improving tool life during machinability operations performed for the material removal process in MMCs. Significant research work can be found focusing on determining the optimal parameters and using the appropriate tools for machining these composites. Several

**Fig. 5** Outline of the review paper including factors affecting the machinability of composites and primary machining characteristics



authors have proposed different solutions to tackle problems associated with the machinability of MMCs; some compared the traditional machining processes and hybrid processes, while others determined the machinability in terms of tool wear and surface integrity [82, 83]. Liu et al. [84] performed a hybrid turning process of MMC machining using an ultrasonic turning process and studied the frequency of the tool wear mechanism which vibrates with a higher frequency along a path which is a relatively lower vibration frequency. The research study depicted that among various cutting parameters, the cutting speed effect was found relatively low in the cutting process. Przystacki [85] performed a hybrid turning process of MMCs using an assisted turning process with laser heating. This hybrid approach where the machining of MMCs was carried out together with laser heating led to benefits such as ease of machining due to improved ductility of the workpiece. Comparing the cutting tool life, the wear of the cutting tool was found reduced using this laser-assisted machining process thereby leading to a longer cutting tool life as compared to the traditional turning using the same cutting parameter. It is important to note that machining performance when compared in terms of the number of cutting tools used to cut various kinds of materials shows that traditional hard tool turning has reduced wear as compared to hybrid machining. Hence, the correct tool selection cannot be eliminated while deciding on the use of hybrid machining

operations. Furthermore, the experimental findings suggest an optimal temperature that can lead to increased tool life for the laser-assisted turning of difficult-to-cut materials. It is reported that this technology may prove to be able to solve some of the problems faced by metal matrix composite processing [86, 87].

#### 4.2 Effect of cutting speed on machining PMMC

During the processing of silicon-based aluminum metal matrix composites, researchers do not observe the influence of cutting speed possesses some important influence on machining force phenomena in the cutting process. However, in some other cases of the metal-cutting process, the study of several researchers suggested a higher amount of cutting possesses a positive influence on the surface quality of the workpiece with other moderate parameters, which shows surface roughness value has a slight downward trend. The higher cutting speed used causes the increment of temperature in cutting zones of the machining process; as the temperature in the cutting operation increases, it can cause a reduction in cutting forces as well. Depth of cut has also been seen as a major parameter in the metal-cutting process which holds the increasing influence on the machining forces; while the cutting speed is the smallest influencing factor, the combination of higher feed along with the spindle

velocity increments increases the cutting force in some cases as metal-cutting processes [88].

The higher reinforcement ratio of composite materials at a higher amount of cutting speed reduces the cutting force which is associated with the thermal softening phenomena of workpiece in the metal-cutting zone. The reduction in cutting force is a determination to have a higher amount of cutting speed, which is a better correspondence observed by Galab et al. [89] based on different theories; Pramanik et al. [90] established three cutting force models for cutting forces, such as plowing force, chip forming force, and particle breaking force. The chip formation force was analyzed through the Griffith fracture theory and the plastic slip line field theory for plow deformation, and particle fracture was analyzed by the Merchant analysis. The experimental findings depicted that cutting forces produced due to the breakage of particles are higher than the cutting force produces due to chip formation in the metal-cutting process. The results show that the force due to the cutting and particle breakage is greater than the force of the chip formation. It is also seen great agreement between experimental and predictive powers. Furthermore, the study also depicted the effects of PCD tools in the turning process of aluminum-based composites (A359/SiC/20p) were thoroughly analyzed machinability characteristics during the metal-cutting process. An experimental study suggests the defects in the PCD tool found subsequently more like an increment with feed rate and cutting forces during the monitoring of the machining process [91]. The authors also observed a reduction in cutting force when turning SiC/Al-MMC at a higher amount of cutting speeds [92]. It is also seen that the effect of SiCp/Al 20vol, on the cutting force graphs, decreases with an increase in cutting speed with slightly higher cutting depth during the machining process because of the thermal softening of the parts [89].

### 4.3 Effect of cutting depth on machining PMMC

The depth of cut in the turning process of metal matrix composite materials plays an important role in the smooth machining process; while selecting the depth of cut value in the turning process, there is a need to consider the cutting tool characteristics and the surface finish of the workpiece. In the turning process of composite materials, SiCp/Al used to play a quite remarkable role in cutting operations observed to be fluctuated with increasing the depth of cut as the inclination angle of the cutting edge of the tool increases, and the surface roughness values increase to the machined component as micro-cracks are found as an increasing trend. Furthermore, the applicable increase of depth of cut and feed rate together gives the surface roughness value of the workpiece a slightly upward trend [88].

Chambers studied the processing of 15 vol% of SiCp in A356 aluminum-based alloy for thoroughly analyzing the influence of cutting depth for machining, it is depicted in the study that tool life does not stimulate by the depth of cut severally. However, the study pronounced that the life of cutting has a slightly decreasing trend at a rising amount of depth of cut. While it possesses higher consequences for wear behavior of tools is not much clear and significant as compared to other cutting parameters including SiCp/Al 15 vol% with uncoated tungsten carbide tools. In addition, an increase in the depth of cut increases the cutting forces in the process when operating composite materials [93].

### 4.4 Effect of feed rate on machining PMMC

Feed rate influences the various factors while performing the turning operation of the metal matrix composite materials; the researchers observed that increasing the feed rate has negative influences on the turning operation from the perspective of the tool wear mechanism. While performing turning on SiCp/Al, the trend of cutting force is also seen higher with increasing feed rate [92]. Experimental operations of the different researchers have depicted that due to lower feed rates, the amount of tool wear reduces because the workpiece surface reduces the physical contact between the tool and the abrasive SiCp at a constant volume of material removal rate [89]. Zhou and Liu studied the properties of CVD diamond tool turning metal matrix composites (SiCp/Al) with different parameters, including ( $f=0.05\sim0.3$  mm/rev), ( $v_c=1\sim6$  m/s), and ( $a_p=1\sim2$  mm) with coolant. The test results have depicted a rise in the cutting parameters producing dominant tool wear, and the coating fails due to the increase in stress levels. The high temperature causes thermal expansion between the tool base and the coating, which ultimately leads to coating failure [24]. El-Gallab and Skald [94] mentioned the effect of a higher feed rate which increases the machining forces; resulting in pits created around SiC particles which form the micro-cracks. A higher amount of feed rate and rise in cutting parameter produces dominant tool wear, some amount decreasing perspective in the tool life. While combining increments of both factors such as feed rate and cutting speed in the turning operation of composite materials puts more pressure on surface quality and higher wear rate of a cutting tool. It is seen that the higher amount of feed rate increases the temperature in the cutting zone and thus combining the effect of the aluminum matrix and the SiC particles; when cutting speed and amount of feed rate are increased by two times, the flank wear amount is doubled compared with the rake face wear amount [95]. Table 1 shows the turning of metal matrix composites (SiCp/Al) with different parameters, along with results and type of MMCs. Also, Fig. 6 represents the dramatic impacts of fundamental cutting parameters on

machinability characteristics of Al-based SiCp-reinforced composite materials found in the open literature.

## 5 Selection of appropriate cutting tool materials for turning PMMC

The turning process of the metal matrix composite materials is majorly dependent on the selection of the cutting tool such as its mechanical and chemical properties to machine the metal-cutting process. In summary, it is particularly important to choose the right cutting tool for the turning process of MMCs. Normally, the cutting tool materials are used to perform the machining of the metal matrix composites. These cutting tool materials chosen for such operation are tungsten carbide (WC), polycrystalline diamond

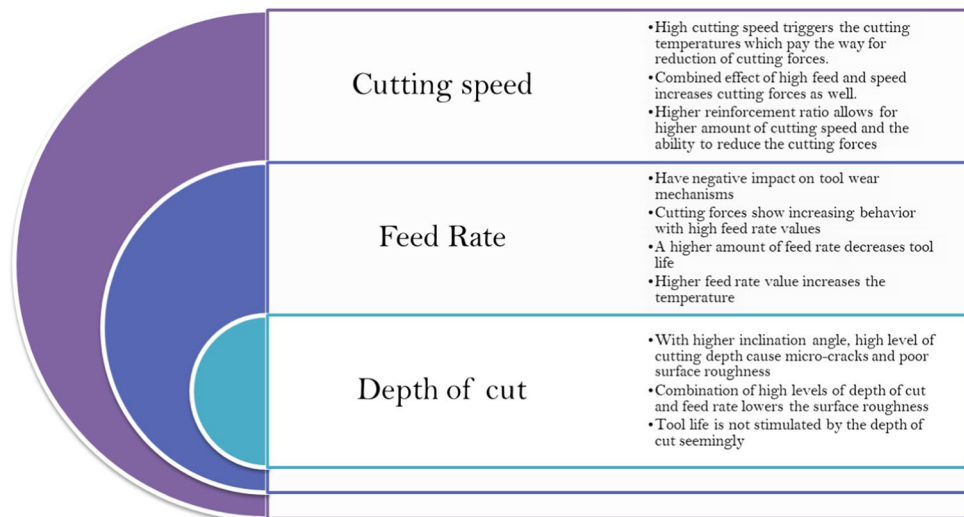
PCD, diamond-coated cemented carbide (DCWC), and cubic boron nitride (CBN), which are preferred [109–111]. Furthermore, the coating layers with hard materials such as those coated with a diamond layer on cutting tools are also preferred for cutting operation [112]. Composite materials are known for difficult to cut materials in cutting operations; because of this, the material used for preparing the cutting tool must be hard enough to perform the turning operation to remove the required materials for the required application. The tool and its mechanism wear of cutting are the key factors that decide the life of the tool. It is a fact that hard materials are used for coatings to perform the turning processes of the hard-to-cut kind of MMC materials, which is believed to cause severe tool wear [113]. To verify the proper machining applicability of cutting tool material performance in the turning operation of MMCs, several

**Table 1** Turning of metal matrix composites (SiCp/Al) with different parameters

SiCp/Al <sub>2</sub> O <sub>3</sub> /Ti MMC fraction	Matrix	Cutting speed	Feed rate	Depth of cut	Cutting tool	Remarks
SiCp 15% (volume fraction)	Al 7075	90 m/min and nose radius 0.42 mm	0.15 mm/r	0.20 mm	Carbide insert [96]	Tool life measuring
SiCp 10% (weight fraction)	Al 7075	180–220 m/min	0.1–0.3 mm/r	0.5–1.5 mm	Carbide insert [97]	Surface roughness optimization
SiCp (5%) MMC New 3	Al	(rpm) 500, 775, 1200	0.11, 0.22, 0.44 mm/r	0.5, 0.75, 1 mm	PCD cutting tool [98]	Surface finish and MRR
SiCp and 45% (weight fraction)	Al matrix	6.283 to 25.133 m/min	Feed rate 0.01 to 0.025 mm/r	0.20 mm, 1.5 mm	Carbide insert [99]	Cutting force analysis and measuring during machining
SiCp 5% (weight fraction)	Al 356	Spindle speed of 1200 r/min	0.25 mm/r	1.0 mm	PCD [100]	Surface roughness of 2.96 $\mu$ m, obtained
SiCp 50 and 45% (volume fraction)	Al matrix	6.283 to 25.133 m/min	0.01 to 0.025 mm/r	0.20 mm, 1.5 mm	Carbide insert [101]	Modeling and optimization of cutting forces and comparisons
SiCp and 45% (weight fraction)	Al matrix	6.283 to 25.133 m/min	0.01 to 0.025 mm/r	0.20 mm, 1.5 mm	Carbide insert [102]	Tool life and surface roughness measuring and optimization using PSO
SiCp 10% (weight fraction)	Al 7075	(170 m/min)	(0.05 mm/r)		PCD [103]	Excellent surface finish of workpiece
SiCp and 45% (weight fraction)	Al matrix	6.283 to 25.133 m/min	0.01 to 0.025 mm/r	0.20 mm, 1.5 mm	Carbide insert [104]	Tool life and surface roughness optimization using RSM
SiCp 50 (volume fraction)	Al matrix	40, 60, 80, 100 m/min	0.05 to 0.1 and 0.2 mm/r	2 mm	PCD insert [105]	Modeling and optimization of cutting forces
SiCp 10% (weight fraction)	Al 7075	60–100 m/min	Of 0.4–0.8 mm/r	0.08–0.16 mm	HSS [106]	Cutting speed does not affect the cutting forces
Al <sub>2</sub> O <sub>3</sub> 10% and 20% (volume fraction) 43	AA6061	30–60 m/min		3 mm	[107]	Chip formation uncut chip thickness
7075 MMC, 6061	Al matrix	60 m/min	A feed rate of 0.1 mm/rev	3 mm	[108]	Surface integrity micro-cracks and voids



**Fig. 6** Some important findings about the effects of cutting speed, feed rate, and depth of cut on composite machining from the literature



researchers have performed research work from such a perspective. The reason for choosing the PCD tool over other cutting tools is due to its physical and chemical properties because PCD is strong enough to complete the machining and hard enough to improve and sustain wear resistance in the turning process of MMC [114]. While several researchers promoted the PCD tools while finding suitable results in their respective research studies and consider the PCD tools as a recognizable and optimal option for metal matrix composite turning. Therefore, several researchers have started a new area of study for finding alternative tools, which provide more economical machining and a choice to metal-cutting operation in the turning process of the metal matrix composites [115]. Various tool materials are used for turning, e.g., cemented carbide, ceramics, cubic boron nitride, and PCD diamond. Due to the high hardness of the reinforcing particles in the particle-reinforced aluminum-based composite material, the selection of tool materials is very difficult [116]. PCD diamond tools are the first choice, and ceramic tools are much better than carbide tools, which have good wear resistance. When using cemented carbide tools for turning, metal matrix composites require suitable machining parameters; such combination includes substantially lower cutting speeds along with slightly higher feed rates to increase the turning life of the cutting tool [117], as compared with the performance of electrode coating.

For understanding the machining performance and life of cemented carbide tools in the machining of composite, literature on the metal matrix cutting process reveals that a higher feed rate and depth of cutting during the cutting process increase the wear and tear process of cemented carbide tool as well as reduce the quality of surface finish of the part [118, 119]. The surface integrity of machined components significantly depends upon the chemical and mechanical properties of the cutting tool and type of workpiece

composite, as well as the particle size and reinforcement process in the workpiece composites. Manna and Bhattacharya [120] processed the machining process under different cutting conditions to maintain a stable built-up edge (BUE) to protect the tool and to reduce surface roughness and sub-surface damage [121].

## 6 Tool wear mechanisms

In the turning process of the MMC materials, tool wear, its mechanism, and related lifetime play a major role in the machinability of hard-to-machine composite material. At the cutting interface between the part and the tool, material removal generates chip formation inducing plastic deformation and hence high temperatures. The latter are contributed by friction between tool and part. These affect the performance of the cutting tool including wear and tear [122, 123].

Tool wear is the most usual phenomenon in all machining processes during the material removal process. In the case of the material removal method of MMCs, tool wear has different mechanisms and interactions because of the presence of hard particles such as SiC and Al<sub>2</sub>O<sub>3</sub> in composite materials. While analyzing and understanding the different mechanisms of tool wear, the effect of cutting parameters and the resulting wear mechanisms on the cutting tool are explained. The factors that gradually wear cutting tools are usually abrasive wear, adhesive wear; diffusion wear, oxidative wear, and tool cutting delamination wear [124, 125].

### 6.1 Abrasive wear

In the cutting process of metal matrix composite, the abrasive wear mechanism of any cutting tool material is a very most important factor [111]. The abrasive wear mechanism

has been found to be the most important wear mechanism during the machining of SiCp/Al-MMCs [111]. It is a typical kind of wear mechanism for the operation of MMCs, which forms as the result of the presence of hard particles, which directly affects the cutting edge in the material removal process. In addition, due to their relative motion, these particles maximize the thermal and mechanical load on the tool [126]. An abrasive wear mechanism can also be defined as such kind of particular wear mechanism which happens due to the shape, volume fraction, and distribution of reinforcement in composite materials are the leading aspects affecting the degree of tool wear [127]. The SEM images of the cutting tool abrasive wear mechanism during machining SiCp/Al 15%SiC are shown in Fig. 7.

## 6.2 Flank wear

Flank wear in the cutting tool is a usual phenomenon and the most important kind of wear mechanism in the material removal process of MMCs. Flank wear is the outcome of thermal and mechanical loads that put pressure to deform the cutting edge of the tool. The fluctuation of cutting forces in the metal-cutting process also possesses a significant impact on tool flank wear [128]. This phenomenon can also occur when the hardness of abrasive particles in the machined workpiece collides with the tool and increases the heat at the cutting edge. Tool flank surface wear measurement method is related to its wear land, which tends to increase during processing. When the metal-based composite is processed, the choice of cutting parameters can also affect the flank wear [129]. As an example, during the machining of a high-volume silicon-based aluminum alloy, the flank wear at  $v_c = 50$  m/min and  $a_p = 0.2$  mm at three tool paths were analyzed to find the cutting tool wear as given in Fig. 8, which illustrates flank wear and SiCp adhesion to the tool [130].

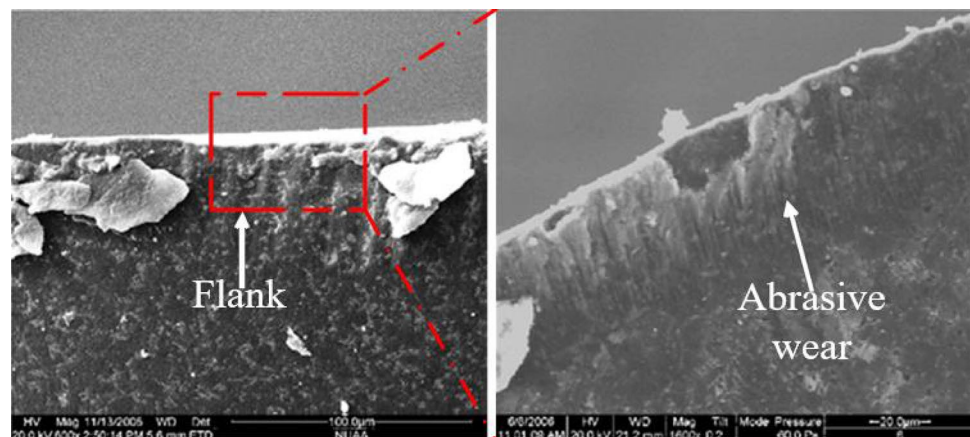
## 6.3 Built-up edge BUE

In the machining of MMCs, the cutting tool possesses some scraped chip grains which stick to the rack of the tool which leads to the formation of BUE. Typically, the key reason for such kind of phenomenon is because of the fluctuation in the cutting speed, which results in increased welding phenomena due to load on the tool-chip interface and, hence, forms the built-up edge (BUE) [131]. It is also believed that a small amount of BUE provides protection to the cutting edge of the tool and generally extends the tool life, which is also called wear protection [132]. Furthermore, it is also a known fact in various kinds of literature that the BUE worsens the surface quality of the finished workpiece if its amount becomes significant. The cBN tool cutting the Al-Si alloy during the cutting process formed the built-up edge-to-rake flaking and edge chipping mechanism as shown in Fig. 9 (a) and seizure of the chips on the tool and built-up edge given in microscope image and SEM images of rake face of the cutting tool shown in Fig. 9 (b) at enlarge view, which show wear land and BUE formation clearly [133].

## 6.4 Adhesive wear

Adhesive wear is a sort of wear that refers to the occurrence of bonding when the cutting tool comes into contact with the machining component during the material removal process [134]. It is also known as a so-called phenomenon of cold welding, in which the plastic deformation occurs under the action of sufficiently high pressure and temperature on the actual contact area of the friction surface, which is the result of the absorption between the fresh surface atoms formed by the plastic deformation of the friction surface [135]. The asperities of the two friction surfaces are caused by relative movement,

**Fig. 7** SEM images of the PCD tool mechanism of Abrasive wear at 15 vol.% SiCp/2009Al composite for 3.6 km [111]. (a) Abrasive wear mechanism at flank. (b) Abrasive wear mechanism at the rake face



(a) Abrasive wear mechanism at flank;

(b) Abrasive wear mechanism at the rake face

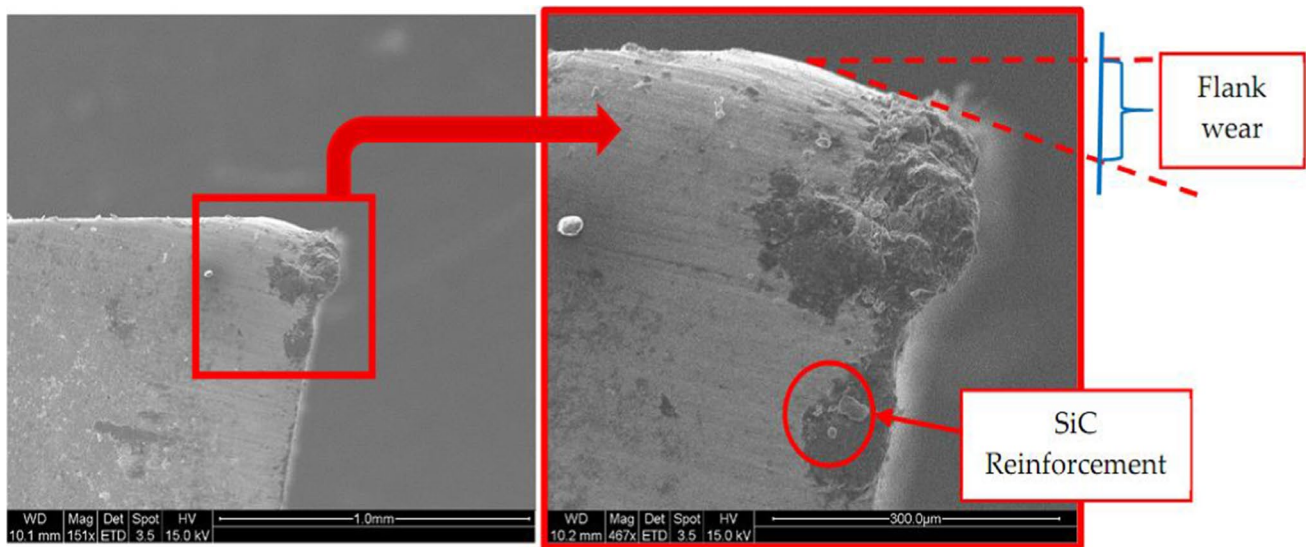


Fig. 8 Flank wear and adhesion of SiC particles [130]

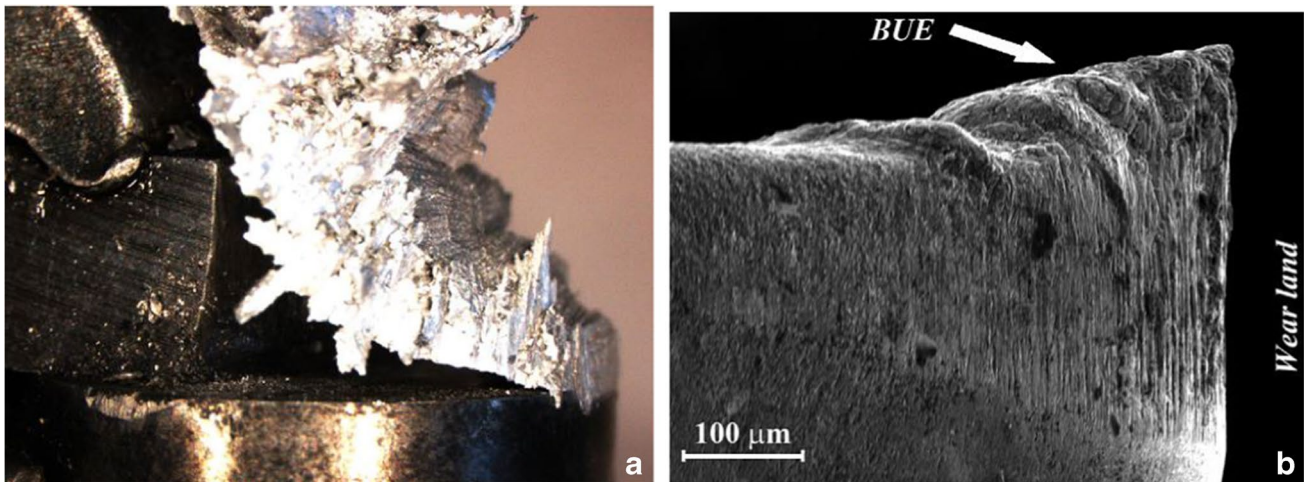


Fig. 9 a SEM micrographs of BUE, b sticky chip grains on rake face [133]

and the particles are sheared or pulled to be taken away by the other side to cause adhesive wear [136, 137]. During machining at different cutting parameters, the cutting tool exhibits different wear patterns [138]. Figure 7 gives several tool wear mechanisms; however, Fig. 10 (b), (c), and (d) show a different wear pattern for the PVD-coated carbide tools, but the adhesive wear mechanism can also be seen in the cutting tool wear patterns [139].

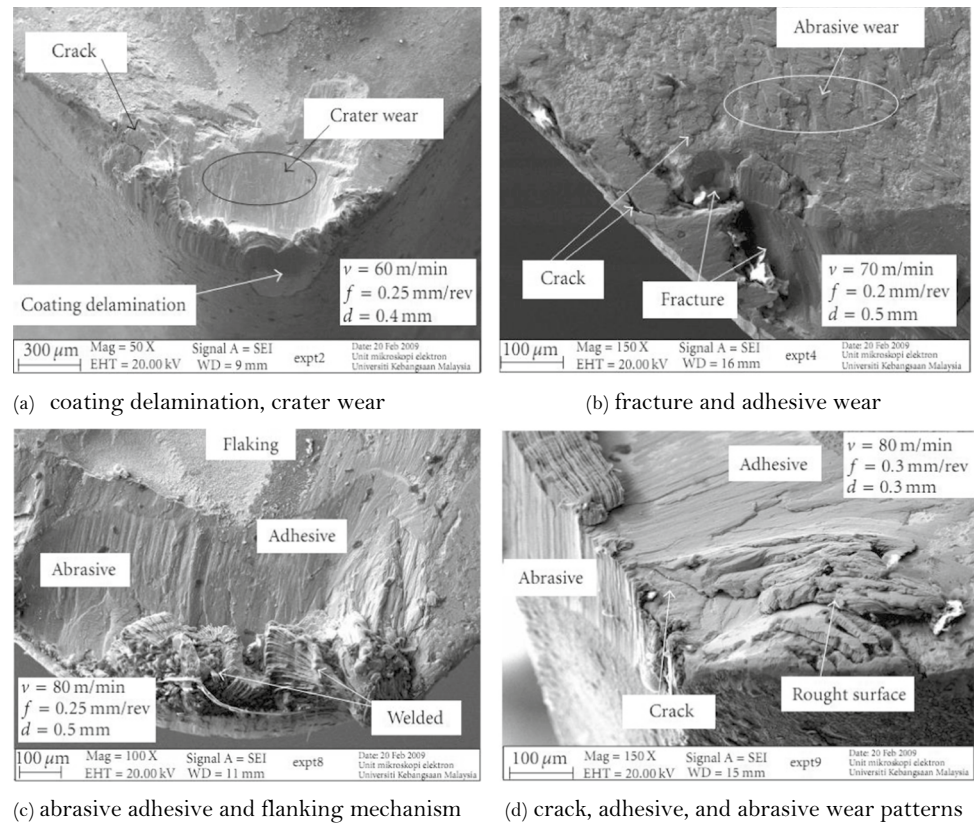
### 6.5 Diffusion wear

The crater wear of the rake face most often occurs in the cutting process during of plastic deformation of materials, which is located near the main cutting edge of the rake face, and the crater wear is mainly caused by the chemical

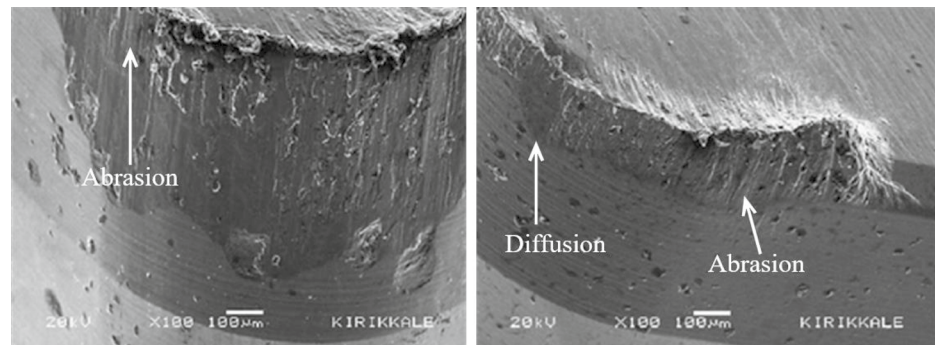
interaction between the rake face of the tool and the high-temperature chip. Specifically, the crater wear is caused by the diffusion and dissolution of the tool material into the chip under high temperature and high pressure, resulting in a decrease in the strength of the tool, accompanied by a debonding between the tool and the chip material and abrasive wear. The crater wear makes the thickness of the wedge thinner and the tool strength decreases [140]. In the turning process, the wear mechanism of cBN and ceramics cutting tools shows the phenomenon of abrasion and diffusion wear mechanisms [141]. The abrasion and diffusion wear mechanisms of the cBN tool formed in the turning process of silicon-based aluminum alloy are shown in Fig. 11, depicting the SEM of wear morphology of the cutting tool.



**Fig. 10** Tool wear mechanism [139]. (a) Coating delamination, crater wear, (b) Fracture and adhesive wear, (c) Abrasive adhesive and flanking mechanism, (d) Crack, adhesive, and abrasive wear patterns



**Fig. 11** Abrasion and diffusion wear mechanism of cutting tool [141]. (a) CBN tool wear for Al-SiC/110 at 100 m/min, (b) CBN tool wear for Al-SiC/45 at 100 m/min



## 6.6 Tool chipping

When the tool is weakened, or the cutting force exceeds the breaking strength of the tool material, it is easy to cause chipping. After large chipping, the tool loses its cutting ability and cannot be used anymore [142]. Occasionally, such breakage occurs when cutting particle-reinforced aluminum matrix composites. Flank wear is the most common when cutting particle-reinforced aluminum matrix composites, followed by cracks, micro-cracking, crater wear, exfoliation, and tool chipping [143]. During turning to the machine of SiCp/Al 15%SiC, using the SCD cutting tool, the chipping

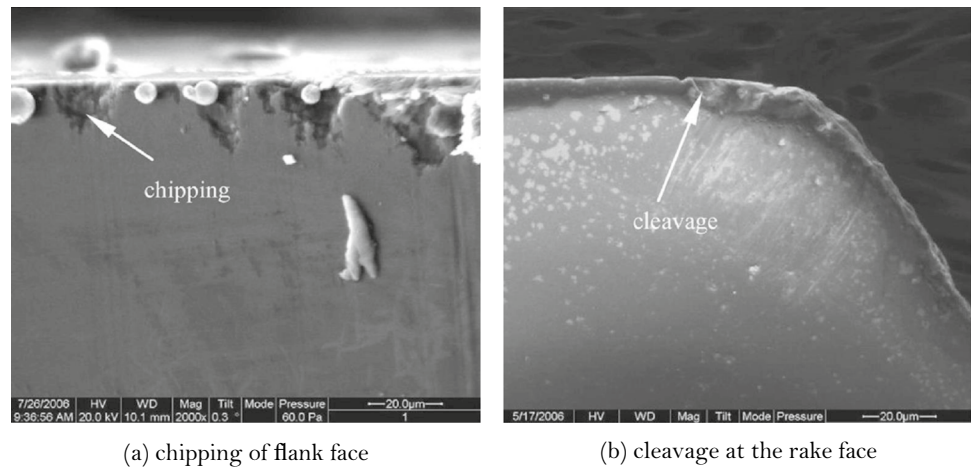
mechanism of the tool is reported as given in Fig. 12 (a) chipping of flank face and (b) cleavage on the rake face at 110 magnification [144].

## 6.7 Delamination wear

When the cutting tool is cutting the material, the micro-morphology of the chip exfoliation phenomena occurs and is called delamination wear. During the cutting operation of difficult-to-cut materials such as particle-reinforced aluminum matrix composite material, the delamination phenomena usually occur on the front and back flank surfaces of



**Fig. 12** SCD cutting tool wear mechanisms [144]. (a) Chipping of flank face, (b) Cleavage at the rake face



(a) chipping of flank face

(b) cleavage at the rake face

the tool. The former flank is the major one, and some small voids appear on the cutting edge [94]. The delamination type of wear is only special to the coated tools and indicates the detachment of coated layer from the substrate, as depicted in Fig. 10 (a), the delamination wear patterns of the cutting tool coating [138]. The reason for this is that the cutting tool has been completely exfoliated by thermal stress fatigue or contact fatigue of the workpiece-contact area, and if the peeling is small, it is considered a worn cutting tool. However, in many cases, since the fatigue crack source has a certain depth from the surface of the tool, the spalling block formed after the crack is expanded is often larger than the wear limit of the tool. Once the peeling occurs, the tool can be ineffective and form peeling damage [143]. Figure 10 shows tool wear mechanisms, which provide the different patterns of tool wear. However, Fig. 10 (a) shows the delamination wear patterns of the cutting tool coating [139].

## 6.8 Oxidation wear

Oxidation wear is a kind of wear which occurs due to the high temperature during the cutting process, and due to the presence of air which produces oxidation phenomena such a wear mechanism is called oxidation wear. The high temperature in the cutting zone reacts with air and creates a soft oxide layer comprising  $WO_3$ ,  $CO_3$ ,  $O_4$ , and  $TiO_2$ . This kind of wear mechanism leads to the loss of material as a result of oxidation.

Temperature and cutting speed on the actual contact area of the friction surface are crucial. The magnitude of these variables decides the wear mechanism type, which can be changed from one type to another with slight differences [94, 140]. Figure 13 shows the wear mechanism for cemented carbide cutting tool used for dry cutting of Ti composites. As can be noted, the oxidation wear characteristics are displayed in Fig. 13 (a) which shows the oxide layer on the nose of the rack face during  $v_c = 100$  to 150 m/min. The generation of

an oxide layer on the nose of the rack face is called oxidation wear. The other wear phenomena of cemented carbide tools such as flank wear edge chipping, rake face, and nose wear are also displayed below in Fig. 13 (b) and (c) [145].

## 7 Chip formations in the turning process of SiCp/Al

### 7.1 Chip formation mechanisms

During the machining process, the machinability effectiveness proposed by different researchers was investigated and evaluated. Some researchers consider the chip formation process as a core part of the machinability performance of SiCp/Al metal matrix composites [146]. The chips and types of mechanisms in the chip formation process in the composites were studied by several researchers, which help to understand and measure the effects of different parameters on the processing performance during cutting. Different cutting speeds form different chip shapes and forms, such as continuous, discontinuous, or semi-continuous, discontinuous chips. This phenomenon also affects different processing characteristics, such as machining vibration, tool wear, surface temperature, quality, and cutting force during processing [147, 148]. MMC structure and choice of cutting parameters used to affect the chip formation process, different chip formation modes, and chip shape evolution laws are the reflections of machining operations and different factors affecting the turning process. The chips are mostly spring coils and c-shaped chips, and the chip curling radius is inconsistent under different cutting conditions. In literature, it is generally found that several authors use slip line theory for defining such kind of phenomenon [149]. There are different reasons for the chip curling and uneven chip formation; however, the difference in flow velocity at both ends of the chips is found to be the core

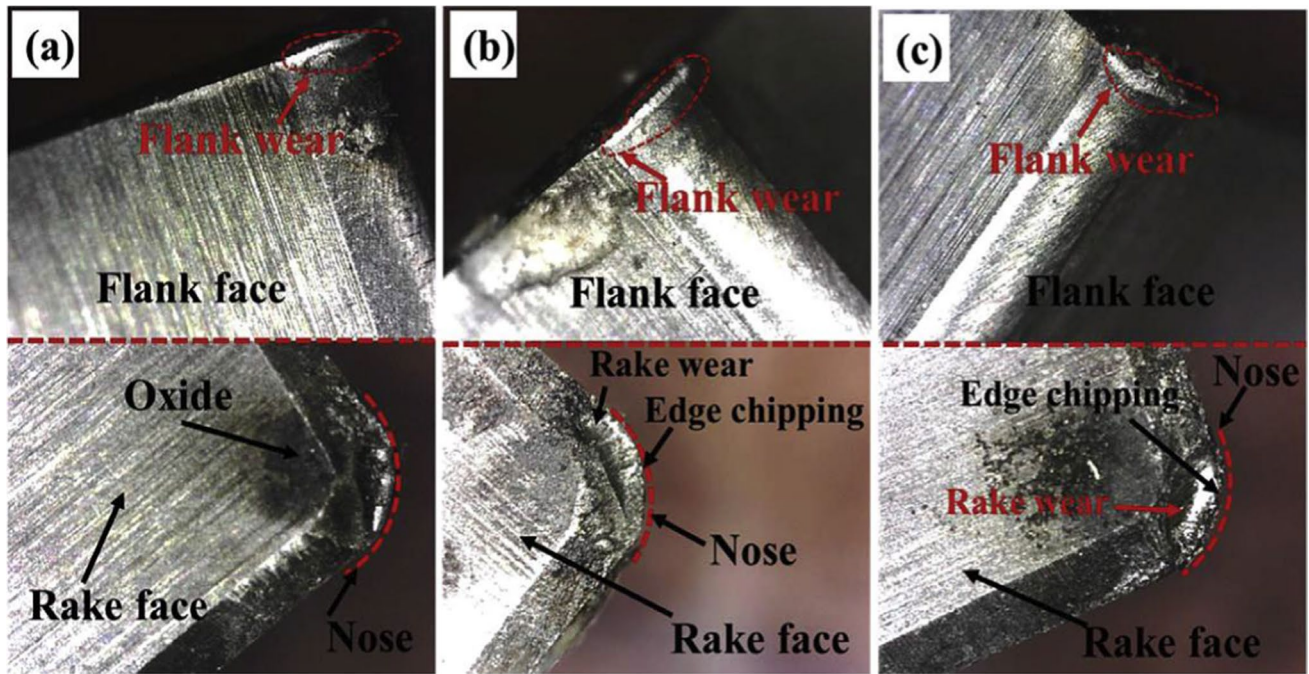


Fig. 13 Carbide tool wear mechanism  $f=0.08$  mm,  $0.25$  mm  $v_c$  = **a** 100 m/min, **b** 125 m/min, and **c** 150 m/min [145]

reason because it produces uneven strain in the deformation zone [150].

Dabade and Joshi et al. [124, 151] reported chip formation during the cutting process; furthermore, studies performed by Mabrouki et al. [150], Opoz and Chen [146], and Ozcatalbas et al. [152] also believed that this is a collapse/fracture/rupture process that occurs with the increase of the angle of the shear plane. However, Patten and Williams [153] reported in their findings that partial shearing and tearing along the shear plane occur during the cutting of MMCs. The literature on chip formation revealed that a higher feed rate leads to banded chips. Furthermore, during the material removal process with the higher feed rates, chip formation behavior alter slightly as the number of winding turns decreases. However, an increase was found in the radius of the coiled chips [124]. During the cutting process, an increase in feed causes spring coils to become C-shaped steel coils with a larger curl radius. As the feed speed and chip wrap increase, the deformation coefficient reduces, but as the cutting speed increases, greater temperatures are generated in the cutting region, increasing the coefficient of expansion for metal-based composite material. Due to the materials' plastic deformation, the cutting process is easy to form curl chips. Figure 14 shows the schematic of the chip formation during the orthogonal machining processes of metal matrix composites [154]. Dabade and Joshi [124] demonstrated that the larger the SiC particles, the lower the yield stress of the materials are, and it is easy to deform.

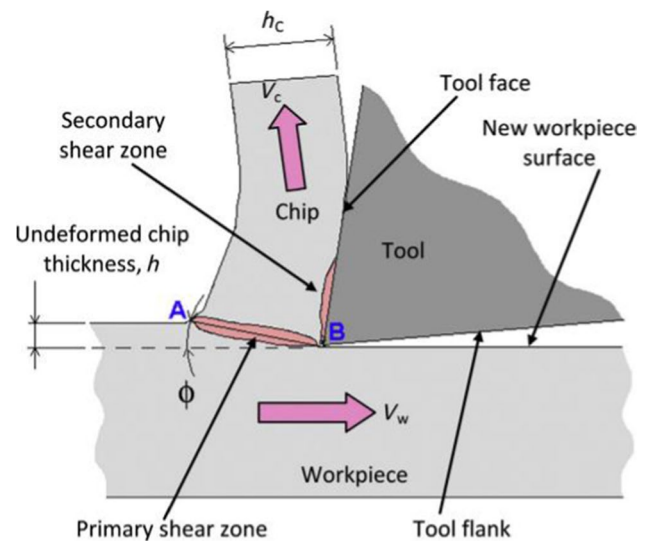


Fig. 14 Schematic diagrams of chip formation during the orthogonal machining processes of SiCp/Al [154]

From the literature, it is found that the size and shape of SiC influence heavily on the chip formation morphology and breakage and cracks in chips such as mono composites exhibit ductile properties because of the nature of reinforcement and their condition of concentration [155]. These kinds of properties and structure types of the composite can produce chips with increasing length and curling type; however, increasing the concentration

of SiC particles can produce very short chips due to the higher brittleness of the workpiece. Short SiC particles are used to pull out from the workpiece and produce pits and increase surface roughness as well as the tool wear; therefore, for increasing surface quality, particle size should be moderate [156].

Mono composites' ductility is retained to a certain extent due to the distribution of reinforcing particles with different concentrations, and hence lengthier chips with curling around are produced. For higher concentrations of the SiC particles, little short chips are produced as SiC particles restrict the formation of lengthier chips with curling. Mono composite with retained ductility tries to curl more, because the particle reinforcement curling process is restricted and lengthier chip breaks in between. The reduction in the length of the chip during the machining process helps for easy disposal and also facilitates good machinability [157].

Fathipour et al. [158] proposed a FEM 2D model for the machining process of SiCp/Al to be simulated and observed the chip formation at different feed rates and cutting speeds as shown in Figs. 15 and 16. They also validated the chip formation using experiments under similar cutting parameters as depicted in Fig. 15. The 2D FEM model as shown in Fig. 17 shows the matrix and particle geometries in the 2D model. The simulated and experimental chip formation mechanisms given in Figs. 15 and 16 show the chip morphology at different feed rates  $f = \text{mm/rev}$  both in experimental and simulated chip formation.

## 7.2 Factors affecting chip geometry

In order to analyze and understand the factors affecting chip geometry during the cutting process of difficult-to-machine SiCp/Al composites, their material removal, and mechanism chip geometry and its formation, the evolution of chip geometry can well reflect the tool-chip friction phenomena during the turning process. The tool-chip friction phenomena have been affected by the cutting temperature and cutting force at the tool-chip contact area as well as the influence on the tool wear and chip formation. Therefore, studying the evolution of chip geometry of SiCp/Al composite material and its influencing factors can not only have a relatively intuitive understanding of the change law of its cutting force but also have important significance for improving the precision and surface quality of workpieces in actual machining (Fig. 17).

The second is the periodic fracture theory [159]. Scholars holding this view believe that ductile tearing or brittle fracture in the shear zone causes cracks in the shear zone, and the initiation, development, and propagation of cracks in the shear zone cause the saw tooth chips to be generated. The periodic fracture theory is generally used to explain the phenomenon of the chipping of low-plastic materials. In the current research on the chip morphology of SiCp/Al with medium to high-volume fractions, the main reason for the formation of saw tooth chips is the sudden fracture of the free surface of the chips caused by the formation and propagation of cracks during the material cutting process.

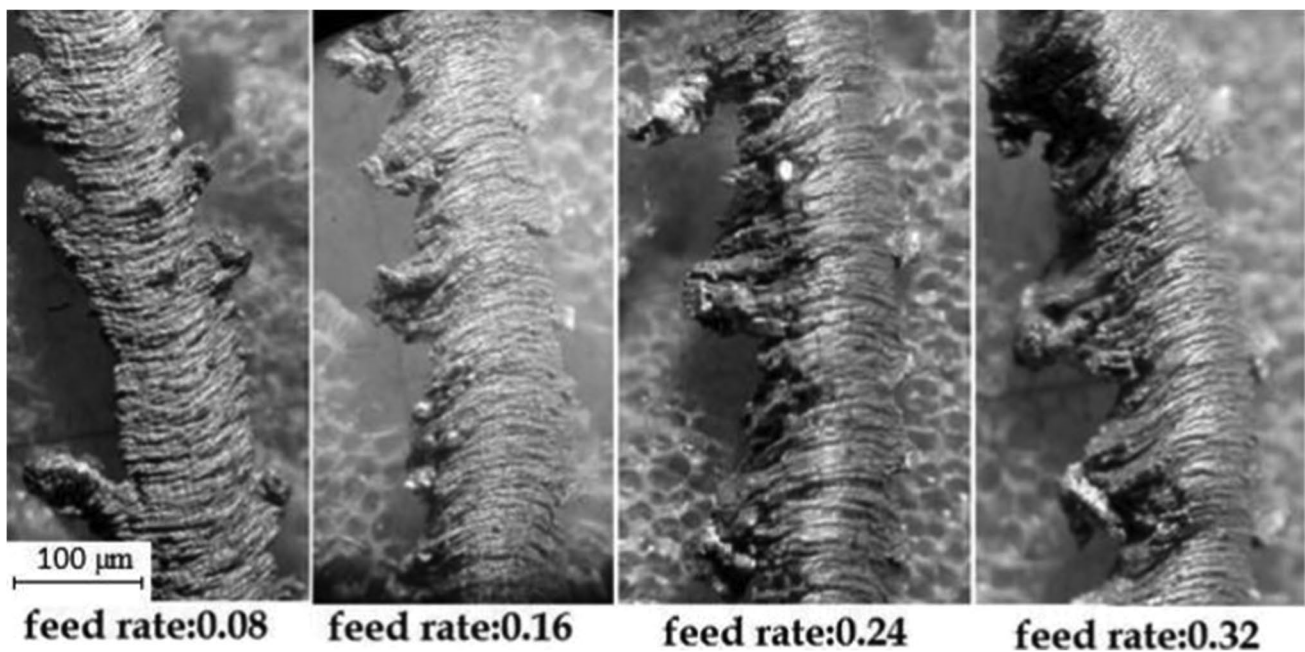
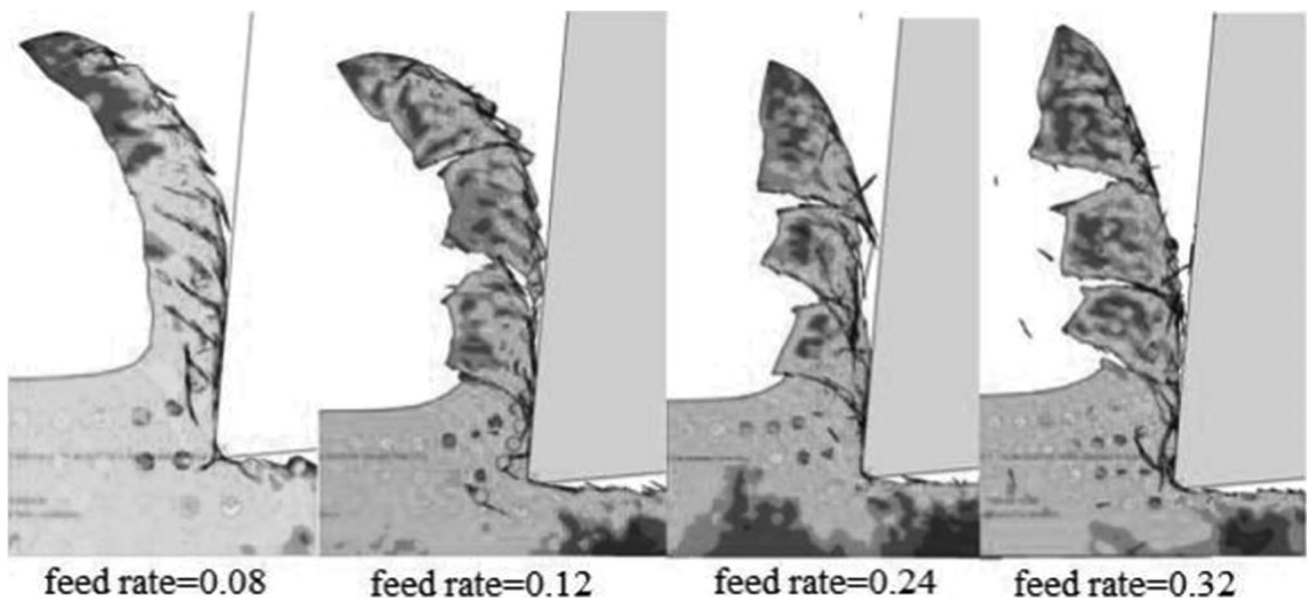


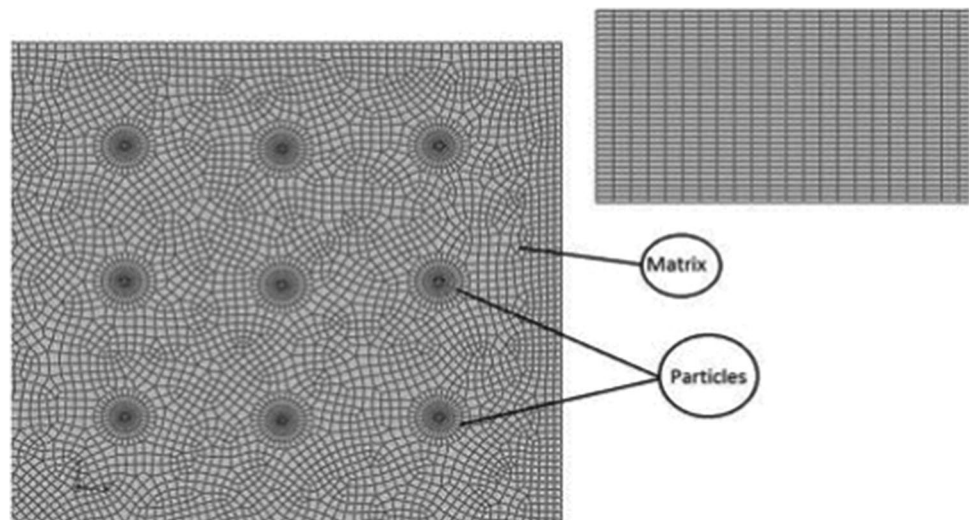
Fig. 15 Experimentally observed chips on varying feed rate ( $a_p = 0.8 \text{ mm}$  &  $v_c = 60 \text{ m/min}$ )[158]





**Fig. 16** Simulated chips on varying feed rates ( $a_p=0.8$  mm &  $v_c=60$  m/min)[158]

**Fig. 17** Cutting simulation model established by Fathipour [158]



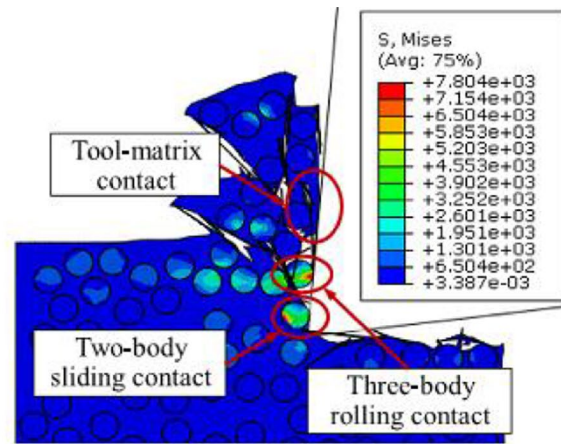
One of the main reasons for the formation of crack sources in SiCp/Al composites is process defects during the preparation of the composite, such as porosity, segregation, and low-strength inclusions, which cause various defects to form at the substrate and the interface between particles and the substrate. Another important reason for the formation of cracks is that in the machining of SiCp/Al, the aluminum matrix material in the shear zone will undergo large elastoplastic deformation and the reinforcing particles will have a certain hindering effect on the deformation, leading to the formation of dislocations at the bonding interface. When the dislocation reaches a certain level, cracks or voids have been generated at the substrate

or the bonding interface. In addition, the collision of the tooltip with the particles and the contact between the particles causes the particles to fracture, break, or pull out; this process is also accompanied by the occurrence of micro-cracks.

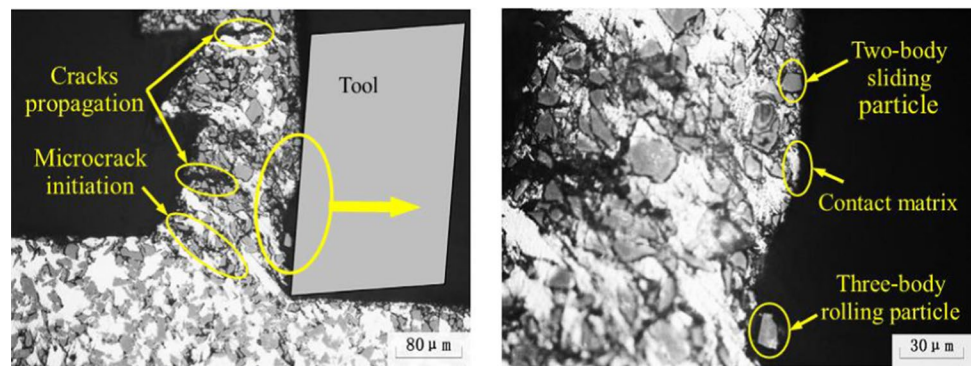
Duan et al. [160] performed a research study to analyze the morphology of chip formation and provided an understanding of the machining process. Figure 16 displays experimental data for the chip formation morphology while Fig. 18 gives the simulated chip formation morphology. Moreover, the details are displayed in Fig. 19 which depict chip formation morphology at different cutting speeds and feed rates. During the



**Fig. 18** The morphology of chips illustrates the variation with the choice of cutting parameters and size of the SiC particle on chip formation [160]. (a) Simulated chip formation and tool matrix contact, (b) Micrograph of the chip root [160], (c) Enlarged view morphology formed chips



(a) Simulated chip formation and tool matrix contact



(b) Micrograph of the chip root [162] (c) enlarged view morphology formed chips

machining of SiCp/Al/composites, the chip thickness increased over the cross section of each chip during the chip generation process.

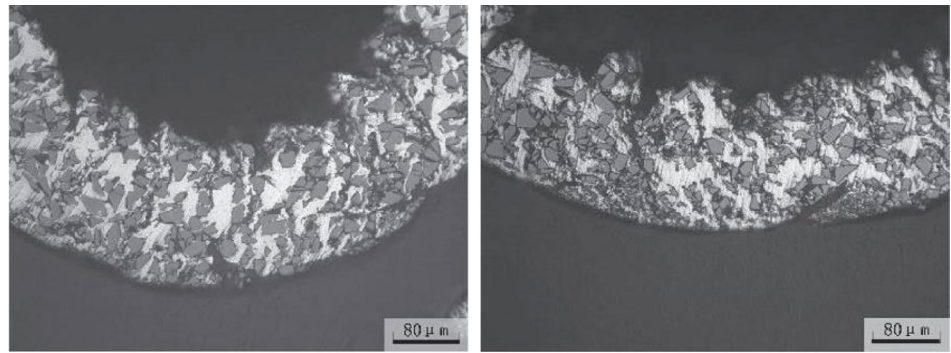
The chip compression ratios remained unchanged which is measured at almost 1.68 in SiCp/Al with different feed rates and cutting speeds. The morphology of chips produced at different cutting parameters such as different ranges of feed rates at different types of MMCs is shown in Fig. 19 at a cutting speed of 120 m/min [46]. Figure 20 shows the von Mises stress distributions for different kinds of composites with different geometries of SiC particles. The simulation of circular SiC particle models is presented and compared with the irregular polygonal particles, which is shown in Fig. 20 (a–d) circular particles, (e–h) irregular polygonal particles. In Fig. 20 (a), with circular SiC particles, as the tool moves forward, the stress concentration on the particle face increases, and the particle starts peeling and bending as can be seen in Fig. 20 (b); in Fig. 20 (c), deboning phenomena occurs as tool start cutting the SiC particles than chip formation begins which can be seen in Fig. 20 (d). Similar phenomena of chip formation can be seen in Fig. 20 (e), (f), (g), and (h) for irregular polygonal particles [46].

## 8 Cutting forces in machining SiCp/Al composites

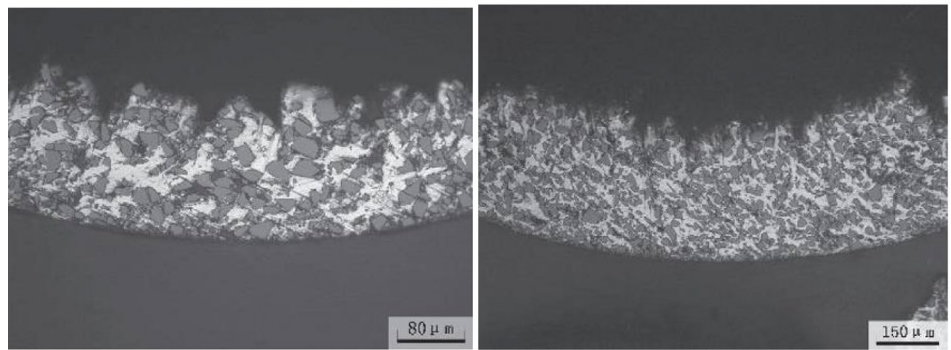
The pattern of cutting force trends in the turning of metal matrix composites (MMCs) has very important theoretical and practical significance to understand the cutting process. When the three observed cutting forces such as force in x, y, and z directions are used as the main influencing factors in the cutting process, which have been found different for different combinations of cutting parameters. There is evidence that cutting conditions change with varying machining process parameters. The fabrication technology, method of fabrication of the composite materials, and distribution of reinforcements along with size, content, and shape influence the hardness and toughness of the composites and hence can play a major role in machining operation for cutting forces trends.

During machining, the generations of the cutting forces are common and a basic physical phenomenon, and are also the basis for studying surface quality, cutting temperature, chip deformation, and the like. Many articles can be found focusing on understanding and analyzing the cutting force generation in machining SiCp/Al composites, mainly predicting the cutting force model by experimental methods [161, 162].

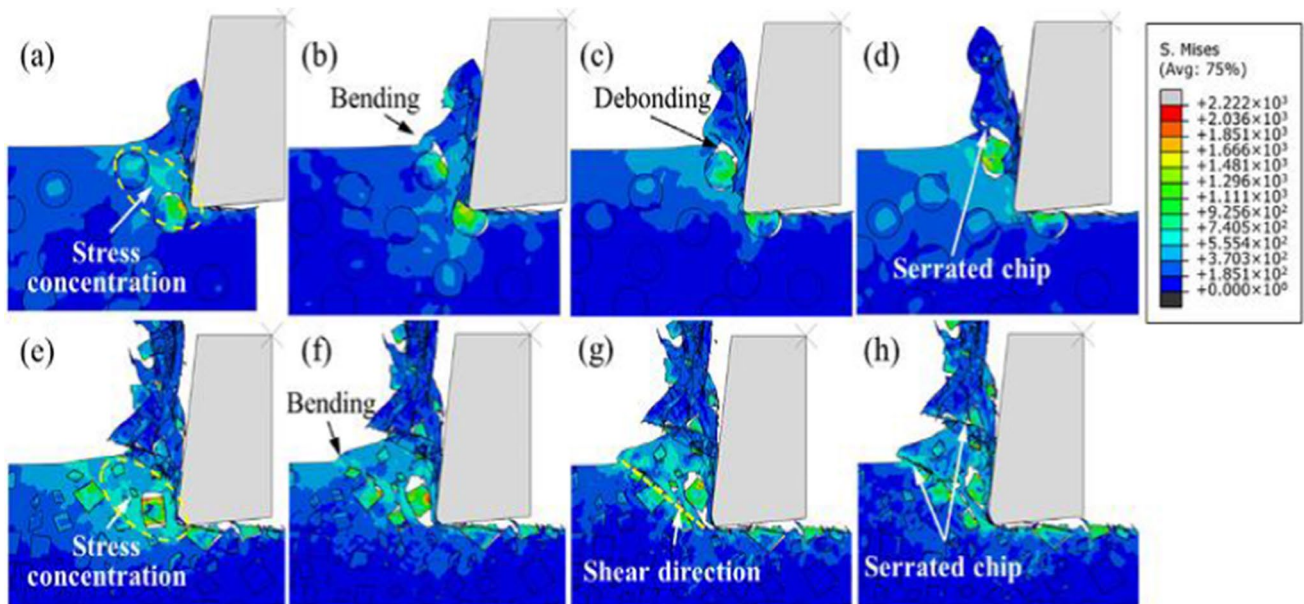
**Fig. 19** Chip formation morphology at different cutting speeds and feed rates [160]. (a) Chip formation at  $v_c=23$  m/min and  $f=0.1$  mm/rev, (b) Chip formation at  $v_c=47$  m/min,  $f=0.1$  mm/rev, (c) Chip formation at  $v_c=120$  m/min,  $f=0.1$  mm/r, (d) Chip formation at  $v_c=120$  m/min,  $f=0.2$  mm/r.



(a) chip formation at  $v_c=23$ m/min and  $f=0.1$ mm/rev. (b) Chips formation at  $v_c=47$ m/min,  $f=0.1$ mm/rev



(c) Chips formation at  $v_c=120$ m/min,  $f=0.1$ mm/r (d) Chips formation at  $v_c=120$ m/min,  $f=0.2$ mm/r



**Fig. 20** The von Mises stress distribution (a–d) circular particles; (e–h) irregular polygonal particles during the chip formation process [46]

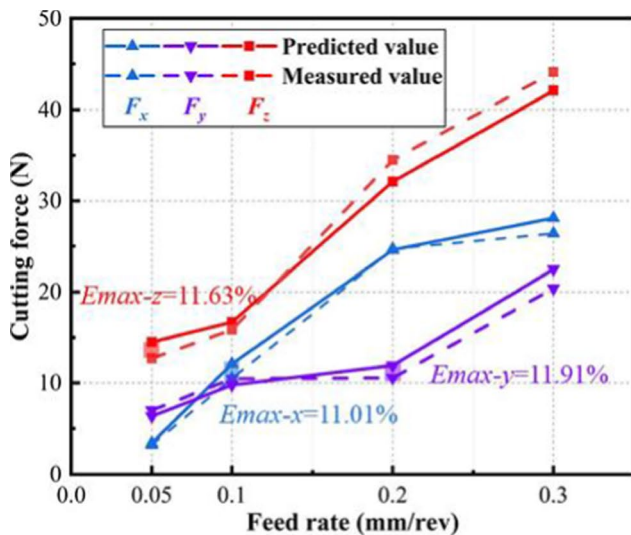
Some studies such as [104, 109] have shown that the increase in cutting force is a result of the choice of machining parameters especially the selection of cutting depths, which produces more influences on the forces. This is because the contact area between the cutting tool and the workpiece in the cutting zone increases during the machining operation. This phenomenon will also produce a higher material removal.

Experimental observations have demonstrated that, while comparing lower to higher amounts of SiCp, volume fraction can increase the fluctuation in the cutting forces, that is eventually the effect of a higher amount of SiCp volume fraction and the cutting parameters such as cutting depth and more feed speed [163, 164]. The fluctuation in the cutting force phenomenon of MMCs is such a complex progression, which is influenced by the nature and structure of the produced matrix, their reinforcement, and interfaces. Many researchers have found in their study that higher toughness and stiffness of SiC particles cause the fluctuation in cutting force; however, the content and the volume fraction of SiCp have more influence on cutting forces [90].

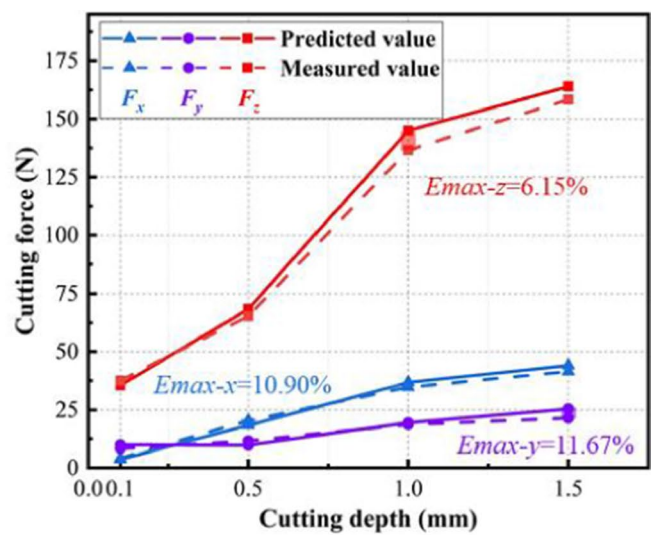
The cutting force is reasonably reduced at a lower cutting depth and a higher cutting speed because it reduces the cumulative edge of the tool, thereby ultimately reducing the force in the machining operation. Another fact is that while increasing the cutting temperature, the workpiece-tool interaction within the deformed area also stabilizes the cutting force, as this will reduce the yield strength of the part during the cutting process. The choice of reduced cutting parameters

such as lower cutting depth and lower cutting speed results in fluctuating cutting forces which lead to varying chip types as accumulated by the cutting edge of the tool [107]. Increasing the feed speed increases the friction coefficient, thereby increasing the friction between the tool cutting edge and the workpiece thereby increasing the cutting forces in the cutting process [45, 165]. It is also mentioned in the literature that the cutting forces depend on reinforcement type and type of matrix material when cutting composites, and hence the reinforcement types and interface bonding strength together with the increasing volume fraction of hard particles possess a higher influence on the cutting force [166, 167].

Zhou et al. [46] studied the machining performance of SiCp/Al as MMCs and measured and analyzed the cutting forces. They compared cutting forces predicted using numerical models with experimentally measured values, under geometric forces in machining SiCp/Al at different cutting depths and feed rates as depicted in Fig. 21. The effects of feed rates and cutting depths on the resulting cutting forces are presented comprehensively, respectively. The feed rate effect and error percentages of cutting forces between the experimental and measured models are given in Fig. 21 (a) and the depth cut measured model and the effect of cutting forces and error percentages are shown in Fig. 21 (b). The machining experiments and simulation were conducted for 25 vol% SiCp/Al; it is seen from the graph that the cutting force increased with the increase in feed rate and depth of cut; higher amount cutting forces were seen in  $F_z$  direction for the cutting force.



(a) Predicted and measured cutting forces of 25 vol% SiCp/Al



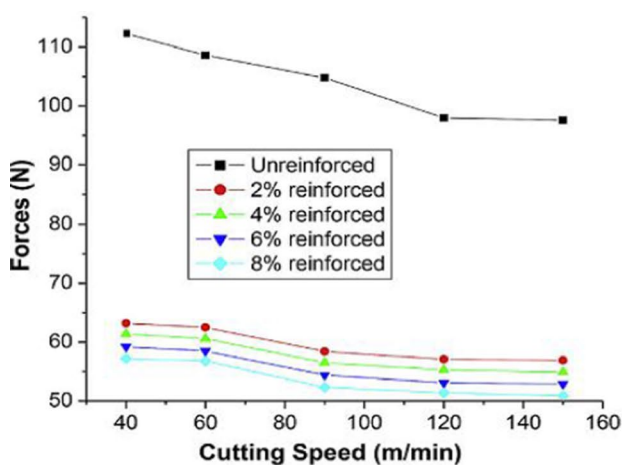
(b) Predicted and measured cutting forces of 25 vol% SiCp/Al

**Fig. 21** Comparison of cutting forces at different parameters in three different directions [46]. (a) Predicted and measured cutting forces of 25 vol% SiCp/Al, (b) Predicted and measured cutting forces of 25 vol% SiCp/Al

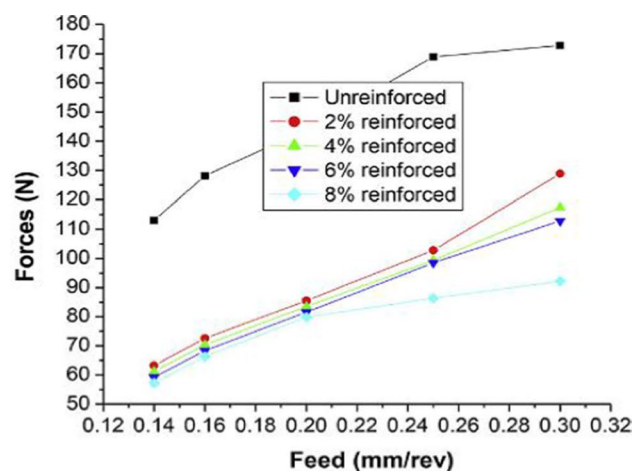


Shoba et al. [165] studied the turning process of SiC-based aluminum alloy under dry cutting conditions and considered the processing characteristics of different weight percent of silicon in aluminum alloy matrix, to understand the influence of cutting parameters on cutting force. Figure 22 shows the effect of SiC particles on cutting force, which demonstrates that as the feed speed and the cutting depth increase, the cutting force exhibits a higher trend. Moreover, with machining with a higher cutting speed, the cutting forces are lower. These trends are recorded under constant cutting speed and federate ( $v_c = 150$  m/min,  $f = 0.14$  mm/rev). Duan et al. [160] studied the processing of the SiCp/Al metal matrix composite

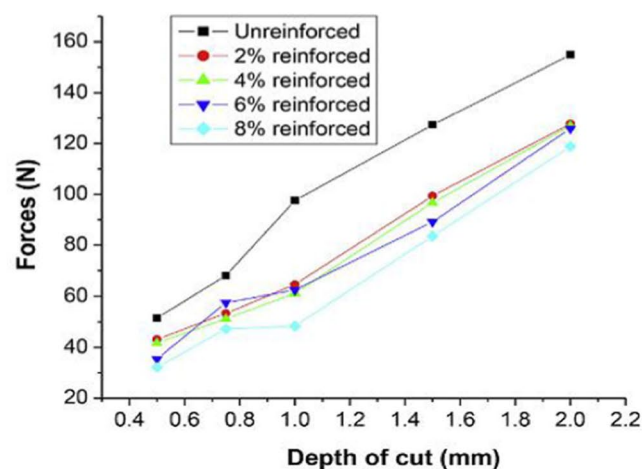
material using a simulation model which is based on three-phase friction to predict chip formation and cutting forces, together with tool-chip interface friction provided for the simulation model. Figure 23 shows the trends of cutting forces in machining SiCp/Al as a function of varying feed rates and cutting speeds; it is seen that the cutting speed has a positive effect on the cutting force, while increasing the speed forces are seen to decline and feed rate also does not have much impact in increasing the cutting forces. However, the higher depth of cut has seen a significant impact on the cutting forces as the depth of cut increases the forces also show increasing trends in all amounts of SiCp/Al-reinforced percentages [160].



(a) Cutting feed 0.14 mm/rev and depth of cut 0.5 mm



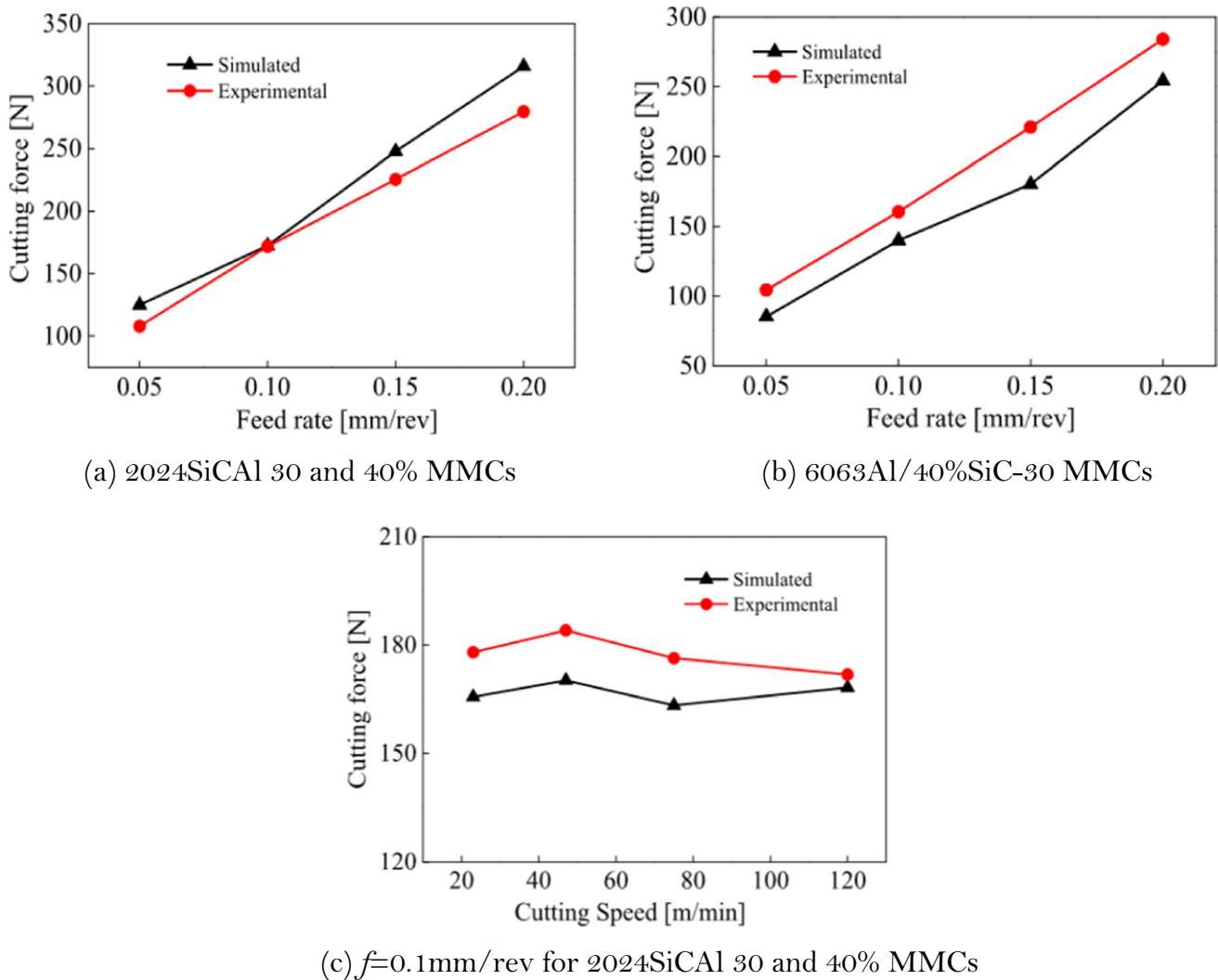
(b) Cutting speed 150 m/min and depth of cut 0.5 mm



(c) cutting speed 150 m/min and feed 0.14 mm/rev

**Fig. 22** Cutting forces under different cutting conditions [165]. (a) Cutting feed 0.14 mm/rev and depth of cut 0.5 mm, (b) Cutting speed 150 m/min and depth of cut 0.5 mm, (c) Cutting speed 150 m/min and feed 0.14 mm/rev





**Fig. 23** SiC/Al machining process cutting forces of different experimental values vs FEM simulated forces at different feed rates (at  $v_c = 120$  m/min) [160]. (a) 2024SiCAl 30 and 40% MMCs, (b) 6063Al/40%SiC-30 MMCs, (c)  $f=0.1$  mm/rev for 2024SiCAl 30 and 40% MMCs

## 9 Surface integrity

In the machining process, attaining a surface finish is a primary goal for machining various metal matrix composite workpieces. The optimization of cutting parameters during machining operations has become critical for achieving the desired workpiece surface finish. Surface roughness and machining processes have been the subject of several experimental and analytical research [168]. When measuring the influences on fatigue resistance, friction coefficient, and compatibility during machining, one of the most important aspects of the workpiece condition evaluation technique is surface integrity.

The surface characteristics of the SiCp/Al metal matrix material as well as the physical and mechanical properties of the reinforcing phases are considerably different, and the interface between the two is more complex during machining.

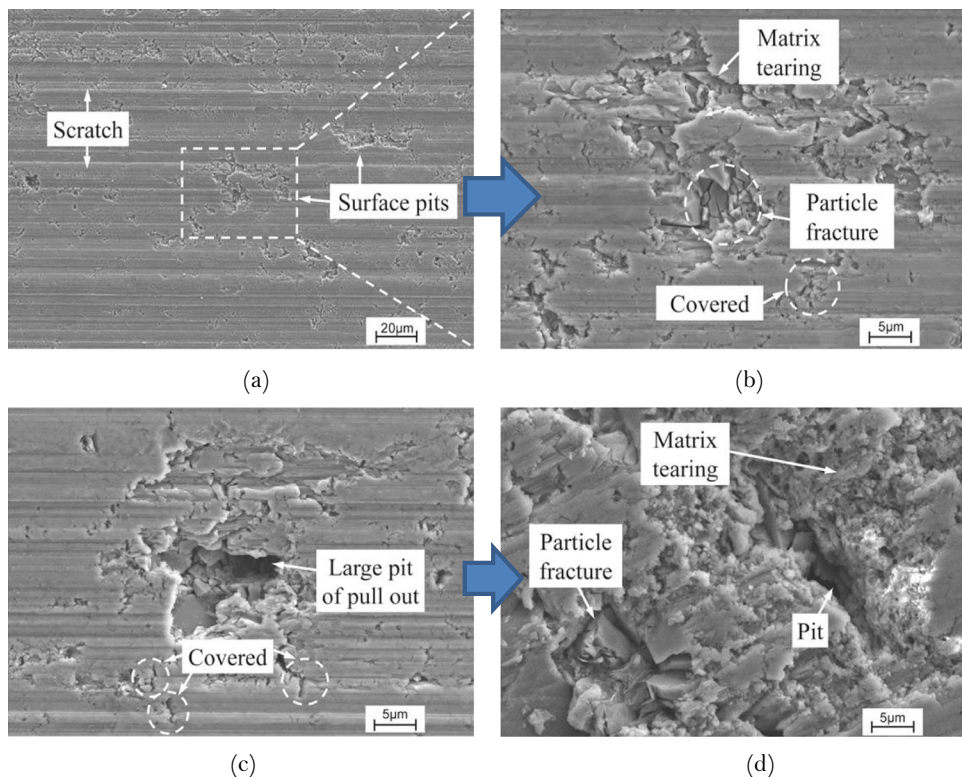
On the machined surface of the SiCp/Al metal matrix composite material, various defects are prevalent. El-Gallab [169] studied the cutting of 20% SiCp/Al composites and found voids and cracks around the SiC particles together with groove marks left by the particles falling off and tearing during machining, which affected the quality of the processed surface. The voids were found caused by the dislocation of SiC, and the groove marks on the surface may be caused by the “scratching” of the falling SiC particles on the machined surface. Furthermore, M. El-Gallab [89] used PCD tools for cutting MMCs and it is found that as the cutting speed increases, the surface roughness decreases. When the cutting speed was greater than a certain value, the surface roughness value no longer changed. They also found that as the feed rate increased, the surface roughness also increased. At the same time, as the content of SiC particles increased, the surface roughness of fine-grained composites improved, while

the surface roughness of coarse-grained composites deteriorates further [170]. Fang et al. [156] studied the machining and related material damage model of the silicon-based reinforced matrix composite material to analyze and understand the machining characteristics including different responses such as cutting force and surface topography. The simulation and experimental studies presented well for understanding the difficult-to-machine material. Figure 24 shows the different machining characteristics of the SiCp/Al composite such as

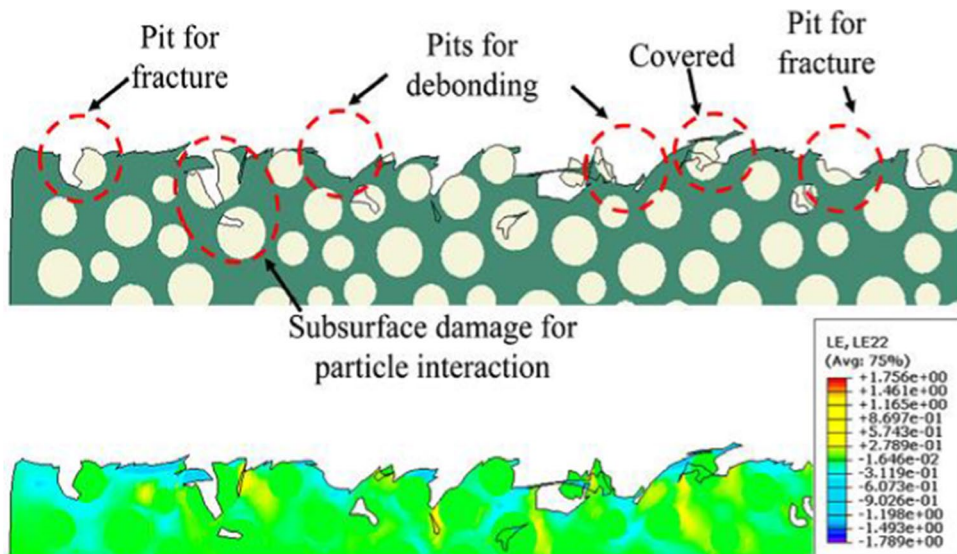
particle fracture, matrix tearing, surface pits, and scratches. However, simulated picture 25 shows the morphology of machined surfaces with similar results to the experiments which show subsurface debonding, covers, pit debonding, surface pits, and scratches [156] (Fig. 25).

Zhou et al. [46] simulated the cutting process of the SiCp/Al composite materials to analyze the deformation mechanism considering two different SiC particle shapes (circular and irregular polygonal), the chip formation, stress distribution,

**Fig. 24** Experimental morphology of machined surfaces [156]



**Fig. 25** The simulation morphology of machined surfaces SiCp/Al [156]

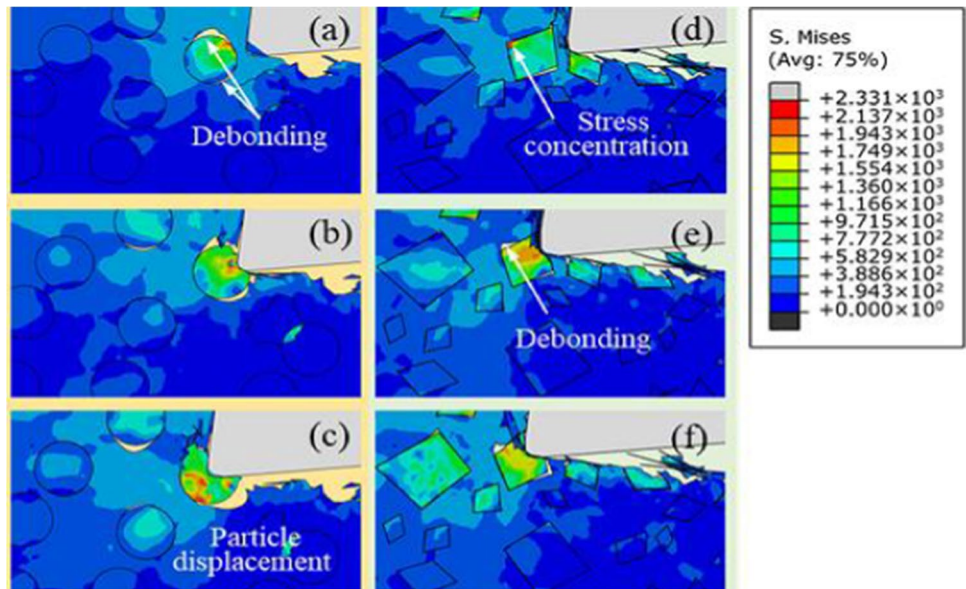


and surface finish s as shown in Figs. 26, 27, and 28. The cutting parameters for the chip formation, surface roughness, and stress distribution analyses were performed using the cutting depth of 25 μm and cutting speed of 250 mm/s. It is observed that the stress distribution was found dependent on the shapes of the particles during tool-particle interaction. Surface roughness was found worse as particles pull out, cavities, and pits according to the particle type and shape morphology [46].

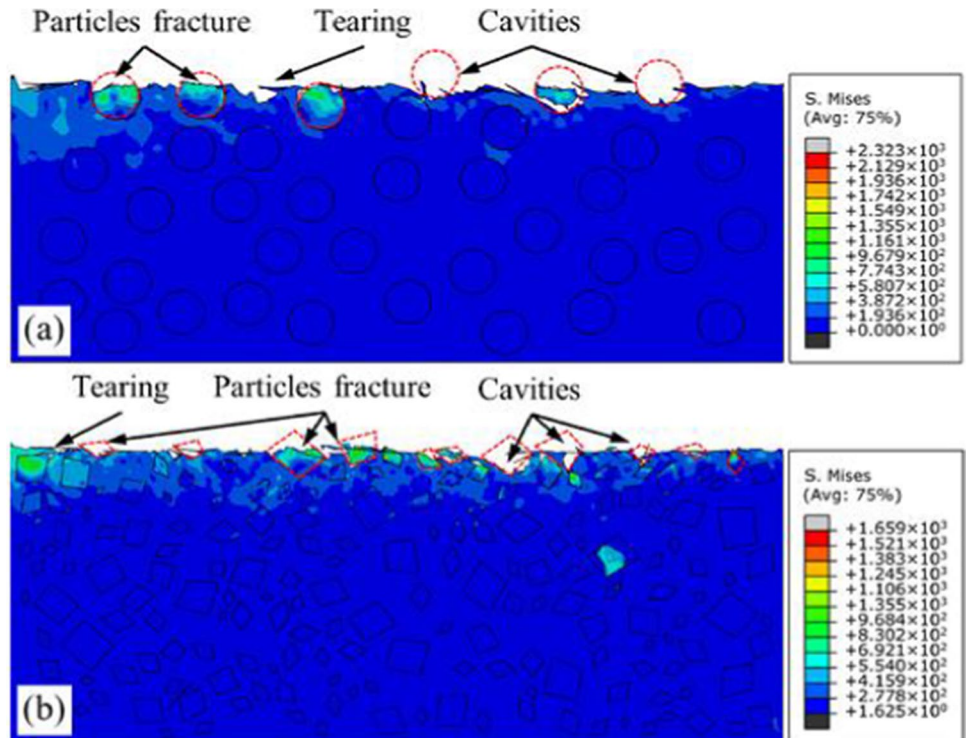
### 10 FEM simulation and analytical modeling of particle-reinforced MMC

Various processing approaches, including conventional and unconventional procedures, were used in the broad machinability investigation of SiCp/Al-MMC performance. The resulting behaviors of different machining processes are not sufficient for a comprehensive analysis of the cutting process

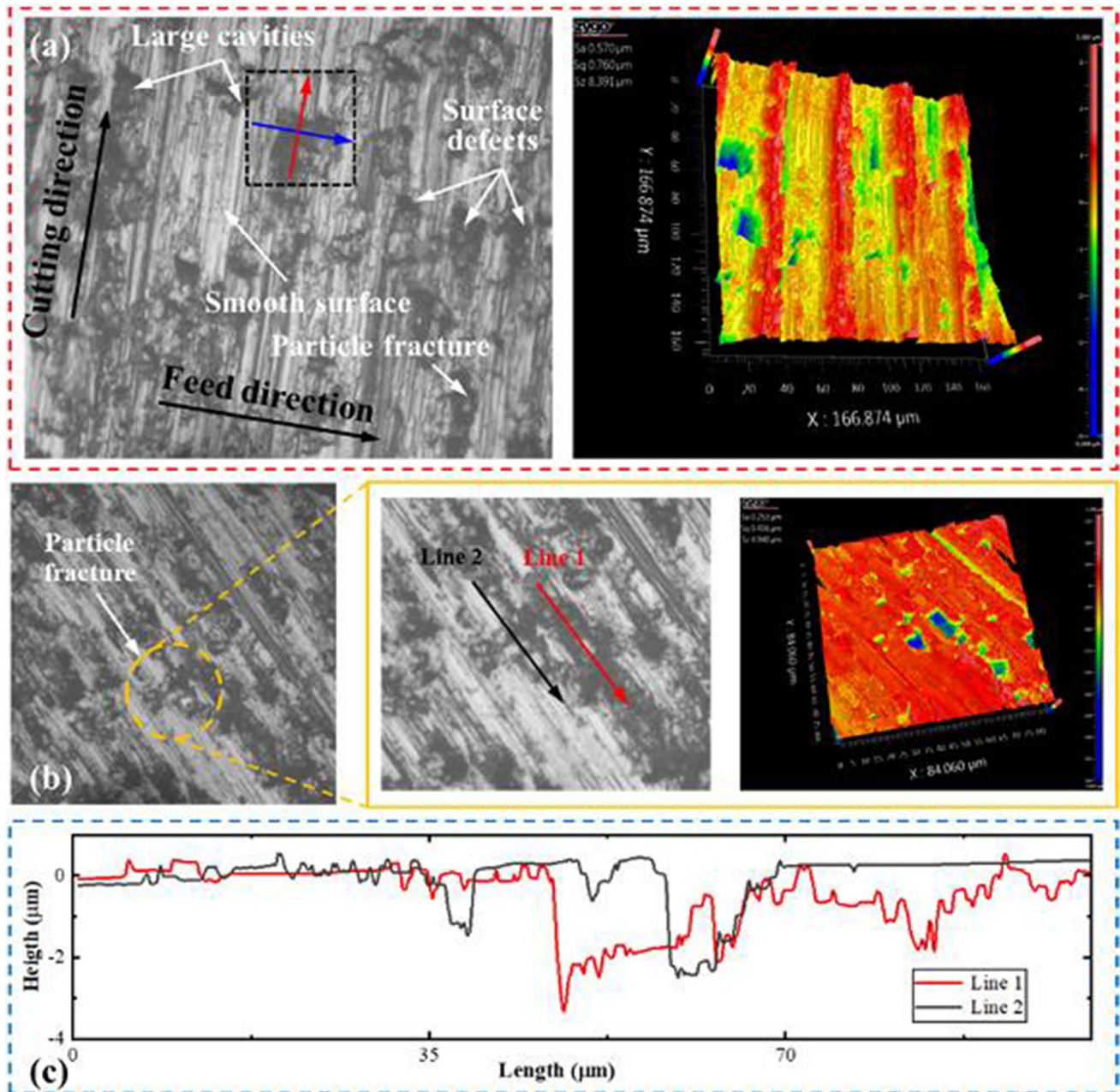
**Fig. 26** SiC particle cutting phenomena, stress distribution of SiC particles with **a–c** SiC with circular geometry; **d–f** SiC with irregular polygonal geometry [46]



**Fig. 27** Surface generated morphology for **a** SiC with circular geometry; **b** SiC with irregular polygonal geometry [46]







**Fig. 28** The surface roughness images: **a** workpiece surface deficiencies; **b** SiCp inserted into matrix; **c** SiCp inserted morphology [46]

of SiCp/Al matrix composites due to inherent limitations in the experimental approach. Therefore, to have a deeper understanding of processing behavior, numerical and analytical models based on experimental data are considered in this study. A complete mechanism model of the cutting process will help to understand the processing behavior of SiCp/Al more widely, thereby reducing the cost of machines and tools used as a result of the experimental approach.

In the literature, analytical models for evaluating machinability, material strength, tool wear, surface roughness, residual stress, cutting force, tool failure, and stress

and strain during the cutting process of MMCs have been established. While three different kinds of categories of the analytical models are classified as per their origins, such as (i) Ernst-Merchant orthogonal cutting theory, (ii) plastic and elastic theory, (iii) machinability investigation, and Taylor's formula for tool life.

The analytical model was developed for SiCp/Al-based composite cutting process to estimate the specific energy and energy consumed by deformation and debonding. The cutting performance of SiCp/Al with different volume fractions was measured in different cutting parameter ranges

[171]. Furthermore, the study performed in [90] through the Griffith fracture theory and the plastic slip line field theory predicted the cutting force of particle-enhanced MMCs using the Merchant analysis. The established theoretical models of particle crushing force, plowing force, and chip forming force were found significant to the outcome of the experiment.

The geometric modeling of SiCp/Al-MMC is an interesting problem. The main obstacle is the accuracy of the geometrical specifications of the reinforcement. Li et al. [117] established a tool wear model for SiCp/Al-MMC machining based on the motion and geometric characteristics of the reinforcing particles. Uday et al. [73] conducted a statistical analysis to examine the processing parameters that affect the shear angle. According to the analytical formula, the chip formation is qualitatively analyzed, and the shear angle and thickness are measured. In addition, the study performed in [75] provided the comprehensive correlation between shear angle and friction angle in the machining operation of metal matrix composite for understanding and estimation of contact stress and cutting forces during chip-tool interface. Lin et al. [172] predicted an analytical model in the turning process of Al-MMC; the modified Taylor equation tool wear equation is utilized in this study for optimizing tool life, and subsurface damage. Manna and Bhattacharyya [118] in their work measured the yield strength effect based on the modified shear lag theory; the model is established according to the fatigue fracture mechanics theory. Furthermore, several models were developed to understand the machining of metal matrix composites; material models were also developed. Different methods for modeling technique include chip formation [173], temperature-independent hardening and temperature-dependent models, Hooke's law [174], the Johnson and Cook models, and plastic/elastic deformation models [175–177].

## 10.1 2D FEA for machining process of SiCp/Al

Machining of SiCp/Al was performed using both 3D and 2D models for the cutting process using FEM software. Several researchers used different approaches on appropriate cutting parameters to develop the FEA models. Shui et al. [178] studied the behavior of particles with various kinds of geometric shapes to perform the study through parametric modeling of particles at low and high vol% fractions. The finite element model of particles and meshes of different geometric shapes is established based on an arbitrary polygon model as shown in Figs. 29 and 30. Three kinds of FEA geometric models were developed to study such as rounded shapes mixed with regular polygon and arbitrary polygon silicon particles. It is revealed from the study that the geometric shape possesses an influence on stress distribution phenomena during the cutting process; therefore, it is found that the cutting force trends of the simulated circular and regular polygons are steady and show that the stress generation is in small quantity. Ghandehariun et al. [179] proposed a meso-mechanical finite element model for processing metal matrix composites. The model proposes the behavior

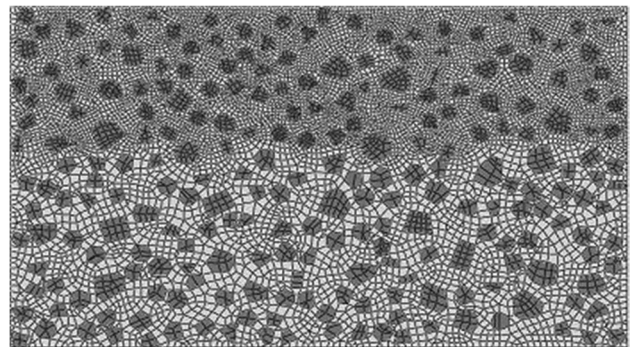


Fig. 30 Meshing on arbitrary polygon model [178]

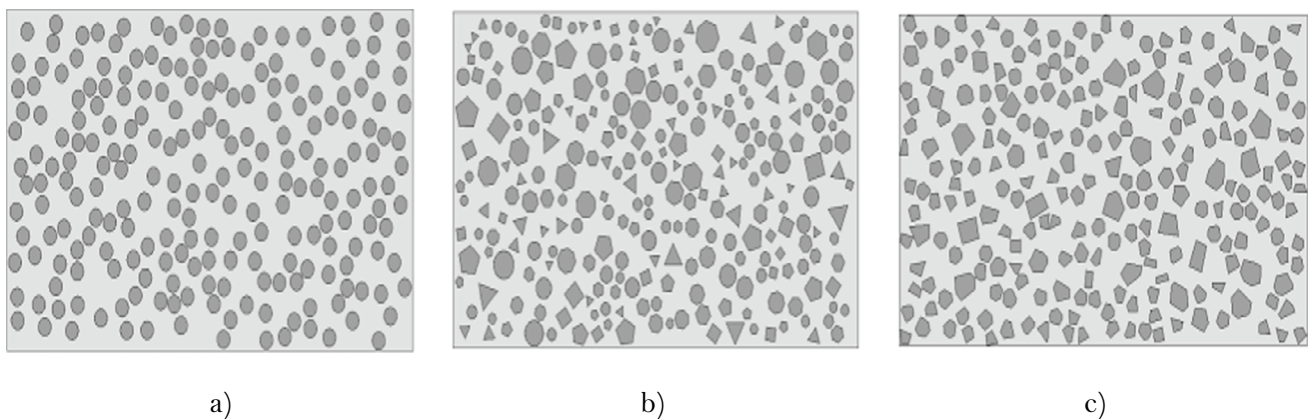


Fig. 29 The geometry structure of the three models (the particles are distributed randomly). **a** SiC with circular shape; **b** SiC with circular and irregular polygonal shape; **c** SiC with arbitrary polygon shape [178]

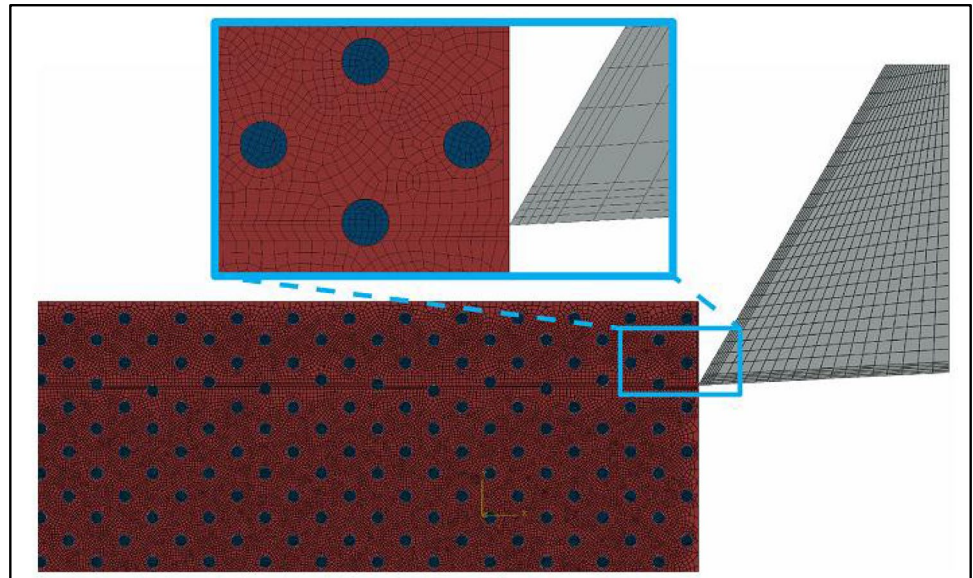


of distinguishing all the components of the metal matrix composite, including particles, matrix, and particle–matrix interface. Figure 31 shows the interaction between particles, matrix and particle–matrix interface, and tool particles in the established cutting simulation model. This model is used to study the fracture and debonding conditions of the tool-particle interaction as given in Fig. 32, depicting three scenarios of tool-particle interaction inline, above the line, and below the line, and their fracture and debonding conditions when comparing the position are studied. The cutting force shown in Fig. 33 predicts the cutting speed of 85 m/min and the width of the cut 3 mm for 6061/10% 15  $\mu\text{m}$   $\text{Al}_2\text{O}_3$ , and developed the FEM model and compared and verified

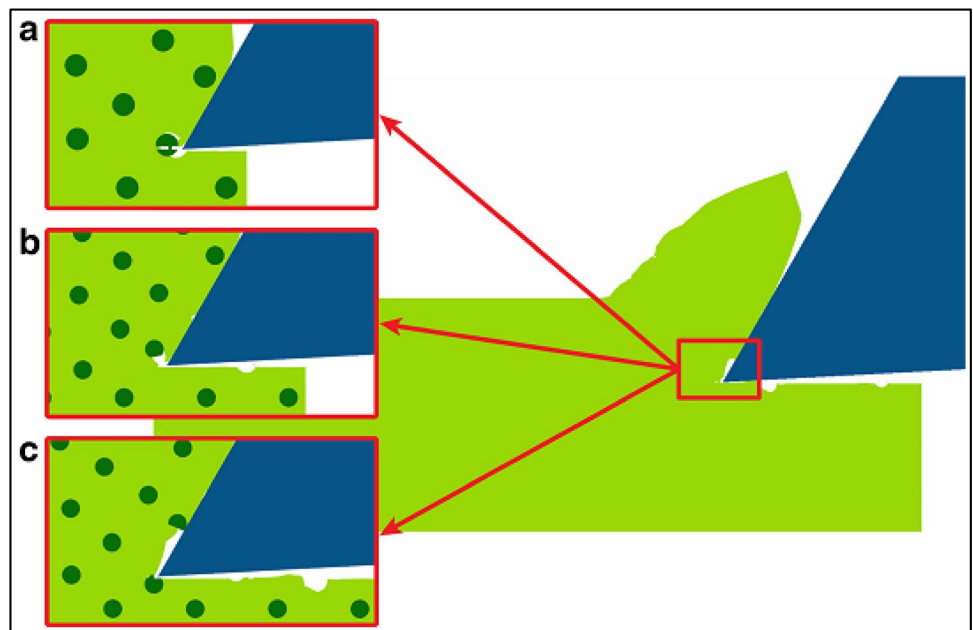
with experimental data. Finite element analysis was used to simulate the thrust forces, and thermal distributions during the cutting process as well as the stress generation and the plastic strain were studied using the Johnson–Cook constitutive models [180]; furthermore, other researchers [180, 181] simulated the chip formation and residual stresses, in high-speed machining of AA7075 – T651 aluminum alloy using the finite element modeling technique [173]; serrated chip formation along with flow stress were also predicted in Prediction of Serrated Chip Formation in Metal Cutting Process by FEM.

The experimental study was conducted on the turning process to measure the cutting forces, and cutting tool wear

**Fig. 31** Cutting simulation model established particles, matrix, and the particle–matrix interface and tool-particle interaction [179]



**Fig. 32** Tool-particle interaction at (a) particle on line, (b) particle above the line, and (c) particle below the line [179]





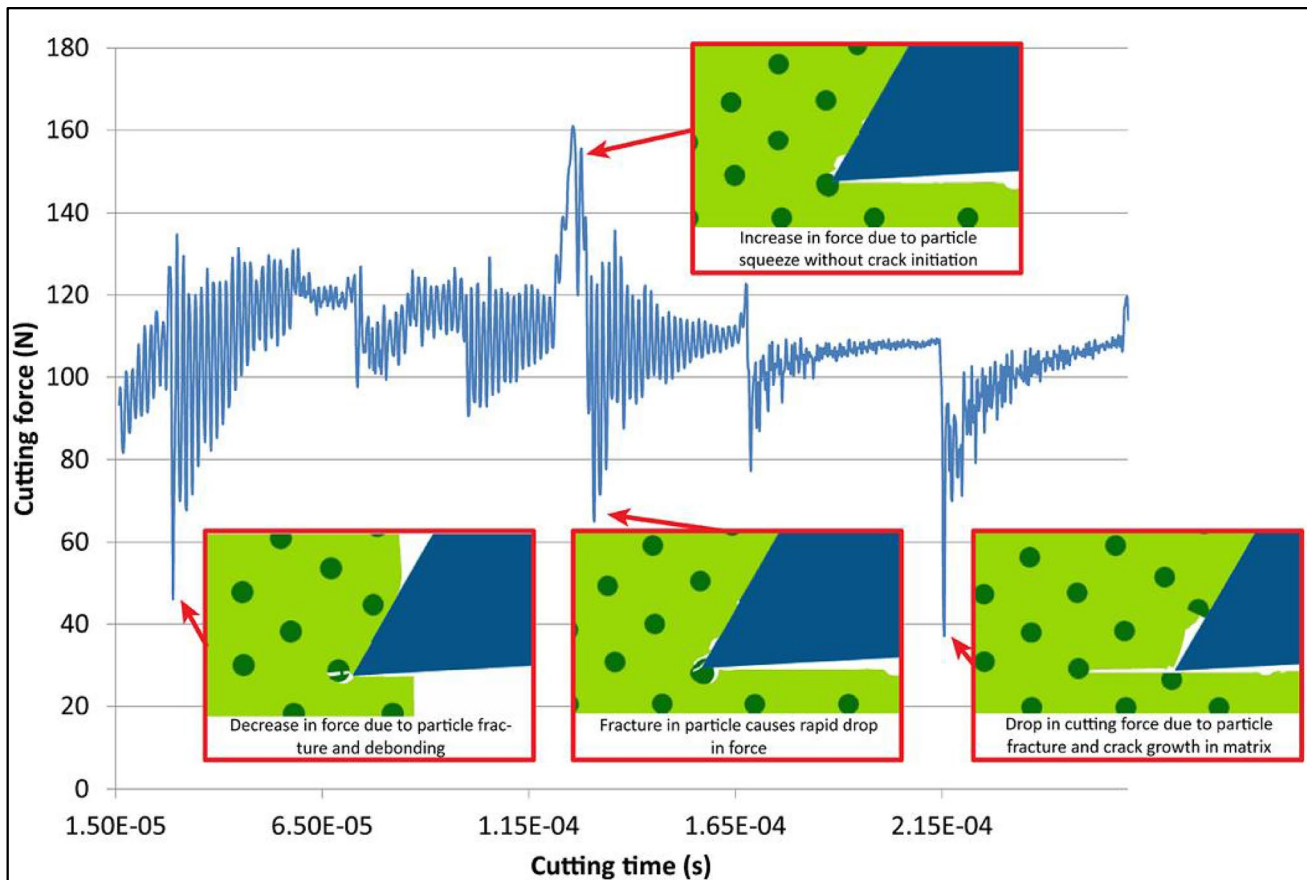


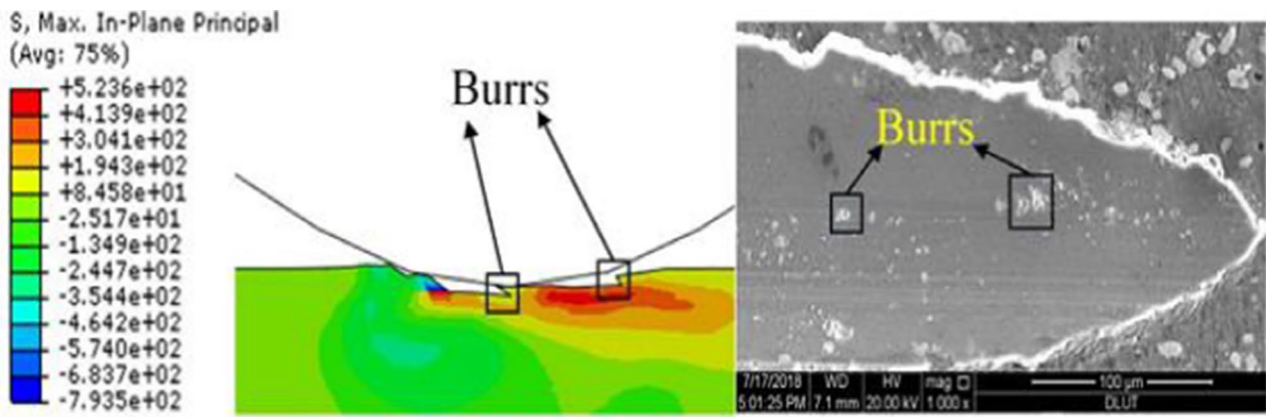
Fig. 33 Simulated cutting forces using FEA [179]

in the machining process similarly the FEM type Lagrangian incremental type and re-meshing chip separation criterion; 3D-FEM simulation was used for simulating and modeling the cutting force and cutting tool wear in this study [182]; semi-phenomenological-based damage model developed silicon-based particle-reinforced composite material in high-speed cutting machining experiments [183]; similarly, Xiang et al. [184] presented the ultra-precision turning process of silicon-based particle-reinforced composite simulated and compared with experimental data.

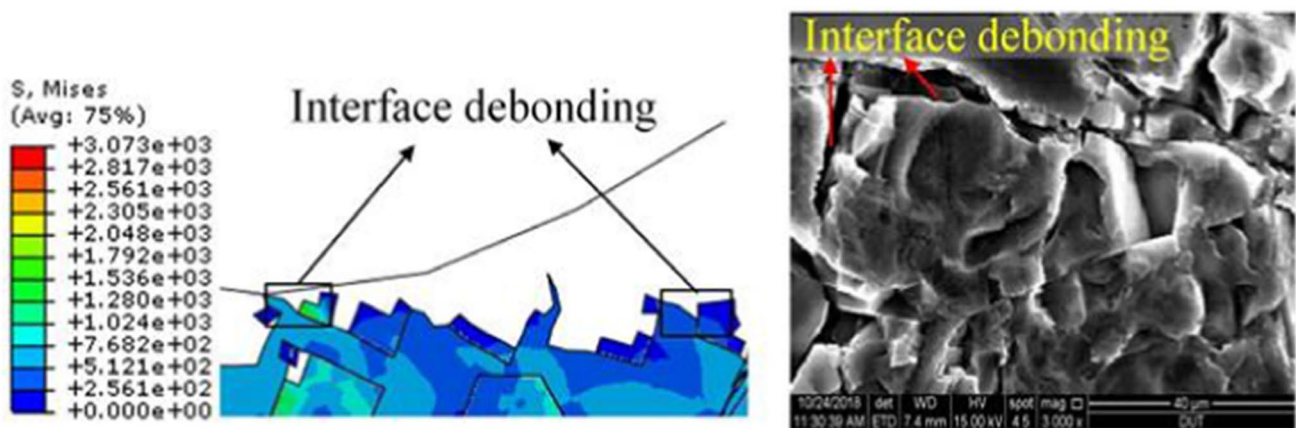
Kishawy et al. [185] use the orthogonal machining process on a metal-based composite material with different volume contents of the particles. The study has also put an influence on the particle phase, studied the influence of cutting parameters, and established a predictive model for cutting forces. Pramanik et al. [186] and others studied the removal method and mechanism of the material during the turning process of the SiCp/Al composite materials and summarized the composition and causes of the cutting force fluctuation into three parts, chip forming process, deformation force, the force required by the plow and particle breakage caused by the radius of the cutting tool. Capello [187] divides the mechanism of residual

stress into three categories of material properties thermo-plastic flow, phase transformation, and changes in volume due to deformation. The residual pull stress is generated a due increase in temperature in the cutting process and residual stress is produced due to the mechanical effect of cutting parameters. The surface residual stress in SiCp/Al composite material is greater than the residual pull stress, which indicates that the effects of cutting parameters are greater than the heat-influencing factors during processing composites. This phenomenon occurs due to the effect of reinforcing particles, which limit the plastic flow of the matrix to some extent in the cutting process. The reinforcing particles are pressed into the machined surface, and the stress distribution is affected, which causes the severe extrusion effect between particles and tools [159].

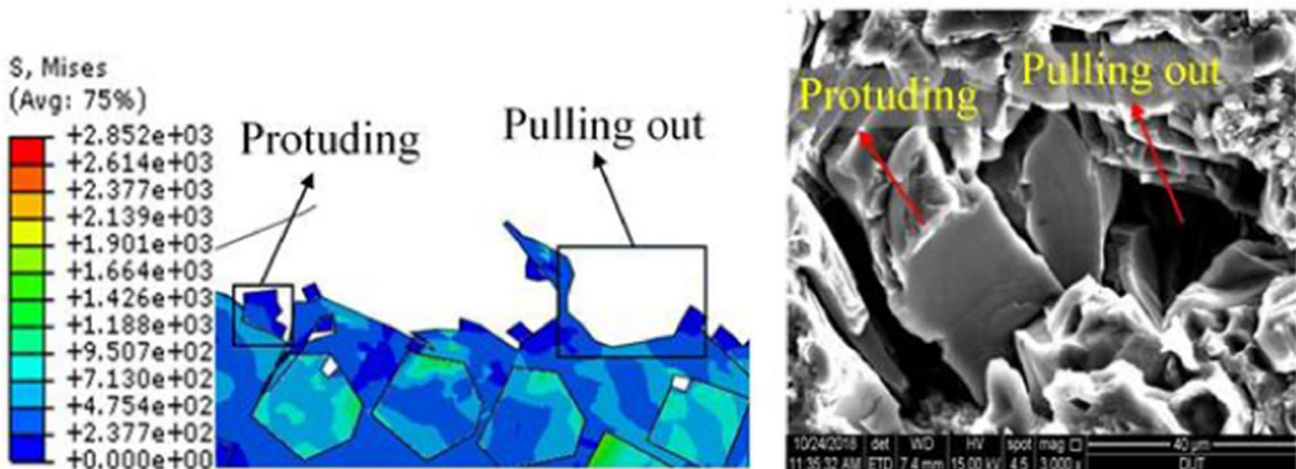
Bao et al. [188] investigated the material removal process and surface integrity of two high-volume fractions of SiCp/Al 45 and 65%SiC particles through experimental and simulation methods to understand the machining characteristics of difficult-to-cut composite materials. The Johnson–Cook constitutive model was taken to simulate the removal process for both 45 and 65% SiC particles. Figure 34 was evaluated using scratch micro-morphology of 65%SiC and Al alloy



(a) simulation morphology of burr formation (b) experimental results shows the burr formation during the removal process



(c) Simulation morphology of interface debonding (d) SEM images of experimental results of interface debonding



(e) Simulation morphology of pulling out and prodding (f) SEM images of experimental results of pulling out and prodding

**Fig. 34** Finite element simulation during cutting high-volume fraction of SiCp/Al 45 and 65%SiC particles. **a** Simulation morphology of burr formation, **b** Experimental results show the burr formation during the removal process, **c** Simulation morphology of interface debonding, **d** SEM images of experimental results of interface debonding, **e** Simulation morphology of pulling out and prodding **f** SEM images of experimental results of pulling out and prodding

for simulation validation. Figure 34 (a) and (b) show the burr formation of experimental and simulation phenomena is due to the large tensile stress, which creates the appearance of burr; Fig. 34 (c) and (d) show the interface debonding in an experimental result which is simulated in Fig. 34 (e); Fig. 34 (f) shows the simulation morphology of defects during cutting process as well as the experimental SEM image which shows the breaking and micro-cracks of SiC and Al tearing phenomena.

## 10.2 3D FEA for machining process of SiCp/Al

Machining of SiCp/Al was performed using 3D and 2D models using FEM on appropriate cutting parameters as shown in Fig. 35 (a) and (b) geometrical model of the A359/SiC composite to analyze the chip formation process, MRM, and surface quality [52]. Figure 35 shows the microscopic morphology of chips which shows serrated chips void fine particles in the shear deformation zone, which leads to periodic chip segments. The surface quality of the machined component of SiCp/Al shows minor cracks; particle pull out and particle debris and subsurface damages can be seen in the 2D model of Fig. 13 (a) and (b). A similar phenomenon also can be seen in the simulated process SiCp/Al using Abaqus Explicit software by Wu and Zhang [189]. They simulated the chip formation and predicted the stress behavior during material plastic deformation as shown in Fig. 36. The 3D views of the cutting cross section presented the distribution of particles and during chip formation. When the cutting tool performs the cutting operation, the tool-particle, particle–particle, and matrix-particle interactions discussed above were also found (Fig. 36 (a)–(c)). Serrated chips formed at the end (Fig. 36 (d)).

Dandekar and Shin [190] have used multi-step 3-dimension finite element analysis methods for damage prediction through Third Wave Advantage and Abaqus/Explicit combines two different software to predict the subsurface damage in SiCp/Al with 20% volume content. The researcher study the equivalent homogeneous material model in Third Wave Advantage, to develop the macroscopic machining model for analyzing the temperature and stress field variables, and then introduced it into the micro-model established by Abaqus/Explicit, to predict the failure and damage SiCp/Al composites. In addition, the random distribution of particle size and position in the composite material is achieved

by the developed algorithm. The efficiency of the cutting force and the secondary surface damages are simulated and verified with the experiment results. The equivalent homogeneous cutting model and microscopic surface failure model are shown in Fig. 37 and 38 [190].

In literature, both 2D and 3D models are used for the machining processing modeling and analysis; it is seen from several studies that FEM models are frequently used as 2D models. The 2D models are easy to develop compared to the 3D models, in perspective of less time-consuming and effort requirements.

## 11 Summary

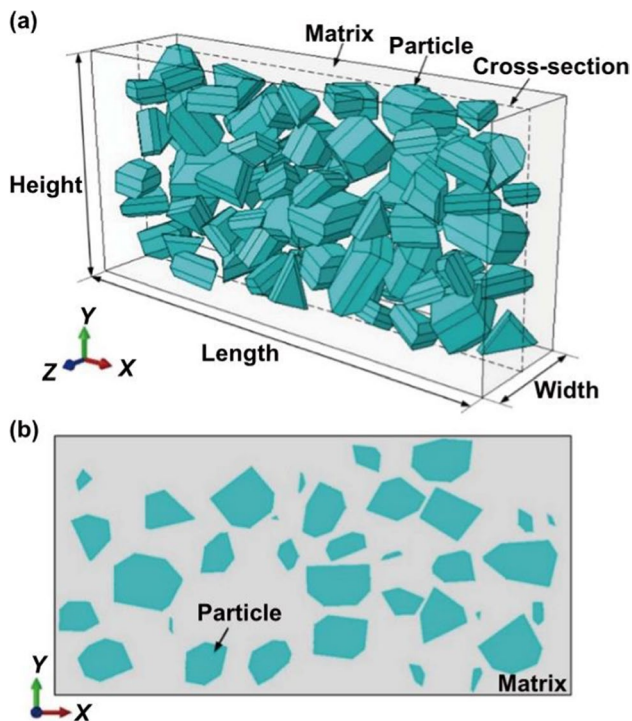
This paper reviews the characteristics of the turning process of particle-reinforced metal-based composite materials. The processing of SiCp/Al metal matrix composites was optimized and modeled using a finite element analysis method. The effects of cutting parameters on the machining process of silicon-based aluminum composites were analyzed.

Different machining factors were analyzed in turning process PMMCs namely tooling methods and mechanisms of tool wear, chip formation phenomena, and surface integrity also thoroughly reviewed in this chapter.

Regardless of how the processing method is used to process the MMCs, it needs to first consider the machining efficiency, surface quality, and tool wear in the cutting process of the metal-based composite. In turning and hybrid turning machining, the processing efficiency can be improved by selecting proper processing parameters, such as higher machining parameters, including cutting speed, cutting depth, and feed rate, and more cutting parameters are easily intensified on the tool wear and shortened the tool life. In addition, the volume fraction of different sizes of SiC particles and SiCp/Al composites have different types of effects on turning processes and processing mechanisms, chip formation, tool wear mechanism, and surface integrity. The increase in the percentage of silicon carbide particles reduces machining efficiency, increasing the tool wear rate, and reducing processing efficiency during the cutting of MMCs. Therefore, various optimization and simulation methods can be employed, namely finite element analysis, regression model, ANN model, and response surface method to predict and find the most suitable machining parameters and processing conditions to cope with the machining process of MMCs.

During the turning process of SiCp/Al MMCs, a variety of machined surface defects are produced such as adhering of SiC particles, chip debris, feed marks, pits, grooves, cracks, and tears being the most common in the cutting process. Generated defects on the machined surface are the major cause of deteriorating the surface quality and integrity





**Fig. 35** Geometrical model of the A359/SiC composite: **a** 3D model and **b** the micro-structure of a cross section at  $z = 16 \mu\text{m}$

of the workpiece. These different kinds of hindrances in the machining process seriously restrict meeting the application efficiently.

At a higher feed rate during the cutting process, the surface integrity deteriorates; however, the cutting speed consequences are not very clear in several machining research works. Cutting tool edge wears created a negative effect with higher cutting speed; therefore, on some occasions, it reduces the surface roughness due to an increase in cutting temperature in the cutting zone which makes the thermal softening of component and decreases the cutting forces. It is attributed to the machining characteristic, tool material process stability, and select range of the cutting parameters.

There is a diffusion wear mechanism in cutting tools occurring due to increasing cutting temperature and chemical affinity between the workpiece and cutting tools; however, the diffusion wear mechanism is not the main wear mechanism for several cutting tools. It is common in coated tools such as CBN and ceramic tools at higher cutting speeds. Oxidation wear is also a result of higher cutting temperature, which shows at higher cutting speeds, oxidation wear is usually shown during machining difficult-to-cut composite materials and alloys.

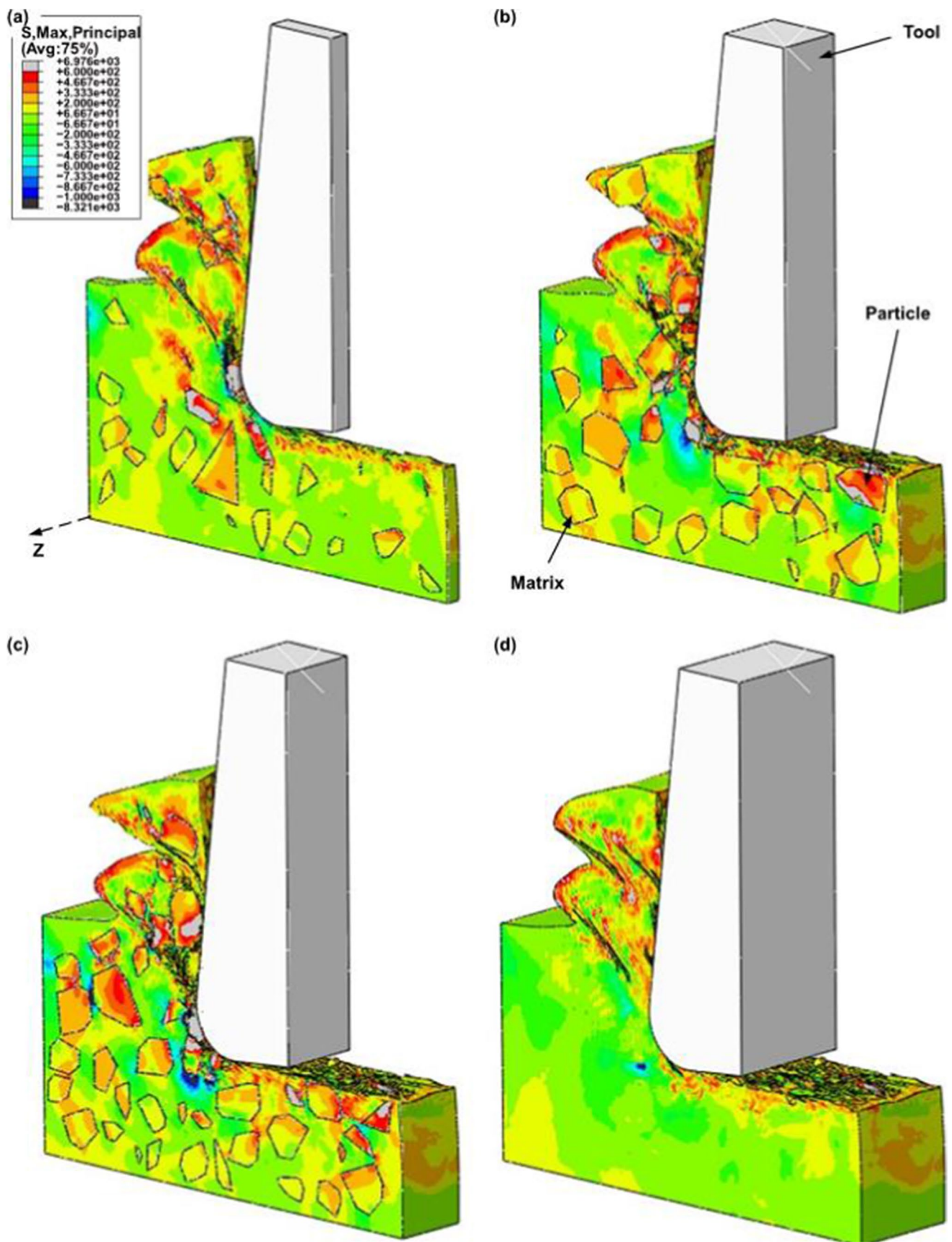
Key tool wear mechanisms in the machining process of SiCp/Al MMCs are found in abrasion and adhesion wear mechanisms which also majorly influence the surface quality of the workpiece. Furthermore, the different results

of the researchers show that the flank wear, chipping, notch, crater, and nose wear phenomena along with the BUE are the most common type of wear in cutting tools; sometimes, the catastrophic failure of the tool also occurs. These types of wear are depending on the choice of cutting parameters and combination machining conditions which influence the generation of temperature and stresses in the cutting process as well as the work hardening and saw tooth chips.

## 12 Future scope and trends

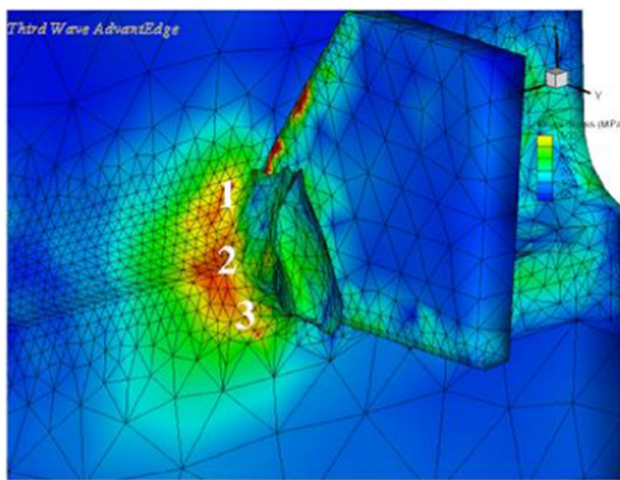
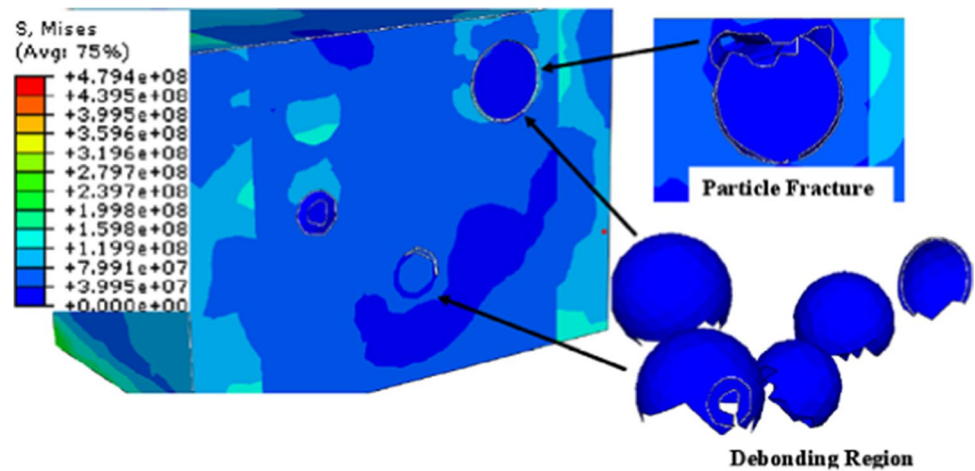
SiCp/Al composite materials have bright prospects in important industries such as aerospace and automobiles. In literature, several researchers explored many unprocessed areas during the SiCp/Al turning process of metal-based composites [87, 90, 188, 191]. Based on the groundbreaking work, a laser-assisted mixture of metal-based composites is provided. A study performed in [192] evaluated the LAM (laser auxiliary processing) of aluminum metal matrix composites and found that the matrix softened in the granules during processing. Similarly, findings in a research study [100] show the best machinability conditions during the turning process of metal-based composites. Using LAM, the author stated that the tool life increased by 180% during high-speed cutting, and further explained this phenomenon by the micro-structure observation of the chip morphology and the micro-structure of the metal-based composite. Under all processes, at higher cutting speeds, they have encountered unexpected high-cut wear, which requires further research and consideration. Some of the research work shows the effects of nanostructure CVD diamond coating on the emissions process and process-ability of the dust for the aluminum alloy/SiCA2009MMC. Dry processing eliminates the recovery cost and environmental hazards caused by coolant. However, it produces an inhalable particle to make a serious threat to health [193]. The hybrid turning process should be focused on the machining process of SiCp/Al composite materials. The cooling and lubrication process should be used in both turning and hybrid turning processes of SiCp/Al composite materials. Furthermore, some intelligent techniques such as sensor and machine learning techniques should be used in the turning process of difficult-to-cut materials SiCp/Al composite.

The machinability research performed under the perspective of hybrid machining is very limited for MMCs in this stage, there is more research needed to perform for improving and realizing the potency of the hybrid machining process with different techniques.



**Fig. 36** The 3D views of the cutting cross section at **a**  $z=4 \mu\text{m}$ , **b**  $z=16 \mu\text{m}$ , **c**  $z=20 \mu\text{m}$ , and **d**  $z=30 \mu\text{m}$

**Fig. 37** Damage observed to a depth of 72  $\mu\text{m}$ ,  $v_c = 300$  m/min,  $f = 0.1$  mm/rev [190]



**Fig. 38** Stress distribution phenomena during the three-dimensional nose-turning process MMC model [190]

The novel contribution of this review is depending upon the advanced methods and techniques for machinability of difficult cut material SiCp/Al and mentions the machining limitation and advantages. Highlighting the issues related to the tool wear, surface integrity, chip formation, and related hindrances and their possible solution and possible future research direction in turning machining and hybrid turning process and their optimization and simulation modeling methods are vital approaches.

In literature, a dry machining process of metal matrix composites is focused on by researchers, which creates issues related to high heat generation built-up-edge formation and adhesion during the cutting process. But there are very few studies related to the SiCp/Al MMCs emphasizing the machinability characteristics related to the different other approaches such as cryogenic machining, oxidizing machining, and hybrid machining techniques, and their finite element simulation modeling is still untouched and need to be taken for consideration.

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**Author contribution** Rashid Ali Laghari: writing original draft, design and conceptualization, validation, and project administration.

Muhammad Jamil: editing and writing—original draft; review of the original draft.

Asif Ali Laghari: drawing and designing figures and conceptualization, review of draft, and validation.

Aqib Mashood Khan: data curation; writing—original draft; and validation.

Syed Sohail Akhtar: data curation; formal analysis; visualization; and writing—original draft.

Samir Mekid: data curation; formal analysis; software; and writing—original draft.

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**Code availability** Not applicable.

## Declarations

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**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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