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ORIGINAL ARTICLE

A review on machining and optimization of particle-reinforced metal matrix composites

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Abstract
This paper offers a comprehensive literature review of the conventional machining processes along with optimization methods used in metal matrix composites (MMCs), such as turning, milling, drilling, and grinding machining processes. The tool wear mechanism and machinability of MMCs along with surface quality are discussed in the number of different manufacturing processes and examined thoroughly. Additionally, the manufacturing of MMC products through nonconventional machining processes such as electrical discharge machining (EDM), wire electrical discharge machining (WEDM), laser machining, electrochemical machining, ultra- sonic machining (USM), and high-speed machining are investigated and considered, in connection with MMC processing are discussed, as alternatives to the aforementioned processes. Moreover, this review focuses on the modeling of the machining process, finite element modeling, and simulation and optimization of soft computing methods in MMCs. The study will emphasize on the most generally used methods, namely, response surface methodology, artificial neural network, Taguchi method, and fuzzy logic as soft computing optimization methods. Finally, the comprehensive open issues and conclusions have drawn on the machining and optimization of particle-reinforced MMCs.

Keywords Al-MMCs · Conventional machining · Unconventional machining · Tool wear · Machinability · Modeling of machining process · Optimization techniques · Finite element modeling and simulation

1 Introduction

Nowadays, metal matrix composites are widely utilized in major industries such as aerospace, automotive, engine's cylinder sleeves, and bicycle frames due to their high wear resistance, elastic modulus, and high strength compared to weight, stiffness, low-density material, high thermal stability, and conductivity [1–5].

Term metal matrix composites (MMCs) provide optimal solutions for several applications and include a broad range of materials proportionally from low casting to complex reinforcement's metallic alloys. MMCs are ascertaining the number of application because of its advantageous properties including high mechanical and excellent abrasion resistance. SiC-reinforced aluminum is most favorable and common among composite material. One of the most popular categories of MMC reinforcements is silicon carbide (SiC) and alumina (Al_2O_3). Magnesium, titanium, and aluminum alloys were generally used as matrix phase. Though the MMC components manufactured to net-near shape through several methods, subsequent processing has found essential for giving them the required size and shape with proper surface integrity [6–10].

A crucial problem with the manufacturing of composite material is that they are causing difficulty in machining operation because of no uniform structure, abrasive properties, and high hardness of the reinforcement phase. The challenges arise due to excessive tool wear, surface roughness, poor surface integrity, and the increased cutting temperature during machining of composite materials. The existence of ceramic particles grades them hard to machine as their rapid effect results to increase tool wear. These facts affect both the performance of the machining process, the techniques, and tools required to manufacture a component. Such as in a case of traditional turning machining process of SiC/Al MMC, very tough and costly cutting inserts, such as PCD cutting tools, are needed to achieve required shape and size. Therefore, for

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machining of MMC, the cutting tool requires sufficient strength, toughness, and hardness to resist the high cutting loads. Muthukrishnan et al. [11] study the tool wear during turning of SiC/Al percentage of 10 and 20 particles by using the PCD tool. The experimental outcomes reveal that the flank wear was maximum along with dominated two-body abrasion and three-body abrasions while it has also proved that the (SiC) particle weight percentage is a dependent parameter on tool wear. Determining the machine tool wear is essential for the automated manufacturing process in order to avoid the machine malfunction due to deficiency or irregularity of manufacturing process. The process deficiencies can be avoided by correcting input variables or by stopping the manufacturing process; lots of work have done by the researchers in the area of tool wear and tool breakage. Adaption of the composite material has limited in many applications due to difficulties in the machining process and leads to excessive tool wear due to the presence of abrasive particles [12, 13].

This review based on the most general description of particle reinforced MMC machining processing of conventional and unconventional operations presented. More precise machining process of drilling, turning, milling, and grinding is studied for understanding the thoroughly operational behavior of MMCs. In case of unconventional machining, the electrical discharge machining (EDM), laser machining, electrochemical machining, ultrasonic machining (USM), wire electrical discharge machining (WEDM), and high-speed machining are considered to know about the machining conditions of MMC materials. The summary of the machining process is also presented. In the final part of the work, the latest modeling and optimization techniques in composite machining are studied which include modeling of machining process of MMC, finite element modeling, and simulation and others include response surface methodology, Taguchi method, artificial neural network, and fuzzy logic. Conclusion and open issues for the future work have drawn from this review.

2 Conventional machining processes of MMCs

Conventional machining processes, such as turning, milling, and drilling, are used to give the desired shape to the workpiece. Conventional machining processes are being investigated a lot in machining MMCs by researchers due to increasing quantities of MMCs which are being used in various engineering applications. The MMCs are being heavily utilized in the automobile and aerospace industries due to their low cost and better mechanical and wear characteristics, in comparison with other alloys and metals [14]. Characteristics of MMCs are quite desirable; they are difficult to machine due to the hard and abrasive reinforcement of SiC used, which results in increasing tool wear and consequently decreases the tool life. This increase in tool wear leaves the machining of MMC as a costly process, if not completely unfeasible [15]. Machining process of MMC component is influenced by work material, cutting conditions, statistical variation, and tool geometry during machining. In order to tackle these issues, a lot of work has performed, in order to conclude the optimum machining parameters and tools for MMCs.

2.1 Turning of MMCs

Turning is most generally and widely used machining process in the industry for the production of the component; this process is used to achieve the required size and shape for the finishing or semi-finishing of the rotational product. A lot of research is conducted by different researchers on several aspects of turning MMCs. Literature suggests that most of the aspects that affect the turning of MMC are mostly dependent on the type of material [16, 17]. Cutting forces are mostly recognized as one of the significant indicators of tool wear in the machining process. Many researchers have experimentally investigated the influences of cutting force on tool wear during turning [18, 19]. Davim, J.P. and Baptista, A.M investigated the relationship between tool wear and cutting force of the PCD tool while turning of MMCs. The evaluation of tool wear with cutting time has considered; increased tool wear is observed at higher cutting speed; two- and three-body abrasions is found to be dominant wear mechanisms [13]. The depth of cut and feed rate produce a major influence on cutting forces and surface quality of turned MMCs. A certain increase in the value of the depth of cut and feed rate increases the chance of tool wear and reduces surface quality. The quality of the finished surface is also affected by the tool materials used for MMC process, because of the tool material grain size which altered the surface quality of the final product [20, 21]. The improved value of surface roughness in hot machining of MMC is observed at 60 °C [22]. The cutting speed along with reinforcement volume fraction and particle size is found to be the dominant aspects of the cutting tool wear. However, coated tools provide more tool life in perspective of uncoated tools. On the other side, surface quality of the uncoated tools is found excellent as compare to coated tools specifically at reduced cutting speed [23–26].

Tool material should be harder than the particle reinforcement metal matrix composite for the machining process, while the cutting insert should be stronger to endure the produced wear mechanisms during the operation to sustain suitable tool life. From the studies, it also seems that the tungsten carbide (WC), polycrystalline diamond cutting tool (PCD), cubic boron nitride (CBN), and diamond-coated carbide tools are good in cutting of composite material and are able to improve the machinability with a good surface finish at moderate cutting conditions [27]. Due to this, mainly, the coatings to tool material are preferred in turning; abrasion wear is a major damage mechanism to the conventional tool and a brittle break is considered in the process [28].

It is very difficult to verify the proper tool for the process of MMC material. In the literatures, several researchers have been verified and promoted that the PCD cutting tool is more appropriate for turning of MMCs. It is due to the strong chemical and physical properties of PCD for the machining process. PCD tools are hard enough and do not chemically react with the component of MMCs [29]. And better machined surface can be obtained when machining SiCp/Al composites with higher cutting speeds [30].

2.2 Milling of MMCs

Milling can be defined as the machining process which utilizes the milling cutter to generate the required size and shape of the component, which is most generally and widely used machining process in the industry. The analysis from different research works is presented to observe the milling machining process of MMCs.

Ozben et al. [31] studied the impact of the process parameters on the metal matrix composite reinforcement ratio of 5, 10, and 15% of SiCp on mechanical properties. Experimental observation shows that increment in reinforcement ratio produces excellent properties such as tensile strength, toughness, and hardness but on the other end in machining process produces higher tool wear and surface roughness which is affected by the speed of spindle and feed rate.

In milling, feed rate is considered important parameters for machining MMCs. Higher feed rate produces the built-up edge (BUE) formation. Similarly, Turgut et al. [32] observed that the cutting force increases with feed rate and depth of cut and it decreases with increasing cutting speed. Surface quality decreases with increasing depth of cut and feed rate; however, the outstanding surface quality is achieved with increasing cutting speed. Abrakiadass et al. [33, 34] studied the machining process of SiCp/Al material in end milling operation which found cutting speed and feed rate are the most affecting on surface quality, while depth of cut has the negligible impact on surface roughness. It is also proved by several researchers that the feed rates seriously affect the tool wear in milling machining of MMC [35, 36]. Reddy et al. [37] experimentally investigated the surface quality and subsurface damage of SiCp/Al using TiAlN-coated carbide end mill cutters, in order to enrich the knowledge of machinability of the material. Measurements of surface roughness were performed through surface roughness tester and the average of values were taken, which shows the better surface roughness and lower tendency to obstruct the cutting tool. In milling of MMC, PCD tool is effective in various sets of cutting parameters and presents more tool life. The carbide and CVD-coated carbide cutting tools are not very effective; they have a lower tool life in the milling of MMC [38, 39].

2.3 Drilling of MMCs

Drilling is a machining operation which utilizes the drill bit for making the hole of circular cross section in the component material. The drill bit is forced into the component and used to make a hole at a required revolution rate according to the nature of the cutting process. Plenty of research had been conducted to investigate the process parameters and cutting tools used for the operation as well as their respective consequences in the finished MMC products. Huang et al. [40] reported that the drilling performance is majorly affected by the variation of the feed rate while machining SiCp/Al with 56% SiCp. Similarly, Rajmohan et al. [41] observed a negligible impact from the drilling speed on the workpiece, but on the other hand, the authors found feed rate as an effecting machining parameter during drilling the hybrid SiC/Al356. In most of the cases, cutting speed is used to observe as the minimal impact provider on the tool life, but the feed rate reduces the tool life [42].

The composition of MMC material, volume fraction, and hardness of reinforcement are the most significant factors that affect the tool life during the drilling process; apart from tool wear mechanisms, these also affect the type of chips formed in the cutting process [43].

There are several factors which can significantly affect the final quality of surface during drilling of MMCs such as cutting tool material, MMC material, cutting speed, and feed rate [44]. J. Paulo Davim revealed the dominant wear mechanism in drilling is an abrasive form of wear on the flank face of the drill; the specific cutting pressure and hole surface roughness were obtained by the multiple linear regressions [45]. It was also exposed that the wear mechanisms are two-body abrasion and three-body abrasion from the drilling of MMCs [46, 47]. CBN and carbide tool's wear mechanism were also observed as abrasion and adhesion wear in machining of Ti-MMC [48].

2.4 Grinding of MMCs

Grinding machining process is particularly required to obtain good surface quality and increase the dimensional accuracy of the workpiece [49, 50]. The grinding of metal matrix composites has achieved much more attention so far due to damage-free good surface finish.

Usually, electroplated diamond grinding wheels are recommended to machine the high volume fraction MMCs. usually, the parameters for the grinding operation are used to define for every machining process, as per the required demand of the such as dimensional accuracy and surface finish. In most cases, grinding machining should be the finishing operation for the respective workpiece and it removes a comparatively very small amount of material, about 0.25 to 0.50 mm depth. However, in some cases of grinding operations such as roughing. Thus, grinding is a diverse field.

Thiagarajan et al. [51] studied the surface quality and damage-free surfaces in the cylindrical grinding of SiC/Al MMC in order to find the effect of different grinding parameters such as depth of cut, feed rate, workpiece velocity, SiC volume fraction percentage, and wheel velocity. Experimentally assessment of surface roughness, grinding force, and temperature demonstrate that the better and damage-free surface is produced at low grinding force at high workpiece velocity and higher wheel speed. However, high depth of cut and feed rate during cylindrical grinding damage the surface and decrease surface finish. It is also mentioned that there are no defects and cracks found on the cylindrical ground surfaces at high workpiece velocities and high wheel speed, depth of cut, and low feed rate [51].

3 Unconventional machining processes of MMCs

The conventional manufacturing processes are always considered to be very hard to process the MMCs due to increasing wear of the conventional tool which influenced by the presence of hard reinforcing particles. As a result, unconventional machining processes are currently researched a lot in machining of MMCs due to increasing quantities of MMCs which are being used in various industrial and engineering applications. The unconventional machining processes is a machining process in which there is no direct contact between the component and the machine tool and another form of energy is transformed from electrical energy and utilized to remove the material. Unconventional machining methods, including electric discharge machining (EDM), electrochemical machining, laser beam machining, and ultrasonic machining (USM), have been applied currently to machine MMCs. It is suggested that the unconventional machining methods are possibly the best choice for machining MMCs [52–55].

3.1 Electrical discharge machining

Among unconventional machining process, EDM and WEDM have been shown to be the most suitable technique for machining MMCs [56–59]. EDM is a widely used unconventional material shaping method which is capable to shape material by high thermal energy due to electric discharge [14, 60, 61]. In EDM, electrode and workpiece avoid the direct contact because the machining process eliminates the vibration problems, chatter, and mechanical stresses. The material removal mechanism in EDM depends on the electrical energy which EDM turn into thermal energy through a series of discrete electrical discharges occurring between the electrode and the component submerged in a dielectric fluid.

The advantage of EDM is its high capability to process the complicated machine parts with precisely required shape, size, and dimensions such as injection molds, cutting tools, dies and different items with complex shapes. EDM mechanism is melting and vaporizing of materials by plasma channel causes detachment of the reinforcement**.**

EDM used in various industrial applications such as electronic industries, automotive, machines, domestic appliance telecommunications, packaging, watches, surgical instruments, and aeronautics. EDM was first started to be used in 1943 when Boris and Natalya Lazarenko, Russian scientists, invented the principles of EDM, later which were found very fruitful for eroding effect on hard material such as tungsten or tungsten carbide [62, 63]. Eroding effects in EDM is controlled through the principle of electric spark discharge on electrodes. Thus, it is thermal abrasion process. The sparks is produced between workpiece and electrode in a dielectric liquid, generally oil or water; the spark produces the temperature which ranges from 8000 to 12,000 °C [64] or as high as 20,000 °C [65]. It also works as a cutting tool; there is not any mechanical interaction between the workpiece and tool during the material removing process; they separated with a small gap which ranges from 0.01 to 0.50 mm; this spark gap is immersed in a dielectric fluid [66–68]. Purohit et al. [69] observed material removal rate increase with increasing hole diameter of the electrode, rotating speed of electrode with reducing the number of grain size of Sic particulates. Tool wear rate was observed higher with decreasing grain size of Sic particulates and increasing the hole diameter of the electrode. Subramaniam et al. [70] studied the performance of different electrode materials such as tungsten, copper, and brass and optimum machining time while electrical discharge machining of SiCp/Al MMC material. Results reveal that the copper performed better as an electrode material and the current is the most important factor.

3.1.1 Wire electrical discharge machining

Wire electric discharge machining or electric discharge wire cutting was first came into operational condition in the manufacturing industry around 1960. In 1974, optical line follower system was applied by D.H. Dulebohn to automatically handle the wire EDM machining process to manufacture the required shape of the component [71]. Wire EDM process is basically a thermoelectric process which works as eroding material from the workpiece through a wire electrode (cutting tool) by a number of distinct sparks. The dielectric fluid is continuously served in the machining zone to produce a thin gap between the workpiece and cutting tool and flush away the eroded debris. In order to achieve the desired accuracy and 3D shapes of the workpiece, the movement of the wire is controlled by numerically electrode wire having a diameter between 0.05 and 0.25 mm [72–75]. Marigoudar et al. [76] studied the impact of different parameters such as wire feed rate, material removal rate (MRR), voltage on quality, pulse on time and pulse off time, material, and kerf during machining of SiCp/Al6061 in WEDM. Voltage is observed as an important factor for MRR and kerf while wire feed rate and pulse off time are less significant factors. Maximum values of material removal rate and kerf were acquired at reduced pulse on time and lower voltage. Pramanik [77] studied the machining of MMC in WEDM with different machining variables such as pulse on time, pulse off time, and current with keeping other parameters constant. Results show that MRR increases with a pulse on time and current, while pulse off time was less effective. Reinforcement content has a negative effect on MRR. MMC with 15% of SiCp creates hindrance to wire for smooth operation, in order to increase MRR need to higher the pulse on time and current during machining.

3.2 Electrochemical machining

Electrochemical machining (ECM) has been extensively used for machining MMCs, due to its long tool life and higher MRR capacity. ECM is based on the principle of anode electrochemical dissolution. ECM frequently is used for difficult-to-cut materials such as MMCs; the electrochemical dissolution is independent of the material toughness and hardness and generates good surface quality [78]. Senthilkumara et al. [79] studied ECM of 15%SiCp/Al and developed the mathematical model of MRR and surface quality. The optimal combinations of these parameters are obtained through experimental data and successfully achieve the maximization MRR and the minimum surface roughness. Senthilkumar et al. [80] also observed the similar effect while ECM on 10%SiC/Al produced by stir casting. Kumar et al. [81] attempted to machine the SiCp/Al356 by using ECM. Taguchi's L27 orthogonal array was chosen to study the effect of various machining parameters like electrolyte concentration, feed rate, applied voltage, and percentage of reinforcement such 5%, 10%, and 15% by weight on maximizing the material removal rate. Results reveal that the SiC percentage has more effect on MRR along with the process parameters such as feed rate, the concentration of electrolyte, and applied voltage. Ayyappan et al. [82] presented the effect of ECM process variables at performance measures, and the final results showed that the process variables including feed, voltage, and current significantly influence the operating costs while the tolerance is influenced by all the parameters.

3.3 Laser beam machining

Laser beam machining (LBM) extensively used as an advanced machining process for machining MMCs, which is a thermal energy–based machining process to cut the material without contact with a component. LBM is working on the principle of melting and vaporizing the extra material to produce the required shape to the component. The materials like low thermal conductivity regardless of hardness or brittleness are particularly favorable for laser machining. LBM can produce very narrow cutting width up to 0.25 mm as well as complex geometry. Hong et al. [83] studied the laser beam processing of a 6061 Al MMC using a 3-kW continuous wave CO_2 laser. The effects of LBM parameters such as shielding gas, laser power, and cutting speed on the quality of the cuts were examined. X-ray diffraction, scanning electron microscopy, and optical microscopy were used to examine the laser-treated zone. Experimental results showed that 6061 Al MMCs were cut effectively using a laser.

Manjoth et al. [84] experimentally studied the laser operation of Al7075–TiB2 composite; the surface roughness, volumetric MRR, and composite dimensional accuracy are targeted in the observation of LBM. Some of the input parameters such as nozzle diameter and power keep constant through the use of air as assisting gas. It was observed that the speed is most significant for surface quality. However, the gas pressure and standoff distance have minimum impact on the surface quality.

Müller et al. [85] found the crucial advantages of LBM while machining the Al MMCs such as rough cutoff applications as well as suitable for high feed rates up to 3000 mm/min. However, the surface quality produced by LBM is not fruitful such as burrs at the exit of the laser were observed and thermal input prompted microstructural changes in the MMC.

3.4 Ultrasonic machining

Ultrasonic machining (USM) is generally associated with lower material removal machining process in nonconventional machining technique. USM removes unwanted material on the basis of using high-frequency oscillations of a shaped tool using abrasive slurry on the brittle work material. In USM process, equipment is safe to operate and little or no heat is produced during the machining process as well as lower machining cost. In USM, cutting tool vibrates longitudinally at the frequency of 20 to 30 kHz with an amplitude ranges between 0.01 and 0.06 mm depends on the work surface with a light force [86]. Zhong et al. [87] experimentally analyzed the MRR in USM with the statistical analyses and developed regression model. Three main factors (i.e., feed pressure, feed speed, and abrasive granularity) influencing MRR were considered. The experimental results show that the regression model correctly reveals the effect of process parameters on the response; the abrasive granularity has the higher effect on MRR followed by the feed pressure and feed speed. Mohanty et al. [88] investigated MRR of USM to machine MMC with different SiCp weight fractions. It is concluded from experimental results that the higher MRR is achieved by increasing voltage and harder abrasive material from the workpiece and with higher slurry concentration. Zhong et al [89] investigated the machinability of SiCp/Al using diamond turning with the assistance of ultrasonic vibration. The effect of different machining parameters was investigated on response parameters such as surface roughness. An experimental result shows that the surface roughness produced with ultrasonic vibration is improved as comparing to that without ultrasonic assistance.

3.5 High-speed machining

High-speed machining (HSM) is considered advanced technologies of improving machining quality, efficiency, and accuracy. The first proper definition of high-speed machining was given by Carl Saleman in 1931 [90]. It is assumed that HSM possesses five to ten times higher cutting speed than the conventional machining and performed on the material having the hardness within the 45–68 HRC. The high hardness material machining requires carefulness because of rapid tool wear and requires high hardness tools such as coated carbide, PCD, TiAlN, TiN, and Al_2O_3 [91]. Collins [92] studied the issues of MMC machining at high speed with PCD cutting tools. The experimental result shows that cutting force increases with increasing abrasion of the tool. Surface roughness in finishing operation was also unsatisfactory. Newly developed single crystal diamond and CVD diamond tool, comparing to PCD tool, shows great performance for high-speed dry machining of SiCp/Al. Liu et al [93] studied the surface roughness and MRR in high-speed grinding of particulate-reinforced titanium matrix composites. Jadhav et al. [94] also obtained the optimum surface roughness by hot machining SiCp/Al at 60 °C preheating temperature.

Mainly, a greater part of research work puts emphasis on machining of SiCp/Al with low volume fraction, i.e., lower than 30%. However, SiCp/Al with a high percentage of reinforcement found many applications. It is reported that high-speed machining SiCp/Al rarely was found in published research work [95]. Wang et al. [96] studied high-speed milling of SiCp/Al with high volume fraction (vol.65%, grain size of 10 μm) with PCD cutting tool to analyze the influence of milling parameters such high cutting speed, feed rate, and tool wear. The flank wear and crater wear were observed in PCD tool, and tool wear increases move as increasing cutting speed more than 300 m/min. Sharma et al. [97] found the inverse effect of cutting speed on cutting force, i.e., the cutting force decreases with the increases of cutting speed. However, the higher force is observed when the cutting depth, approaching angle, and feed rate variables were increased. Brun et al. [98] found PCD tools achieve a better life during cutting vol.40%SiCp/Al and suggested that the lower cutting speed will increase the tool life. Wang et al. [99] indicated that the cutting speed exceeding 300 m/min in machining MMCs is not in favor of industrial applications for the abrading action of SiCp and generation of temperature as well. The higher feed rate was suggested in machining MMCs to produce machined surface with good quality. There is an important role of PCD grain size to reduce the tool life at exceeding cutting speed [100].

4 Summary of machining processes of MMCs

4.1 Machinability

The term machinability can be described as the material characteristics during the machining process; from the definition, it is understood that there are numerous factors that can affect the machinability of materials.

Material composition and microstructure of MMC define a major portion of the machining process's parameters; many factors during machining are dependent on the structural and chemical composition of the material. Such aspects contain the developing surface alterations, forces, developing faults, and the chipping process. Final machinability of the component is also heavily affected by the mechanical and chemical relationship between the reinforcement and matrix material of an MMC. The important factors that characterize the machining performance and cutting tool during machining include tool type, tool geometry, and stability of machine and tool material.

Machinability of the material is mainly described on the bases of tool life. This method mentioned by several researchers, and it is very fruitful when relating with material which possesses the related type of properties and power intakes, but one is more abrasive and thus reduces the tool life. The major drawback with this method is that tool life is not only dependent on the type of material, it also includes other machining aspects such as cutting tool geometry, cutting tool clamping, the tool material, and cutting parameters. Also, the machinability of material for one cutting tool type cannot be compared to another tool type (i.e., carbide tool to HSS tool). The detail of the above-described properties was shown in Fig. 1 [38, 101].

Some of the factors which are more dominant during the machining process of MMCs are summarized below.

- Tool life and wear mechanisms
- Cutting force and power required
- Chip formation and behavior
- Built-up edge (BUE) formation trend

In the machining process, cutting tool interacts with the workpiece and chip formation process begins by shearing the workpiece material. The produced heat from the plastic deformation of the workpiece material and the friction between the workpiece and cutting insert transferring in the tool make this cutting process become more severe.

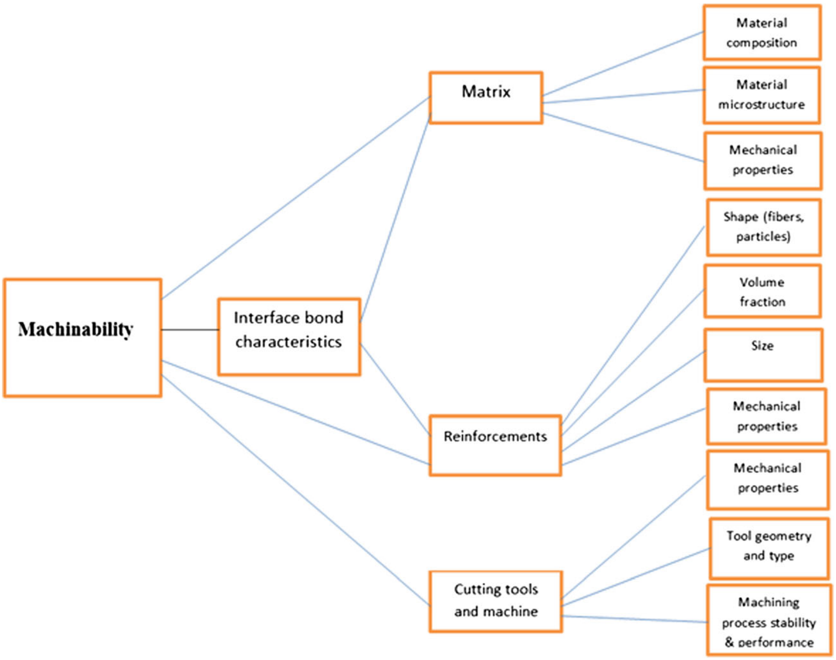

Fig. 1 Properties that affect the machinability of a material [38]

From the literature, it is concluded that besides MMC materials, variation, tool material, and typical machining parameters in conventional machines have a major effect on the surface quality of machined MMC. Higher feed rate deteriorates the surface quality. However, higher depth of cut possesses an adverse effect on the tool life. In machining parameters, cutting speed does not play a significant role in the surface quality, but affects much on the tool life as well as the BUE. In MMC machining, tool material possesses a major role on both tool life and surface quality. PCD tool finds better tool life and surface finish with wide ranges of cutting parameters.

In unconventional machining process, the material removal of MMC is achieved through melting and vaporizing the material from the component. In EDM and WEDM, generally, the tool wear, surface quality, and MRR increase with higher current, pulse on time, and voltage [102, 103]. Tool wear resistance increase with electrode possesses higher melting temperature in machining of MMC. The chip shape produced in the cutting process is different. There are saw tooth, continuous, disintegration, and other forms. This is related to the generation of cracks and the effect of the extended path [104].

4.2 Tool wear mechanisms

4.2.1 Abrasive wear

Abrasive wear mechanism is recorded as most principal wear mechanism occurring in the machining process of MMCs [105]. Abrasive wear is the type of wear which occurs as a result of the reinforcement particles impacting the cutting edge during machining MMCs. Furthermore, these particles maximize thermal and mechanical load on the cutting tool due to their relative movement [106]. In particular, the volume fraction, shape, and distribution of the reinforcement inside the MMCs are the main factors that affect the extent of abrasive wear on the cutting tool [107].

4.2.2 Flank wear

Flank wear is considered the most common type of tool wear. It is a result of mechanical and thermal load that strains the cutting edge. Cutting forces have the major impact on the tool flank wear [108]. It also develops when abrasive and hard particles of the workpiece material impact and increase heat at cutting edge. The flank wear is measured by its width, which is increasing constantly during machining. Flank wear is also affected by the cutting parameters during machining MMC [109].

4.2.3 Built-up edge

BUE is formed when some chipped off particles of chip stick on the rack of the cutting tool. Usually, the main cause for this phenomena lies with the higher cutting speed, which increases thermal loads in the cutting tool-chip interface [107, 110]. BUE offers protection to the tool cutting edge; it generally increases the tool life, which also called abrasion protection [38]. But the BUE degenerate the surface quality.

5 Latest modeling and optimization techniques in composite machining

5.1 Modeling of machining process of MMCs

The widespread machinability study of MMC's properties using various machining processes, both conventional and unconventional, and consequent behavior of these processes should not be adequate for the comprehensive expertise of MMC cutting processes due to intrinsic weakness in the experimental techniques. Therefore, numerical and analytical models have been utilized in accordance with experimental data in order to understand deeply the machining behavior of MMCs.

Well-developed model for the wear mechanism would broadly help to understand the behavior of the machining process and consequently reduce the experimental cost of the machining process.

Several researchers have developed the analytical models to understand the machining behavior of MMCs and offered the fundamental understanding of many issues such as machinability, material strength, tool wear, cutting force, chipping, failure, and stresses in MMC machining process.

There are three different types of analytic models, which are categorized at the basis of their respective origin: (i) Ernst-Merchant orthogonal cutting theory, (ii) the theory of plasticity and elasticity, (iii) the Taylor formula for machinability study and tool wear.

Kishawy et al. [111] predicted the energy-based analytical cutting force model for the orthogonal cutting process of MMCs. Specific energy and energy consumed for deformation and deboning are estimated. The cutting performance was also measured on different ranges of feed on different volume fractions of SiCp/Al.

Hung et al. [112] identified the cumulative wear of turning and facing tools and predicted the analytical models derived from the Taylor equation for Al-MMC. Results show that the tool wear does not influence the order of different machining speeds. However, abrasive wear was found to be the dominant wear mechanism. Models derived from the modified Taylor equation are used to optimize the tool life and study cutting conditions and related subsurface damage [113].

Pramanik et al. [114] predicted the cutting force for particle-reinforced MMCs using Merchant's analysis with the aid of the Griffith theory of fracture and slip line field theory of plasticity. The theoretical model developed for particle fracture force, plowing force, and the chip formation force is in good agreement with the experimental measurements.

Geometry modeling of MMC is a fascinating issue. The major hurdles are the precision of specification of the reinforcement geometry. Xiaoping Li et al. [115] developed a model of tool wear for MMC machining using the correlation based on the movement of reinforcement particles and their geometric characteristics. Uday et al. [116] conducted the statistical analysis to examine the machining parameters influencing on the shear angle. Qualitative analysis of chip formations was conducted from analytical formula to measure the shear angle and thickness. The model shows that the volume fraction and size of reinforcement expressively influence the chip formation mechanism. Furthermore, Pramanik et al. [117] investigated the relationship between friction angle and shear angle for machining MMC to estimate the contact stresses and cutting forces at the chip tool interfaces.

Tevatia et al. [118] developed the fatigue crack growth live model for short fiber–reinforced MMC under the controlled strain conditions. Yield strength effects were measured on the basis of a modified shear lag theory, and the modeling was established on the basis of fatigue fracture mechanics theory. Several material models have also developed for understanding the machining process of MMCs. In the literature, several models have been developed to study the MMC materials, which are modeled using Johnson cook model, plastic/elastic deformation model [119, 120], temperature-independent hardening and temperature-dependent models, or Hooke's law [121, 122]. For chip formation modeling in machining MMC, Tsai-Hill model was employed [123].

5.2 Finite element modeling and simulation

Finite element modeling (FEM) is one of the most common and widely used techniques in numerical simulation for analyzing the machining processes. FEM technique provides the facility for examination of the machining processes with all its complications in terms of material elasticity, plastic behavior, material metallurgy, fracture mechanics, heat transfer, and the effect of using coolants, etc. Finite element analysis is also providing prediction functions of material deformation, cutting forces, temperature, stress, and strain during a specific machining process. The literature associated with the simulation of machining process using finite element methods from 1976 to 2002 was compiled by Mackerle [124, 125]. Chen et al. [126] presented a 3D finite element end milling model with equivalent homogeneous material (EHM) model, which was drawn from the quasi-static and Split-Hopkinson pressure bar tests is developed with ABAQUS software in order to define the cutting process of SiCp/Al6063/30P. The model was confirmed with experimental results, which reveals that projected forces are reliable at a chosen speed and feed rate combinations. The deviation of *Fy* and *Fx* cutting forces are controlled within 20%.

Liu et al. [127] presented the simulation of thin wall part machining process of SiCp/Al composite with PCD tools. During 3D machining process simulation, cutting forces were put into observations due to the deformation of part. Fathipour et al. [128] built 2D finite element models of SiCp/Al based on

ABAQUS/Explicit to simulate the machining process with titanium carbide (K10) cutting tools. Machining forces and chip formations were investigated for three different MMCs with 5%, 15%, and 20% of SiCp respectively. The simulation results are very close to the experimental ones. Mahesh et al. [129] presented the hot machining and finite element analysis of SiCp/Al220 with 10% and 30% of SiCp respectively, by using cemented carbide coated with TiAlN. And cutting parameters and preheating temperature were considered. Finite element analysis results were found very close to the experimental ones. Liu et al. [130] studied the 2D microscale finite element models composed of a SiCp/Al particle to observe the influence of the particles of a tool and cutting speed. The examined simulation results and the experimental measurements of micromilled surfaces were compared and the results are very close. Wang et al. [131] studied the high-speed machining of the high volume fraction SiCp/Al6063 and simulated the process by using 2D FEM in ABAQUS/Explicit software. Interaction of matrix was predicted with multiphase models, which was also found very helpful for predicting particle and tool as well complicated stress distribution phenomena in the cutting region.

5.3 Optimization techniques

There are several methods to optimize the machining process. Soft computing method is a typical category, including response surface methodology (RSM), artificial neural network (ANN), Taguchi method, and fuzzy logic. These methods are based on two factors, i.e., the under observation machining process and the nature of the optimization methods.

5.3.1 Response surface methodology

RSM introduced by George E P Box and K B Wilson in 1951 [132] is used to optimize the response of process which is influenced by several input decision variables through various statistical and mathematical techniques. RSM particularly uses the structure of the designed experiment to attain optimal response.

While using the RSM, the first step is to establish the optimization model in the design of an experiment. For example

$$Y = F\ (x_1, x_2, \ldots, x_\mathrm{n})$$

where Y is the desired function and F is the response function of variables (x_1, x_2,…,x_n). For optimization of machining process, (x_1, x_2,…,x_n) represents a combination of machining parameters.

Gaitonde et al. [133] observed that feed rate is the dominant variable influencing on cutting power and force while turning the MMC material with PCD tools by using RSM approach. Similarly, Arokiadass et al. [134] used the RSM approach to observe the SiC weight percentage on flank wear and the obtained results are in close agreement with the experimental ones. ARSM mathematical model was developed in [135] to investigate the impact of machining parameters on Al-SiC-Gr hybrid composites. The adequacy of the model was checked through ANOVA, and the turning process of the composite is enhanced by using the proposed methods. Premnath et al. [136] experimentally investigated the milling of Al 6061-aluminum alloy reinforced with different weight fractions of Al_2O_3particles. The RSM model is used to optimize the parameters, and the predicted values of the model are close enough which can fairly predict the response. Tamang et al. [137] studied the turning of SiCp/Al with the TiN-coated carbide cutting tool to investigate the mechanism of tool wear and surface finish. ANN and RSM models were developed to predict the accurate values. RSM approach was also applied to optimize machining parameters of CNC end milling of LM25 SiCp/Al with carbide insert, and the deviation of the predicted values is less than 5% [138]. The machinability evaluation of MMC based on RSM is presented in [139], and a conclusion was drawn that surface roughness is affected by BUE formation at lower cutting speed.

5.3.2 Artificial neural network

ANN is one of the widely used soft computing techniques for modeling the MMC machining process to establish the mathematic relationship between the input and output via an appropriate training process. Further literatures on the characteristics of the ANN were detailed in [140–142]. ANN was considered a highly reliable technique. The effective application of ANN depends on the determination of hidden layers and number of neurons in hidden layer and also the most suitable training algorithm.

Santosh et al. [143] studied the turning of SiCp/Al with PCD tool and a multiresponse predictive model was developed using ANN. The model predicts very good outputs with average percentage error of 4.46% for surface roughness and 7.26% for MRR. Liujie et al. [144] developed the separate ANN machining models of Al-MMC corresponding to cutting speed and feed rate. Feed forward ANN model was built and trained by using comprehensive data sets. The results show that the cutting speed significantly influences the tool wear and machining power. Jeyapaul et al [145] investigated the machining process optimization of 15%SiCp/Al with coated and uncoated tungsten carbide. An ANN model was developed for analyzing the relationship between input parameters (i.e., cutting speed, feed rate, depth of cut, and tool materials) and response parameters (i.e., cutting force, cutting power, shear strength, MRR, and surface finish). The optimal process parameters are selected based on the output given by the ANN.

5.3.3 Taguchi method

The Taguchi method is a statistical technique and often comes in to practice before the number of experimental runs. It is used to perform the desired experimental runs in such a way so as to find the less set of experiments with the acquired number of variables and values. After the completion of experiments, the obtained results are often analyzed using ANOVA to estimate the influence of each variable on the results. The correlations between the variables are also acquired by ANOVA analysis [146]. Taguchi and statistical techniques were used to investigate the turning process of SiCp/Al with coated carbide tools, and the results reveal that cutting speed is the most significant parameters affecting on flank wear and feed rate on surface roughness [147]. The predicted values are very close to the experimental ones. Ashok et al. [148] also adopted the Taguchi method to study the turning process of SiCp/Al with carbide tools. The results of the experiments demonstrated that the predicted values of surface roughness and flank wear from the Taguchi model are in good agreement with experimental results. Sriprateep et al. [149] utilized the Taguchi technique to predict tool wear, surface quality, and required power for turning A356/20/SiCp-T6 MMC with PCD insert. The results reveal that Taguchi method is appropriate to resolve the stated problem with the minimum number of trials. Shetty et al. [150] presented Taguchi's optimization methodology in turning 15% vol. SiCp/Al6061 (SiC particle size is 25 μm) with cubic boron nitride (CBN) KB-90 grade along with steam as cutting fluid. It was found that steam pressure is the most effective parameter among the all-significant parameters.

5.3.4 Fuzzy logic optimization

Numerous methods based on the fuzzy set theory, such as fuzzy expert system, a combination of genetic algorithm and fuzzy system, and the gray-fuzzy analysis method, is a vital tool used for predicting the MMC machining process. Fuzzy logic is a most influential technique for the making of an effective rule-based confident expert system [151]. The gray-fuzzy theory is also renowned as the significant for manipulation of uncertainty and discrete data. Thus, a combination of the two methods can provide an improved reasoning grade for the prediction system and shorten the uncertainty of the final results [152]. Gray-fuzzy analysis is utilized by several researchers for making the prediction models. The comprehensive discretion is detailed in [153]. Gray fuzzy is such an optimization method which is successfully used for machining process prediction of MMCs.

Santosh et al. [154] studied the turning process of SiCp/Al with PCD tools and a multiresponse predictive model was developed based on gray-fuzzy logic. The predictive model exhibits adequate correlation with the experimental result as long established by the validation test. Kalaichelvi et al. [155] took the spindle motor current to observe the wear mechanism in turning SiC/Al LM25 with cemented carbide tool. The relationship is developed in the model to figure out the impact of parameters on the current signal of spindle motor. Hence, the tool wear mechanism and its state were concluded and predicted through the fuzzy approach. The data sets of the operations were in close agreement with the experimental ones. The effect of machining parameters on surface roughness was presented to study the milling process of SiCp/Al356in [155]. Analysis of variance reveals that feed rate and spindle speed have a significant effect on surface roughness. The combination of high spindle speed, low feed rate, and low depth of cut can produce better surface roughness. And a developed fuzzy model was used to develop an expert system for process control. The prediction accuracy of the model was verified with accuracy up to 88.44%.

6 Open issues

There is a substantial amount of literatures available in the manufacturing process of MMCs. However, still, there are major areas to be considered for thoroughly understanding the machining behavior of particle reinforced MMC materials.

- Modeling of machine process as well as MMC material.
- Removal mechanisms of MMC material in conventional machining parameters are suitable for surface roughness. However, in case of unconventional machining parameters, it still needs to work a lot. For example, laser machining used to melt the workpiece surface will lead excessive heat generated during the cutting process.
- There are vast challenges of the optimal combination of machining parameters for both conventional and unconventional machining processes.
- There is a potential area for unconventional machining for exploring the interaction between plasma, electrode, and workpiece.
- The major problem in conventional machining of MMC is the excessive tool wear and breakage of the cutting tool.
- There is not enough literature available for understanding the EDM and electrochemical machining of MMCs; there is a need for deep investigation to understand the unconventional processes.
- It is observed in the literature that the surface roughness prediction model is focused on by adopting soft computing methods.
- Geometry modeling of MMC is a fascinating issue. The major hurdle is the reinforcement geometry with high accuracy.

7 Conclusions

The state of the art in machining and modeling in scientific research of MMCs has been presented in this study. Due to the excellent mechanical and thermal properties of the MMCs, it possesses a lot of potential for the future industrial applications. The machining processes of MMCs are challenging and it needs to be addressed urgently. Extensive research has been presented by many researchers on the machining process of MMCs in order to understand the nature of machining MMCs. The machinability, tool wear mechanism, surface quality, and its optimization are thoroughly studied in this review.

- The study in conventional machining process of MMCs such as turning, milling, drilling, and grinding machining processes shows that the PCD has been found excellent than PCBN and carbide-based tool materials.
- Cutting speed in machining MMC plays a major role. Some studies show that the cutting speed is more responsible for tool wear and surface roughness due to heat generation in the machining zone and interaction of chip-tool component.
- Unconventional machining processes exhibit certain advantages in machining MMCs due to no physical contact between the cutting tool and the component. Operation of laser machining was found adverse for surface finishing because of excessive heat produced during the manufacturing process.
- The optimization methods show that there are various successful and robust applications such as response surface methodology, genetic algorithm, Taguchi technique, fuzzy logic, and artificial neural network. These applications are found reliable in the design of experiment and selection of optimal parameters. Many researchers also employed the sensor-based signals and found promising results; the cutting force was also observed as a successful input parameter for developing models.
- Finite element modeling and simulation provide an alternative practice for investigating the interaction between the cutting tool and composite materials.
- Tool materials with hardness lower than SiC particle do not survive enough tool life in the machining process.
- From the literature, it is understandable that the predominant wear mechanism during machining MMCs is two-body abrasion and three-body abrasion.

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