

Developments in Conventional Machining of Aluminium Matrix Composite Material: A Review

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Abstract: Aluminium matrix composites (AMCs) materials are continuously displacing traditional engineering materials because of their advantages of high stiffness and strength over homogeneous material formulations. Properties of AMCs can be tailored to the demands of different industrial applications by suitable combinations of matrix, reinforcement and processing route. Presently, several grades of AMCs are manufactured by different methods. The hard ceramic component that increases the mechanical characteristics of AMCs causes quick tool wear and premature tool failure in the machining operations. Therefore, the solution of the machining problems is one of the prerequisites for a widespread industrial application of AMCs. This paper provides a review of various research activities and various developments in the field of conventional machining of AMCs. Researchers have explored a number of ways to improve machining efficiency by traditional methods. This paper presents an overview of AMC material that reveals the role of the reinforcement particles on the machinability of AMCs and provides a valuable guide for a better control of their machining processes.

Keywords: Aluminum Metal Matrix Composite, Conventional Machining, Machinability, Surface Roughness, Tool Wear

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1 INTRODUCTION

During the past 50 years, materials, and design have changed the emphasis to pursue lightweight, environmentally friendly, low cost, superior character and high performance materials. Parallel to this trend, Metal matrix composites (MMCs) has been attracting growing interest. MMCs attributes include alterations in mechanical behaviour and physical properties by the reinforced filler phase. MMCs are materials in which reinforcement, typically a ceramic based material, is added with the purpose of improving the material's properties. Aluminium alloys are light in weight and they find wide applications in industries. Aluminium and its alloys have the most attention, as matrix materials for MMCs.

The change in volume fraction of reinforcement in the aluminum matrix causes the change in the properties of the AMCs. Adding magnesium to Al-B composite, through increasing the hardness of the obtained composite substantially shows increased Vickers microhardness [1]. Of the variety of ceramic materials that can be used as reinforcements, silicon carbide (SiC) and aluminium oxide (Al_2O_3) are the two that have shown the greatest use as a result of their favourable combination of density, price, and property improvement potential. Reinforcements also come in a variety of forms: continuous fibers, whiskers, and particulates. Change in the properties of the composites depends on type of reinforcement, its forms and its volume/weight percentage in matrix.

The young's modulus of nanocomposites (Al_2O_3 -SiC) decreased by increasing the volume percent of SiC and the values of hardness and fracture toughness of the nanocomposites increased by increasing the volume percent of SiC up to 7.5% and then decreased slightly. The ballistic energy dissipation ability is decreased by increasing the volume percent of SiC up to 5% and then increased slightly [2]. When these reinforcements are combined with an aluminium matrix, the resulting material has significant increases in elastic modulus (stiffness), wear resistance, and in some cases, strength and fatigue resistance. The shape and size of AMCs can be altered using rolling, extrusion, machining and joining.

Machining of AMCs cannot be completely avoided and most of the components have some degree of machining. Machining of metals is very common and is easily performed, however, machining of AMCs is generally considered as difficult to machined materials. Machining of AMCs is carried out by both the conventional and non-conventional method of machining. Previous research works which have been carried out in this area using conventional machining is summarized in this study.

The machinability of AMCs can be improved by appropriate selection of the reinforcing phase, its volume fraction, size, and morphology as well as the composition and hardness of the matrix material. Cemented carbide tools were used to machine some of the less abrasive materials at slow speeds, but if higher production rates are required or the more abrasive materials are to be machined, polycrystalline diamond (PCD) tooling is required [3]. Thixotropic machining for the shaping of AMCs involved deforming the remelted composite in a thixotropic state and releasing the applied stress while the composite was still in that state. However, the process-induced cracking was particularly severe when the cutting tool tended to adhere to the thixotropic composite [4].

The laser heat-assisted machining of Al_2O_3/Al composite material obtained good results. Experimental results showed that during machining the cutting force was reduced by 30-50%, the tool wear was reduced by 20-30% [5]. The experimental results of machining on aluminium alloy reinforced with 20% of particulate silicon carbide-SiC with cemented carbides K20 grade cutting tools in radial turning showed that the shear angle decreased with the chip compression ratio. On the contrary the chip deformation increased with chip compression ratio. The normal stress is always higher when compared with shear stress. Both stresses decreased with the increase of feed rate. For the same feed rate the normal stress is higher when higher cutting velocity is used. On the contrary, the shear stress slightly decreased with the cutting velocity [6]. The best results were obtained with TiN coated HSS twist drill when drilling Al/SiC MMCs with the lower cutting point angle of 90° , higher feed of 0.2 mm/rev and higher cutting speed of 87.96 m/min [7].

Hayajneh et al. [8] investigated the influence of some parameters on the thrust force and cutting torque during drilling of self-lubricated aluminium/alumina/graphite hybrid composites synthesized by powder metallurgy.

Thus, this paper is focused on the aluminum matrix composites. The primary aim of this paper is to provide a comprehensive literature review on machining of aluminium matrix composite material with the focus on chip formation, finite element modeling, grinding process, surface quality, ultra-precision machining, cutting forces and tool wear, etc.

2 CHIP FORMATION PROCESS

The types of chip formed are not only related to the type of the shear zone, but are also influenced by material properties, cutting conditions and tool geometry, etc. Problems with surface finish, dimensional accuracy and tool life can be caused even by minor changes in the chip-formation process.

Hence, it is necessary to understand the chip forming mechanism for a material. Large amount of added particles (56% vol. graphite) assist in fracture during chip formation. Discontinuous chips, low specific cutting energy and tool wear on the nose were the characteristic features found during turning of aluminium alloy matrix composite [9]. Higher abrasion resistance of the coatings on the cutting tool resulted in increased tool life performances and different chip formation. In the chip formation process, the reinforcing particles pile up along shear planes which divide the deformed chip into layers. The phenomenon is more evident as the cutting speed or feed increase, because the increased temperature enables the alumina particles to move more freely. The effects of localized forces and thermal load cause the coating to be removed along a line parallel to the cutting edge [10].

Chips of aluminium alloy are found to be curl through circles of wider and larger diameters as the rake angle decreases. It may be due to sticking of workpiece material on the tool face. Initial radius of chip increases with decrease in the volume of reinforcement, especially, at lower rake angles. This could be due to the changes in the length of the contact onto tool face. In developing appropriate cutting tool geometry, breaking of the chips is necessary for compaction of chips in a constrained environment (flutes of drills, tooth cavity in broaches, taps, etc.). Curled and continuous chips not only occupy more volume but also creates difficulties in chip disposal system. The understanding of chip curling and breaking will thus help in developing better tools for composite materials [11]. It was revealed from the research that during the formation of chips, deformation occurs along the shear plane and stress concentration occurs around the Al_4C_3 particles which facilitate the formation of the micro cracks. These micro cracks propagate at the particle/matrix interface facilitates the fracturing through the chip cross-section.

This effect reduces the chip sticking period, segment thickness, tool/chip contact length and also cutting forces [12]. The shear angle decreased with the chip compression ratio; on the contrary the chip deformation increased with chip compression ratio [13]. The machined chip microstructure was refined in the sub micrometer level due to large strain deformation imposed by the cutting tool [14]. It was observed during the machining of coarser reinforcement composites (Al/SiC) with the use of PCD/CBN tools that at lower cutting speed (40 m/min) thin flakes, needle type as well as segmented chips are formed, whereas at higher cutting speed (120 m/min) generally, semi-continuous, continuous, scrambled ribbon, and tubular helix chips are formed. The length of the chip and the number of chip curls increases with an increase in feed rate at given cutting speed and depth of cut.

In case of finer reinforcement composites, the chip segments are longer in length and gross fracture occurs at the outer surface of the chips only. Whereas in coarser reinforcement composites, complete gross fracture causes formation of smaller chip segments. Secondary crack formation is evident at the inner surface of the chips in case of finer reinforcement composites due to its higher ductility [15].

3 FINITE ELEMENT MODELLING

Monaghan et al., adopted a sub modelling approach in order to analyse the micro mechanical problem [16]. Simulation of the metal cutting process was performed on the SiC particle (35% by volume) reinforced A356 aluminum alloy using FORGE2. The micromechanical sub modelling was performed using ANSYS 5.2. The machining model of the aluminium alloy without the reinforcement and the resulting hydrostatic pressure distribution were used as inputs for the ANSYS micromechanical sub models of the composite. Mariam et al., presented a 3D thermo-mechanical finite element model of the machined composite work piece [17]. The model is used to predict the effect of the different cutting parameters on the workpiece subsurface damage produced due to machining. The model predicts high localized stresses in the matrix material around the SiC reinforcement particles, leading to matrix cracking.

Zhu et al., developed a plane-strain thermo-elasto-plastic finite element model and used to simulate the orthogonal machining of alumina/aluminium 6061 AMCs using a tungsten carbide tool [18]. Simulations were carried out employing temperature dependent material physical properties. The model is used to investigate the effects and shear stresses on the alumina particles. Chinmaya et al., developed a multi-step 3-D finite element model using the commercial finite element packages for predicting the sub-surface damage after machining of A359/SiC/20p [19]. Material properties are defined by applying the Equivalent Homogenous Material model for the machining simulation while the damage prediction is attained by applying the resulting stress and temperature distribution in a multi-phase sub-model.

4 SURFACE QUALITY

The machined surface quality of composites is one of the most important concerns which affect the actual application of the composites. The structure of AMCs is composed of a soft matrix and hard reinforcing particles. Under the cutting force the Al matrix and the reinforced particles do not deform uniformly. Thus, it is

expected that there will remain a work-hardening and stress in the machined surface layer. Dry high-speed turning tests, at different cutting parameters were conducted in order to investigate the effect of the various cutting parameters on the surface quality and the extent of the sub-surface damage due to machining. It was found that the surface roughness improves with an increase in the feed rate and the cutting speed, but slightly deteriorates with an increase in the depth of cut [20]. Cutting with a larger removal rate increases the possibility for tensile residual stress in the machined surface layer of the composites [21].

The tool produces a poor surface finish because of large nose radius, large force and vibration by different rotating parts [22]. The metallographic analysis revealed severely damaged machined subsurface with numerous geometrical defects and plastically deformed aluminium matrix. The lower the reinforcement volume fraction and the coarser the particulates, the higher are the variations in matrix microhardness. The microhardness measurements on the aluminum matrix beneath the machined layer showed higher values when machining under wet conditions with reduced depth of the plastically deformed zone [23]. Feed rate has the greater influence on surface roughness followed by cutting speed and percent volume fraction of SiC [24]. Researchers carried out experimental work using CBN inserts with and without wiper on cutting edge and also by varying the other process parameters. During the experiments, cutting forces from the machining zone were monitored and after machining, surface finish, microstructure of the surface and the residual stresses in machined surfaces were measured. It was observed that the wiper geometry on the inserts reduces the surface damage and lowers the cutting forces [25].

Graphitic composites exhibit lesser thrust force, burr height, and higher surface roughness when compared to the other material. The reduced thrust force and burr height was attributed to the solid lubricating property of the graphite particles. The higher surface roughness value of Al 2219/15SiCp-3Gr composite was due to the pullout of graphite from the surface [26]. The presence of the reinforcement enhances the machinability in terms of both surface roughness and lower tendency to clog the cutting tool, when compared to a non-reinforced Al alloy [27]. The results showed that drill, type was about 15 times more important than the second ranking factor (feed rate) for controlling the surface roughness. The effects introduced by tool type and feed rate on surface quality in this study were larger than the effect of spindle speed, heat treatment, and drill point angle [28].

Results revealed that surface roughness increased with increasing the cutting speed and decreased with increasing the size and the volume fraction of particles [29]. The graphite particles into aluminium MMCs and

the variation of hard SiC particle content increases the surface roughness i.e. in Al 2219/15SiCp-3Gr compared to graphite free composites. The pits and valleys formed due to the smearing and removal of graphite particles from the surface of the workpiece generates voids on the surface of the component leads to higher surface roughness values. The SiCp particles between tool and workpiece easily remove the graphite particles from the surface of the workpiece creating craters on the machined surface. Better surface finish can be obtained at highest speed and lowest feed.

The PCD tool performs better than other tools used in the study. The graphitic composites produce discontinuous chips leads to easy machining [30]. The results of the full experiment revealed that the most significant milling parameter for surface roughness was milling speed, followed by the interaction between feed rate and milling speed, then the feed rate. In terms of residual stress on the machined surface, axial depth of cut had the highest influences on surface residual stress, followed by milling speed and feed rate. The results of single-factor experiment demonstrated that surface roughness improved slightly with the decrease in feed rate, while the effect of milling speed was negligible [31]. Experimental results indicate that the surface roughness is more sensitive to a change in size than a change in volume fraction of reinforcement. An investigation of sub-surface integrity involving microhardness variation has shown that depth of altered material zone changes with a change in size of abrasive reinforcement in MMCs.

5 GRINDING

When grinding AMCs, the decrease of wheel cutting ability may be caused by both wear, due to the abrasive action of the reinforcement, and clogging of the wheel due to chip adhesion. This is due to the extreme abrasiveness of the reinforcement material which is responsible for rapid tool wear [32]. The study used grinding speeds of 1100–2200 m/min, a grinding depth of 15 μm for rough grinding and 1 μm for fine grinding, and cross-feeds of 3 and 1 mm for rough and fine grinding respectively, while maintaining a constant table feed rate of 20.8 m/min. The surface finish values, Ra, were scattered in the range 0.15–0.70 μm for the rough-ground samples, whilst a narrower range of 0.20–0.35 μm was achieved for the fine-ground samples. Grinding using a 3000-grit diamond wheel at depth of cut of 1 μm produced many ductile streaks on the Al₂O₃ particles. Both the Al₂O₃ particles and aluminum matrix were removed by micro machining. There were no cracks and defects found on the ground surfaces. There was almost no sub-surface damage, except for a rare cracked particle being found. Rough

grinding with a SiC wheel followed by fine grinding with a fine-grit diamond wheel is recommended for the grinding of alumina/aluminum composites [33]. It has been found that the decrease in cutting ability of the grinding wheels is mainly caused by clogging of the active surface due to chip adhesion rather than by flattening of the grits caused by the abrasion of the hard reinforcement [34]. Better surface finish and damage free surfaces were obtained due to low grinding force at high wheel and workpiece velocities with white Al₂O₃ wheels during cylindrical grinding. The surface finish and damaged surfaces were found to be high at high feed and depth of cut during cylindrical grinding [35].

6 ULTRA PRECISION MACHINING

Few articles have been given relating to the ultra-precision machining of AMCs to address the issue of the effect of cutting parameters, cutting tool material and geometries, and reinforcement on the type of surface/subsurface damage. It also provides important references for selecting the proper cutting parameters and tool geometries. The tool materials (i.e. High speed steel, titanium nitride coated high speed steel, tungsten carbide, CBN, and PCD) used in machining of AMCs were ranked. CBN and diamond tools fracture the SiC particulates along their crystallographic planes and induce little damage in the matrix, while other tools not only delaminate the particulates from the matrix, but also roughen the particulates, and significantly deform the matrix [36].

The machining results of A359 +20% SiC composite with PACVD diamond coated tools with different thicknesses (10-30 μm) showed that the K10-C (coarse grain size) result in an enhanced tool life. The diamond coating allows prolonged tool life but the problem was the frequent detachment of coating, both with or without lubricant [37]. In the machining of SiC-reinforced AMCs with brazed PCD tools, and CVD diamond coated tools, the initial flank wear on both the PCD and the CVD diamond tools was generated by abrasion due to the very hard SiC particles present in the workpiece material. Further tool wear in these areas is believed to be caused by a combination of the abrasive wear and the adhesive wear mechanisms [38]. The surface generation in diamond turning of Al/SiC composites is affected by the cut through and pulled out mechanisms in cutting the reinforcement. Better surface finish can be achieved with the use of whisker reinforcement and smaller volume fraction of SiC reinforcement [39]. A data dependent systems (DDSs) analysis provides a component by component wavelength decomposition of the surface roughness profile of the machined surface. The cutting results indicate that the characteristics of the wavelength

components analyzed by the DDS analysis method are correlated well with the surface generation mechanisms. Since the relative powers of the wavelength components are used to measure the contributions of the cutting mechanisms to the total roughness; this resolves the shortcomings of the conventional spectrum analysis method in characterizing the surface properties such as pits and cracks in ultra-precision machining of MMCs [40].

The results showed in ultra-precision turning tests on SiCp/2024Al and SiCp/ZL101A composites to investigate the surface quality using SPDT and PCD cutters that the surface quality debased with increasing the feed rate or using of high volume fraction materials. Dry cutting would deteriorate the surface finish. A lower surface roughness value can be produced when a positive tool cutting edge inclination, zero rake angle or bigger flank angle was selected [41]. It is revealed from results which are obtained from turning the composite bars using coarse grade PCD insert under different cutting conditions that the feed rate has highest physical as well as statistical influence on the surface roughness (51%) right after the depth of cut (30%) and the cutting speed (12%) [42]. PCD tools during turning of SiC particle-reinforced 2009 aluminium matrix composite under wet machining conditions showed that micro wear, chipping, cleavage, abrasive wear and chemical wear were the dominating wear patterns of SCD tools, and PCD tools, mainly suffered from abrasive wear on the rake face and adhesive wear on the flank face. The chips formed by PCD tool were more discontinuous and fragmentary than that for a straight - nose SCD tool [43].

7 CUTTING FORCE AND TOOL WEAR

The machining of MMCs reinforced with particulates causes problems because of rapid tool wear due to the extremely high hardness of particles such as silicon carbide and aluminium oxide. The tool wear is always similar to the flank wear, as observed in other studies. The wear of the clearance face is mainly due to abrasion, caused by the reinforcing particulates [44]. Further researchers found that a triple-coated carbide, having a top layer of TiN, performed best in terms of flank wear, but gave the poorest surface finish in machining of an Al/SiC. Overall, the worst results were obtained when machining with uncoated carbide, because of the structure of MMCs, the inclusion of a hard abrasive ceramic reinforcing phase makes these materials difficult to form and machine [45].

During the machinability study of A359/SiCp round composite bars using tools with 25 mm PCD inserts it was found that the MRR increases with the higher feed rate [46]. The carbide tools can be utilized in a

roughing operation, while CBN, PCD tools could be used to finish-machine the composites for machining of AMC reinforced with SiC or Al₂O₃ particles [47-48]. The tool life of the conventional tools was observed to decrease with increasing percentage and coarseness of SiCp in the composites in the machining of eutectic Al-Si (LM6) and hypoeutectic Al-Si (LM25) alloys reinforced with 10%, 15%, and 20% SiCp of two particle sizes using conventional HSS and WC tools with varying cutting speed, feed, depth of cut, and environment [49].

The results obtained from machining of Al/ SiC composite using PCD tools indicate that PCD tooling offers superior performance over carbide, both in wear resistance and the quality of the surface finish produced. Observations of the morphology of the wear scars on the tools indicate that the wear process involves both adhesive wear and of the build-up of defects within the diamond particles leading to eventual micro- and macro-fracture in a fatigue-like process [50]. The major damage mechanism is abrasive wear for conventional tools and brittle break for high hardness tools in the cutting of composites. A built-up edge can occur on the face of the tool at a lower cutting speed; it cannot protect the flank face of the tool from abrasive wear. The volume fraction and the size of SiC particle are found to be the major factors affecting the tool life.

When the composites are cut by conventional tools or by most ceramic tools, SiC particles in the composites also micro-cut these tools due to their high hardness [51]. The cutting forces in machining with PCD tools show a slow, progressive and gradual increase during the cutting time. The three components feed depth and cutting of the machining force in turning, increased with the flank wear of the inserts [52]. The abrasive wear of the tool is accelerated when the percentage of the reinforcement in the AMC exceeds a critical value [53]. The tool life decreased considerably with increasing cutting speeds for all tests. Among cutting tools, the wear resistance of Al₂O₃ coated tools showed better performance than those of the other tools without chip breaker geometries in the machining of SiCp reinforced composites [54].

It was observed that abrasive wear was the main mechanism responsible for wear of tools in machining composites. Chipping on the cutting edge was effective at higher speed for higher weight fraction composites but formation of a built-up-edge was evident at lower cutting speeds for lower weight fraction composites [55]. The wear pattern and its mechanisms of single crystal diamond (SCD) and cutting speed, increased with increasing cutting speed. Tool wear was lower when coated cutting tool was used in comparison to uncoated one. Surface roughness influenced with cutting speed and feed rate, where higher cutting

speeds and lower feed rates produced better surface quality [56]. The resultant cutting force was considered to consist of components due to chip formation, ploughing and, particle fracture and displacement, and the calculations of these force components were based on Merchant's shear plane analysis, slip line field theory and Griffith theory, respectively. The predictions revealed that, the force due to chip formation is much higher than those due to ploughing and particle fracture [57].

The flanks wear of carbide tool were increased by a factor of 2.4 with the increase of cutting speed from 180 to 240 m/min at a feed of 0.1 mm/rev and a depth of cut of 0.5 mm. Flanks wear of PCD insert increased by only a factor of 1.3 with the increase of same cutting speed, feed, and depth of cut [58]. The increase in volume % of SiCp reinforcement over the matrix results in higher tool-work interface temperature and needs higher cutting force during the machining process [59]. It was observed that the increase in cutting speed first led to an increase and then a decrease in main cutting force values (Fc), and the increase in feed rate was accompanied with increased main cutting forces. The most consistent results in terms of cutting force values were displayed by 10% MgO reinforced composites [60].

8 DISCUSSION AND FUTURE TRENDS

Machining of these composites is difficult, that is the obstacle for the commercialization of these AMCs. Past research demonstrated that conventional tool material experience rapid and excessive wear in the machining of AMCs due to the very hard, severely abrasive, dispersed ceramic reinforcements. The difficulties associated with the machining of AMCs must be minimized if these materials are to be used more extensively. Therefore, the machining of AMCs is now considered to be one of the most interesting areas of manufacturing science requiring urgent attention. Since AMCs are relatively new materials, comprehensive machinability data have yet to be established.

Research in this area is critical for certain applications and for the life-cycle engineering of these materials. Fundamental mechanisms limiting the expanded use are still not understood. What controls toughness and strength? What is the influence of constituent properties? What is the effect of particle size, shape and distribution? Systematic investigations are required of the fundamental links between microstructure and properties. Much work to date has focused on only a few commercial or near-commercial materials, which have been characterized in detail, but do not provide full insight into basic microstructure-property relations, such as the link between particle size or spatial

distribution and mechanical properties. Not much work has been done on Aluminum Matrix Composites Reinforced with Si_3N_4 , AlN and ZrB_2 , SiO_2 , B , BN , B_4C , may also be considered in future.

9 CONCLUSION

A review of the research work on AMCs with Conventional machining is presented in this paper. The research work of the last 25 years has been discussed. For each and every method introduced and employed in the machining process, the objectives are the same: to gain a deeper understanding of the effects of reinforced particles on forces, residual stress, chip shape and shear and friction angles with varied machining parameters and to enhance the capability of machining performance i.e. low tool wear and better surface finish and to get better output product.

PCD tools are extensively used for the machining of AMCs. In terms of tool life, carbide tools are superior, especially if carbide grades of fine grain size are used. The main machining problem of AMCs is the extensive tool wear caused by the very hard and abrasive reinforcements. Tool wear is influenced by the percentage, size and density of the reinforcement. Carbide tools, either uncoated or coated, withstand significant levels of tool wear after a very short period of machining, where diamond tooling is considered the most viable tooling option.

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