REVIEW OF MACHINING METAL MATRIX COMPOSITES

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ABSTRACT

Metal Matrix Composites (MMC) is a material which has been widely used in the aerospace and automobile industries since the 1980s, and has been classified as a hard to machine material. During the intervening years only a limited amount of research has been conducted into the cutting action of MMCs. As with traditional materials it is important to understand the wear mechanisms that contribute to tool wear reducing tool life. This review has been carried out to establish the optimum machining parameters vital to maximizing tool life whilst producing parts at the desired quantity and quality. The objective of this research is to evaluate the effectiveness of the machining parameters for these hard to machine material MMC.

Keywords: Metal Matrix Composites, machining parameters, wear mechanisms, hard to machine material, tool life.

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1.0 Introduction

Metal Matrix Composites (MMCs) are a relatively new category of composite material that consists of a ductile metal matrix reinforced by strong particles, fibers or whiskers [1, 2 & 3]. Common matrix metals include aluminum, titanium, magnesium, cobalt, copper and various alloys of these materials. The reinforcement material is generally a brittle ceramic material, typical examples include Silicone Carbide (SiC) and Boron Carbide (B_4C) and more recently, TiC [4, 5]. MMCs are increasingly desired for their improved specific properties that combine the toughness and ductility of the metal matrix phase with the hardness and strength of the reinforcement phase [6, 7]. Increasing the demand for MMCs materials to be used for aerospace machined products. However, as yet to full explanation of several unique machining properties of MMCs remain unsolved. Giving rise to conflicting reports on certain characteristics of MMCs [8] during cutting, it is generally agreed that they are very difficult to machine [9]. Research into improving or quantifying the machinability characteristics of MMCs have been performed since the early 1970s, with Figure 1a showing the steady increase of studies completed based on available papers.

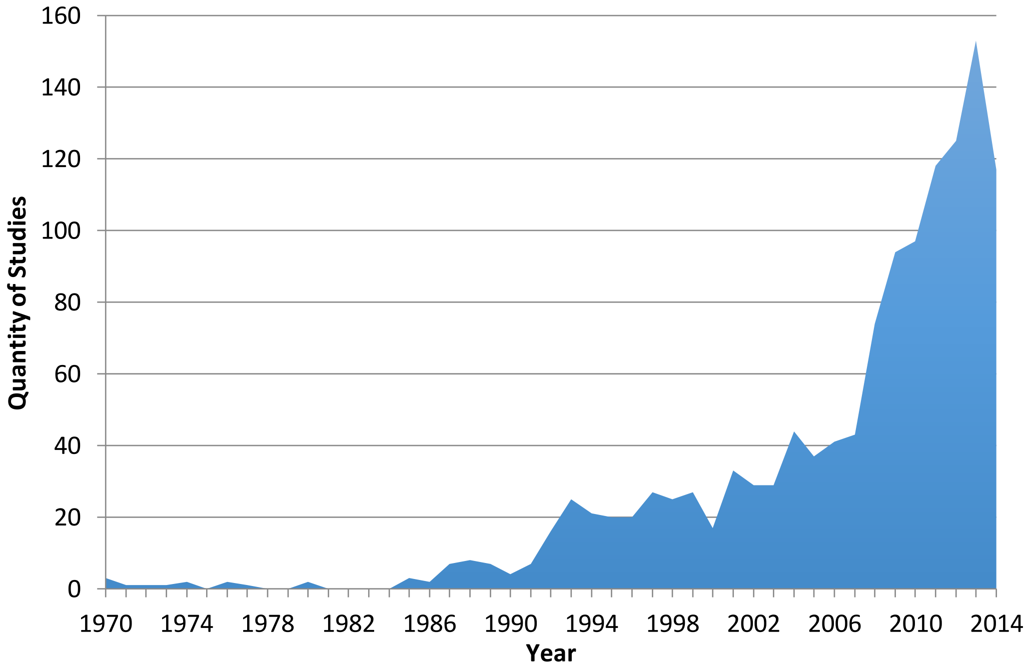

Figure 1a: Volume of MMC machinability studies by year sourced from a variety of journals database and web sites

MMCs have in recent times become commonplace in the aerospace, and performance automobile industries [10], where the high cost of machining the material can be afforded.

However, a wider product base of using MMCs has been extensively disrupted by the difficulties associated with the material's machinability [4]. The conventional single-shear plane cutting models are unsuitable for modeling the cutting process of MMCs during machining [11]. Very few attempts have been made into generating predictive models for the behavior of MMCs during the machining process [12-15]. Further study into the prediction of the machining forces, and machining parameters are required to fully understand the behaviour of the material [16]. This review considers numerous research investigations which have been conducted throughout many industrial countries as shown in Figure 1b in determining the effects of the machining parameters, and machinability of MMC material.

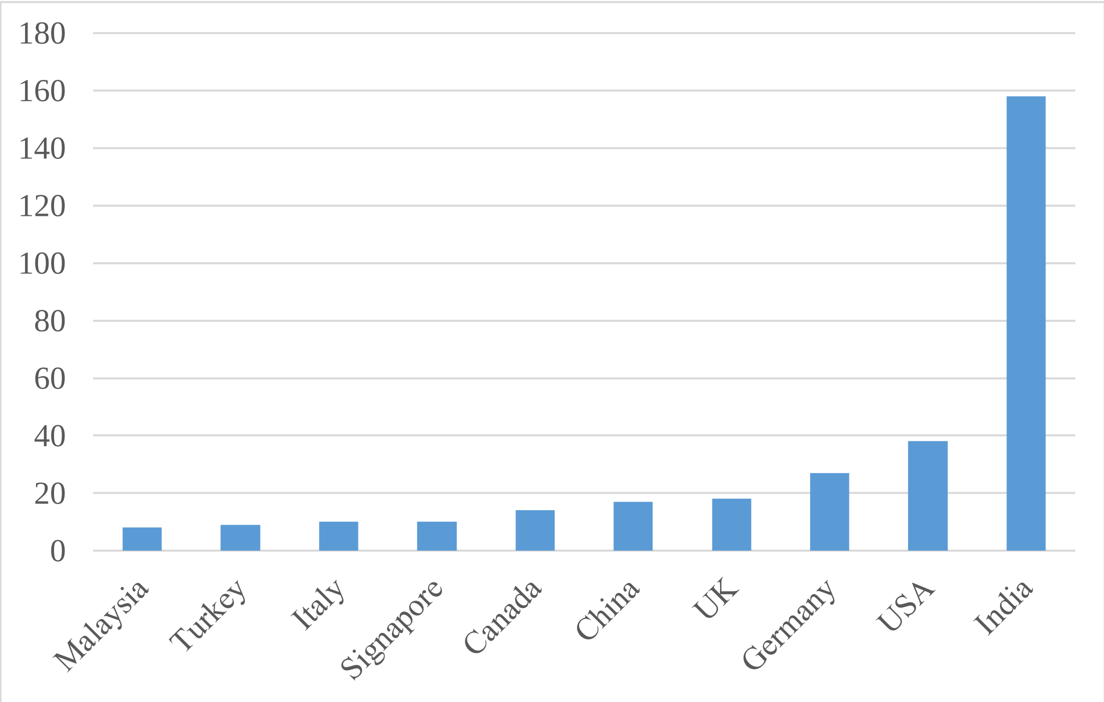

Figure 1b: Distribution of research performed over the previous 20 years thought the world, data retrieved from Scopus database search with the phrase [MMC machining parameters]

2.0 Effects of Tool Selection

The majority of investigations into MMC machinability have been performed using cemented carbide or polycrystalline diamond (PCD) as the cutting tool material. Figure 2 shows the distribution of the tool types used during cutting process for the experimental machining tests surveyed in this review.

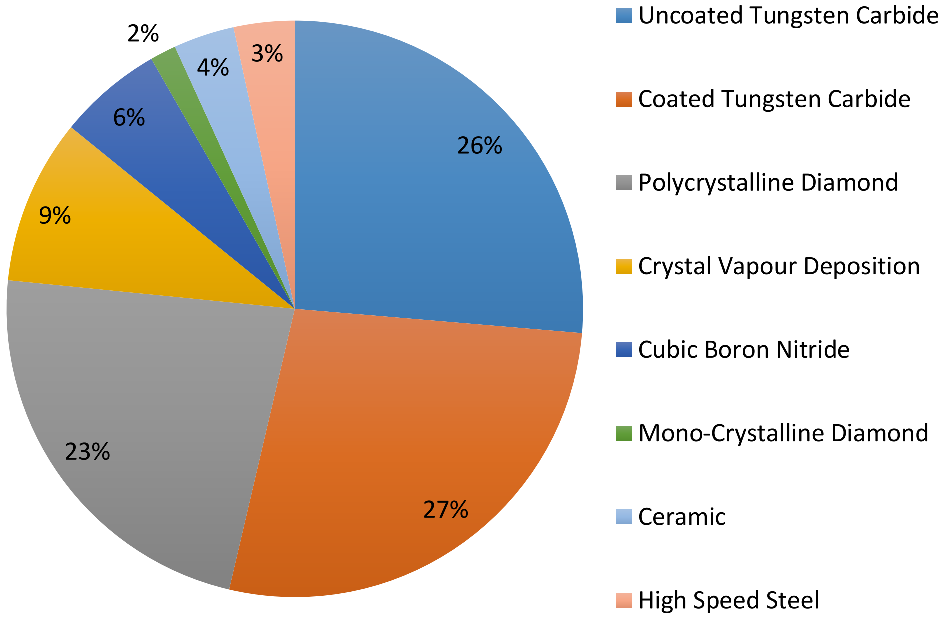

Figure 2: Tool type used in the machining of MMCs from journals

The majority of studies were conducted on lathes, with the next favored machine tool being the vertical mill in addition to milling there were some drilling operations being examined. The recommend twist drill used was normally PCD diamond coated. However, many studies contend that carbide tools are a suitable alternative under certain conditions [17]. This is especially useful since carbide tip are cheaper, and tool wear starts relatively quickly allowing different parameters to be examined to determine their suitability. Which is obviously ideal for examining cooling methods in determining if the onset of the wear mechanisms have been slowed down or not. The studies revealed that carbide tools were used 53% over other materials, and from the papers surveyed coated or uncoated carbide tips where evenly used. Studies into the feasibility of high speed steel (HSS) and ceramic tools have found them both to be unsuitable for MMC applications [17-19], as ceramic tips are brital and HSS wear too quickly. However, TiN coated HSS tools can be economic for short run production [20] and twist drills. Cubic Boron Nitride (CBN) has also been investigated as a potentially viable tool material however testing indicates that PCD tools are more appropriate [21-23] and is the most suitable tip material for production purposes.

2.1 Cemented Carbide Tools

The feasibility of using cemented carbide tools to machine MMCs is a point of contention among the scientific community. It has been suggested that cemented carbide tools are not suited to the machining of MMCs by many researchers [24-26]. A number of conflicting studies have concluded that carbide tools are useful for machining MMCs under certain conditions [27-29]. Carbide tools have been found to be effective in short run machining operations [30, 31] or for roughing operations [32]. It has also been proposed that they perform with industrially acceptable tool life at low cutting speeds (20-30 m/min) and high feed rates when machined using a lathe [19]. Certain carbide tools at cutting speeds of 250 m/min have been observed with a tool life of 40 min when lathe machining Al-SiC based composites [33]. Hung *et al.* performed investigations into various tooling types and concluded carbide type tools to be the most economical method for machining MMCs [34]. Figure 3 displays the results attained for tool life from these experiments.

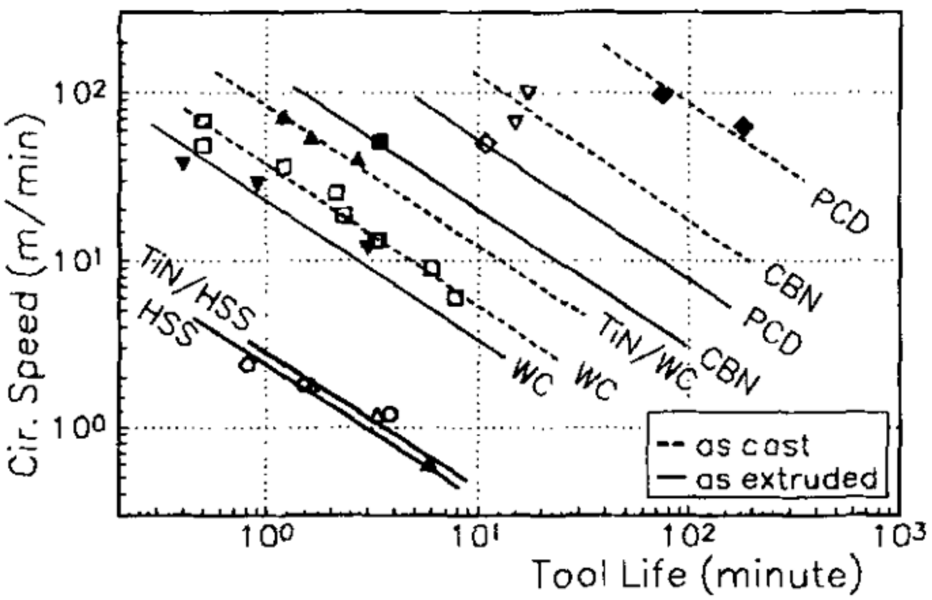

Figure 3: Tool life vs. cutting speed for selected tool material types [34]

An investigation conducted by Chambers [35] using K10 carbide tools at cutting speeds between 20 and 1000 m/min upon Al 5% Mg/Saffil supported the use of cemented carbide tools. The study also noted subsurface damage extending to a depth of 20 µm which was not related to the particle reinforcement fraction or the cutting speed. Limited investigations have been performed into the use of carbide drills [36-39]. A study by McGinty and Preuss [36] found that carbide drills were capable of producing 120 holes through a material 12.7 mm thick at cutting speeds between 8 and 30 m/min using feed rates between 0.15 to 0.3 mm/rev with acceptable levels of wear.

Carbide tools with ceramic coatings have been successfully applied to the machining of steels for decades, yielding significant improvements over the use of uncoated carbide tools. In conventional machining scenarios, they have been known to have a tool life upwards of 200 – 300% that of an uncoated tool [40]. Investigations into the use of coated carbide tool tips while machining MMCs have concluded that the coating has little effect upon the tool life due to the rapidity of the removal of the coating through wear [41, 42]. Sun *et al.* reported acceptable tool lives with respect to wear using coated carbide tools [43]. This conclusion is contradicted by a study performed by certain research, which identified coated carbide tools as yielding improved tool life [44, 45]. It has been suggested that the use of carbide coated tools yields improvements in the surface finish of the machined MMC material over the use of uncoated carbide tooling [46]. Several studies have identified the primary mechanism of wear on tools while machining MMCs as being abrasion [33, 47, 48]. As such, any improvements in the lifespan of a tool will be exhibited as a function of an increase in the hardness of the tool tip or the coating applied to it [17].

2.2 Polycrystalline Diamond Tooling

Polycrystalline Diamond (PCD) tools have been used for the machining of MMCs for many years with much success [49-54]. This success is has been attributed to the fact that the hardness of PCD tool tips is greater than the majority of reinforcing particles and fibers that make up the reinforcement phase [55, 56]. There is a general consensus among researchers that the use of PCD tooling offers a significant increase in tool life over carbide tools, making it the ideal tool material for machining MMCs [51, 57-59]. The tool life of various tool materials as shown in Figure 3 clearly showed that PCD tools provided the longest tool life.

A study by Chambers and Stephens [60] found that PCD tools were far superior to other tool types when machining an aluminum-based, 5% Saffil, 12% SiC material on a lathe. While most studies have found that PCD tooling yielded an improvement in tool life, Chen and Miyake [61] noted that the improvement in tool life was far less than expected while testing an Al-Mg5 alloy reinforced with 20% Saffil on a lathe. The life of the tool was only doubled, in contrast to significant gains in tool life when machining conventional materials.

Chambers and Stephens [60] observed the primary wear mechanism while machining MMCs with PCD tools to be abrasion. Many other studies suggested that the wear observed was primarily abrasive [33, 35, 62, 63]. One study identified microchipping in a PCD tool and therefore concluded that increasing feed rate and depth of cut to maximize material removal rate (MRR) would be unsuccessful. This conclusion contrasts the findings from studies into carbide tool tips, which suggest maximizing these quantities to improve MRR over the lifespan of the tool. Increases in cutting speed have been shown to yield an increase in the rate of tool wear similar to that of carbide tools [64].

2.3 Chemical Vapour Deposition Tooling

Diamond coated tools created using the Chemical Vapour Deposition (CVD) method have also been investigated as a suitable tool tip for machining MMCs. Andrews *et al.* [65] compared CVD tools to PCD and noted significant lack of performance from CVD tooling. A comparison of PCD and CVD tools using carbide tool performance as a reference point found that CVD tools performed unsatisfactorily [18]. The study concluded that while the CVD tools showed improved tool life, PCD tools had twice the useful lifespan due to the tendency of the diamond coating on CVD tools to detach during machining. Investigations by Kremer & El Mansori determined that the use of rough or multi-layered CVD coatings yielded lower machining forces than using smooth coatings while machining SiC reinforced aluminium [66].

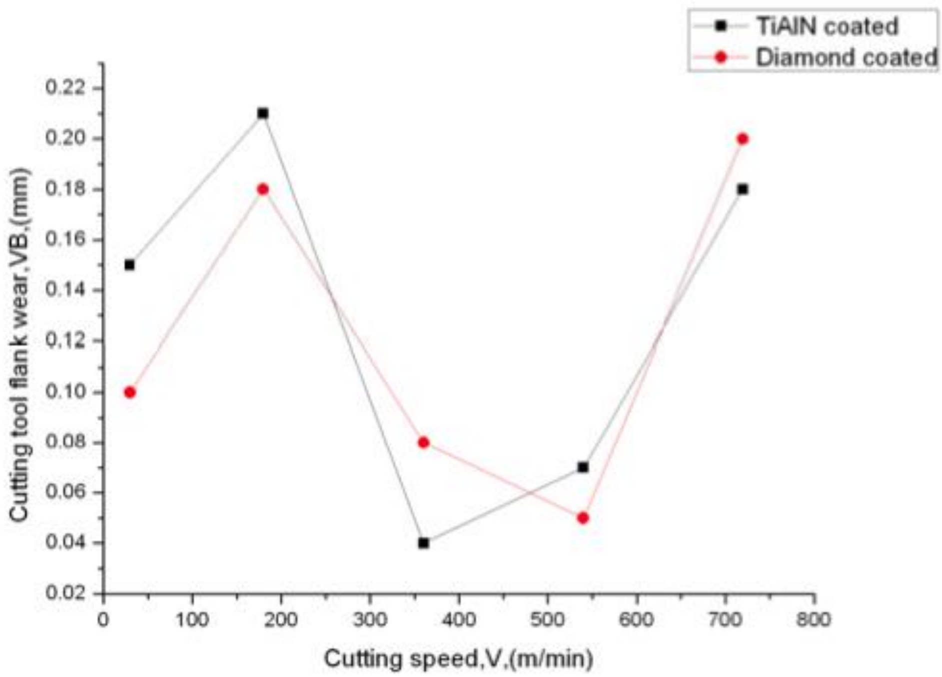

Figure 4: Tool flank wear of coated carbide and CVD tools for the same material removal [67]

Figure 4 shows a comparison between flank tool wear on a coated carbide tools and CVD tool tip. A study into the behavior of CVD tools while machining MMCs suggested that the primary failure mode at low cutting speeds is coating failure, while at high speeds the primary failure mode is edge chipping [67]. The same study also observed that at milling speeds above 720 m/min, CVD tools are highly prone to rapid and catastrophic edge chipping, resulting in tool failure. Coating failure was identified as a major issue for wear while machining MMCs with CVD tooling during additional studies [68]. Another study by Chou & Liu also identifies coating failure as a major issue in the use of CVD tools [69]. Research performed by J. Paulo Davim suggest that CVD tooling developed catastrophic levels of flank wear 10 times faster than PCD tooling, making CVD a far less desirable option for the machining of MMCs [3].

2.4 Cubic Boron Nitride Tooling

Cubic Boron Nitride (CBN) tools have a much greater hardness than conventional carbide tools, but are not as hard as PCD tools [70]. CBN tools have been compared against carbide and PCD tooling, and were found to perform similarly to uncoated carbide tools in certain work [21, 15]. In a study comparing CBN tools to PCD on a lathe at 50 and 400 m/min with a depth of cut of 0.3 mm and 0.1 mm/rev feed rate, PCBN tools suffered from significantly larger built up edge and suffered from a shorter tool life [22]. These findings are in conflict with more recent work by Hung *et al*. and Looney [27, 71]. Hung tested multiple tool materials on a lathe and found the use of CBN tools improved useful tool life by a factor of almost 5. The same study showed that PCD tools yielded a lifespan improvement at a factor close to 5 over CBN tools. Chipping of the tool tip was identified as an issue while machining with CBN tools [27]. This observation was supported by Ciftci *et al.* [21] who identified tool fracture as being the primary wear mode in a CBN tool while machining an aluminum, 16% SiC MMC with reinforcement particle sizes of 110 μm. During the same study, abrasive flankwear was identified as the primary wear mode while machining material with 30 μm and 45 μm sized reinforcement particles. Research performed with CBN tool material has been found to be very limited with data retrieved from Scopus database only finding two studies each in India and Turkey and one from China, using the search phrase (tool life when machining MMC material).

3.0 Effects of Machining Parameters

One key step towards maximising the efficiency and sustainability of the process of machining MMCs is to optimise the machining parameters [72]. Matching the machining parameters to the tool material and the desired surface finish is vital to establishing an economically machining process. The optimisation of the machining parameters also improves the sustainability of the cutting operation, a factor which is becoming increasingly critical in the machining and fabrication industry [29]. Research reports generally good surface finish from machined MMCs [73, 74] however work by Cheung *et al*. have shown that in circumstances where the reinforcing fibers or particles are pulled from the workpiece during machining, the surface finish may deteriorate [75].

3.1 Cutting Speed

Investigations into the effects of cutting speed on abrasive flank wear have shown that minimum wear is achieved by optimising cutting speed, rather than by simply minimising or maximising it [76]. Ciftci, Turker and Seker trialled multiple cutting speeds on a lathe with a constant feed rate and depth of cut of 0.12 mm/rev and 1 mm, respectively. They found that machining at cutting speeds of 150 m/min produced less flank wear than cutting at speeds of 100 m/min or 200 m/min [21]. A study by Pandi & Muthusami suggests that surface roughness is also improved at medium cutting speeds [77]. Other studies suggest that increases in cutting speed will improve surface finish [78-82]. Figure 5 shows the surface roughness at various feed rates and cutting speeds was observed by Kaarmuhilan *et al*. to support the use of medium cutting speeds [50].

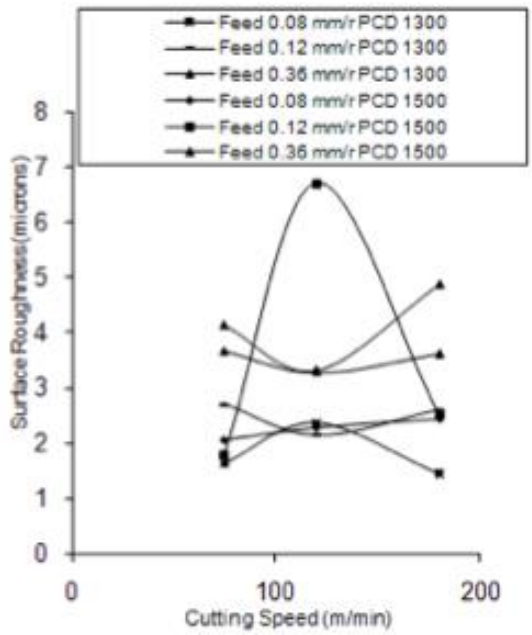

Figure 5: Cutting Speed versus Surface Roughness [50]

Many studies have suggested that lowing cutting speeds will produce less tool wear [80, 83, 84] by diffusion, during the machining of metal matrix composites. Diffusion wear becomes an issue as the tool material softens during high temperature machining [85]. It has been shown that high cutting speeds are primarily responsible for softening of the tool tip due to the temperatures generated at high speeds [86]. Research has shown cutting speed to be the primary parameter to influence the required machining power [29, 87, 88]. The same work identified 100 m/min as the preferred cutting speed on a lathe for good surface finish. However, it was recommended to use higher cutting speeds to improve sustainability of the cutting process. The cutting speed is also the major contributor to cutting force according to an analysis performed by machining Al/SiC/B4C material on a lathe [89]. The aforementioned cutting test recommended the cutting speed to be 100 m/min ideally when using PCD tool tips.

The cutting speed has been identified as the primary influence upon the wear mechanisims of the cutting process [90]. The size of a built-up edge has been found to be highly dependent upon cutting speed. It has been observed that the size of the built-up edge formation is inversely proportional to the cutting speed of the machining operation [91, 92]. The results of the same research also supported the conclusion that built-up edge was detrimental to the surface finish of the workpiece and therefore cutting speed should be kept high to avoid poor surface finish. It appears that the selection of cutting speed must therefore take into account three primary factors; the desirability of a built-up edge, the importance of surface finish and the importance of tool life. Lower cutting speeds seem to improve tool life and develop built-up edge, however higher cutting speeds improve the surface finish of the machined product.

3.2 Effect of Feed Rate

Studies have shown that at higher feed rates, the rate of abrasive wear on the cutting tool decreases [93-96]. One of these studies attributes the decrease in wear to the thermal softening of the workpiece material as interface temperature rises [19]. Lin, Bhattacharyya and Lane suggest that the feed rate will also make a significant contribution to the thermal softening of the tool material [97]. Another study suggests that the decrease in wear at high feed rate is caused by the reduction of contact between the tool tip and the abrasive particles of the dispersed phase of the material [98]. Studies have also shown that the effect of feed rate is not as significant as cutting speed upon the usable tool life [63, 99]. A study performed using a lathe by Pendse & Joshi found feed rate to be the primary influence upon surface finish [100]. Figure 6 shows the effect of feed rate upon specific cutting force as observed by Gaitonde *et* *al.*. The trends in this figure show that an increase in feed rate had an overall reduction in the specific cutting force [101].

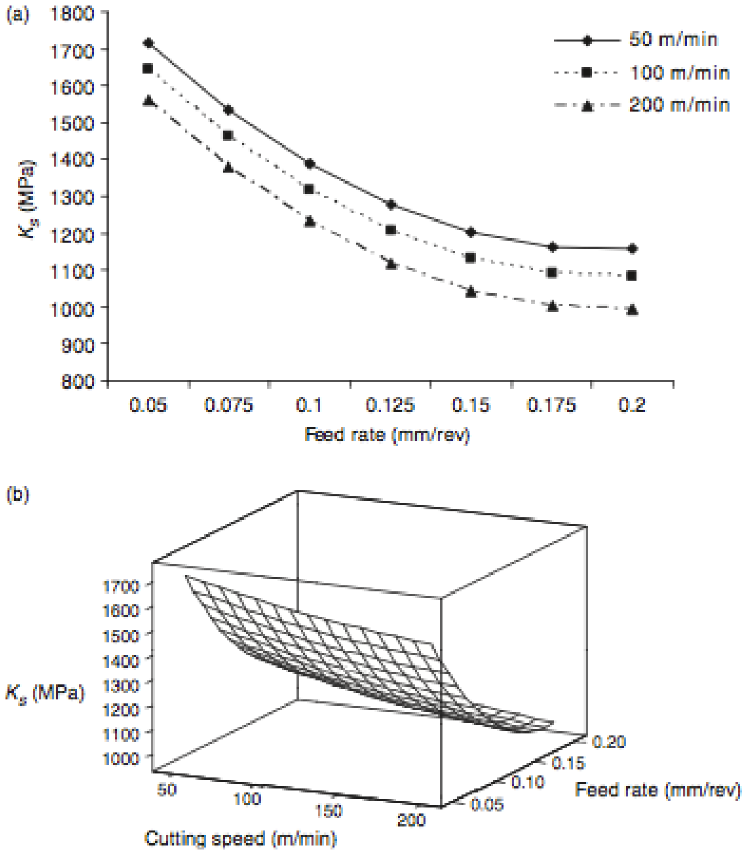

Figure 6: Effect of cutting speed and feed rate on specific cutting force [101]

Feed rate has been identified as a major contributor to the machining power [101]. Many studies into optimising the parameters of MMC machining have identified the feed rate as the parameter that contributes the most to the cutting force [29, 37, 38, 102]. Radhika *et al.* used ANOVA to conclude that feed rate had the highest influence upon the surface roughness when machining MMCs [103]. Chandrasekaran and Devarasiddappa performed mill tests and used fuzzy logic in their analysis. They identified feed rate as the main contributor to surface finish and recommended minimizing it to improve the quality of the finish [104]. This suggestion is supported by Kilickap *et al.* and Srinivasan *et al.* [80, 105]. Multiple researchers have produced similar recommendations using ANOVA techniques on lathe tests [72, 89, 106]. A study into the sustainable machining of MMC material by Boswell *et al.* using milling tests supported the conclusion that feed rate was the primary influence on surface roughness, however the results of their testing found that surface finish improved with an increase in feed rate [29] which is contrary to conventional wisdom. Another study indicated that at low speeds, particle pull-out has a greater influence on surface roughness than the feed rate [107].

3.3 Effect of Cutting Depth

The majority of studies into the machinability of MMCs have yielded corresponding results as to the effects of the depth of cut. Turning studies by Rabindra Behera and G. Sutradhar suggest that an increase in depth of cut yields an increase in total resultant cutting force [108] Several quantitative analyses using methods such as ANOVA upon lathe tests have suggested that the depth of cut has the least significant effect upon the rate of tool wear and the quality of the machined surface finish [63, 72, 89, 104, 109]. The same result was attained using experimental methods in several other studies [24, 35, 110]. In one of the experimental works, the test results suggested that the best material surface finish was achieved at the lowest depth of cut, and the depth of cut had significant influence upon the cutting force [29]. The study found that the negative impact of a large depth of cut was offset by the benefits of increased material removal rate. Another ANOVA based analysis of the machining parameters by Bansal & Upadhyay [63] suggested that the depth of cut had more effect upon the tool wear and the surface finish than the feed rate. Another turning study performed by Kishore *et al*. also suggested that depth of cut had a significant impact upon the tool wear [111]. The implications of these studies suggest that if economical use of tool tips is desirable, the depth of cut should be maximized. If the surface finish is the primary concern, the depth of cut should be minimized in order to reduce the surface roughness.

3.4 Built-Up Edge

The benefit of the formation of a built-up edge during the machining of MMCs has been a topic of some controversy among researchers. Many believe it is beneficial to the overall machinability, whereas others believe it should be avoided. The development of a built up edge is reliant upon temperatures at the machining interface that are sufficient to melt the metal matrix material, which may then build up on the machine tool [41, 112]. It has been suggested that built-up edge occurs ideally at low cutting speeds [113]. Many studies suggest that the controlled formation of a built-up edge will result in an extension of the useful tool life during machining by protecting the tool from abrasive wear [41, 114-116]. It is suggested that the built-up edge protects the tool from the abrasive particle wear caused by the dispersed phase, acting as a sacrificial coating that is constantly replenished as the metal matrix is machined [85] [42].

It has been suggested in other research that a built-up edge can be detrimental to tool life during machining [109, 117]. These studies suggest that the built up edge will adhere to the tool tip and as the forces at the tool interface affect the tip the built-up edge will be sheared from the tool tip, removing a portion of the tip in the process [117]. The result of such an occurrence could potentially be a catastrophic failure of the machine tool, requiring an interruption to the machine process, replacement of the tool and potentially destructive effects upon the surface finish of the workpiece [23].

A built-up edge will only provide limited protection from flank wear unless the built-up edge is so large that it causes unacceptable damage to machined surface finish[8]. Irrespective of its size, built-up edge has been shown to yield a measurable decrease in the surface finish of the workpiece [21, 41, 118, 119]. The desirability of a sustainable built-up edge will therefore be dependent upon whether the preservation of the machine tool or the quality of the surface roughness is of higher priority. Finishing operations with the presence of a built-up edge are less likely to produce desirable results.

4.0 Effects of Coolant Selection

During the machining of traditional materials, tool life and surface finish issues are helped by using coolant to reduce friction and for dissipating the generated heat. A variety of different cooling methods need to be investigated when machining MMCs, as each will yield differing results during machining. As metal matrix composites have developed into a commercially available material, several attempts have been made to determine a suitable method of cooling MMCs during machining, none of which have yielded results comparable to the cooling of traditional materials [119-121]. All of the more mainstream machine coolants that have been applied to traditional materials have been investigated thoroughly for their effects upon the machining of MMCs. Several more unconventional methods have not yet been investigated as a means for cooling MMCs during machining. The investigation of coolants for the machining of MMCs remains an important research topic, as researchers have yet to discover a truly effective method of cooling the heat generating zone of the tool.

4.1 Dry Machining

Research into the application of lubricants while machining MMCs has been a focus of many recent studies as researchers attempt to find ways of overcoming the machinability issues pertinent to the material. It has been suggested that the use of a cutting fluid could be redundant due to the lack of improvement in the performance of a machine operation under cooling [8]. Dry machining has been applied successfully to conventional materials in the past [122-124]. Conflicting studies suggest that the control of thermal properties at the machining interface will affect both tool life and surface finish [85, 121].

Dry machining generally generates significant increases in machining temperature over the use of coolant, meaning the conditions will likely be suitable for the formation of a built-up edge. This means that the practice of dry machining is likely to subject the machining process to the benefits and drawbacks associated with built-up edge. The increased temperatures also increase the risk of wear by diffusion, which occurs when atoms from the reinforcement matrix and the tool tip are exchanged, resulting in a weakened tool tip and the associated negative impact upon the tool’s properties [125]. Increases in machining temperature have been shown to lead to an exponential increase in the rate of diffusion wear [126].

4.2 Flood Machining

Flood cooling is a well-established method of cooling machining operations, which involves the practice of “flooding” the tool interface with a coolant delivered by a low pressure pump [40]. Flood cooling has been shunned in more recent years due to concerns about environmental and health effects of older cutting fluids [9]. Modern cutting fluids have been developed based upon vegetable oil emulsions and now do not pose a health threat to the machine operator [127] as in the past. Environmental issues are still relevant as the coolant with use will become contaminated and requires suitable disposal measures. This means that the suitability of flood coolant during machining can be assessed based only upon performance and economical criteria.

The use of traditional cutting coolants while machining MMCs was investigated in depth by Hung, Yeo and Oon [119]. They performed a series of cutting operations, removed the built up edge from the used tool and performed measurements to determine the scale of any tool erosion. The results of their investigations concluded that the use of a cutting fluid would neither increase nor decrease the life of a cutting tool.

An investigation on drilling MMCs by Cronjager and Meister suggested that the application of a cutting fluid was responsible for a one sixth reduction of tool life [30]. The theory proposed to explain this reduction was that the reduction in temperature assisted the matrix to retain its strength, rather than deforming due to temperature. Another study found that the application of flood coolant had no effect at low cutting speeds, however the machining forces decreased significantly at higher cutting speeds [24]. The same work found that the surface finish deteriorated slightly when flood cooling was applied to the machining process. Cronjager [30] performed drilling and milling tests upon various reinforced aluminum composites, noting that the surface finish decreased when flood cooling was applied during the machining operation.

4.3 Minimum Quantity Lubrication

Minimum Quantity Lubrication (MQL) involves the application of an oil, emulsion or water as a fine spray onto the machining interface using air or aerosol as a coolant transport medium [128]. MQL is a relatively recent innovation in machining that has been developed in response to the financial and environmental concerns with the use of flood cooling [129]. MQL has been successfully applied to conventional machining operations and is rapidly becoming one of the most widely utilized methods of lubricating and cooling machine processes.

The viability of applying MQL to MMCs has been investigated in a number of recent research works [120, 130, 131]. Solhjoei *et al.* [130]performed a series of high speed milling tests with carbide tooling upon samples of alumina reinforced aluminium of varying reinforcement particle concentrations. The results of the study suggested that the use of MQL would yield satisfactory machine surface finish and tool wear when machining 10 & 15% alumina reinforced MMC. The same study suggested that MQL was not appropriate for 20% reinforced MMC due to the extent of the flank wear observed during testing.

Research performed into the use of MQL support its viability as a coolant and lubricant when machining MMCs [131]. Braga *et al.* [120] performed drilling tests comparing the use of MQL as a lubricant with traditional flood coolant, as well as comparing diamond coated drill bits with K10 carbide drills. The results of the study showed that the use of MQL yielded similar or improved surface finish and tool wear results as the tests performed using flood coolant.

4.4 Other Cooling Methods

Compressed air cooling involves the direction of a jet of compressed air into the machining interface. The application of air cooling has been investigated as a coolant for the machining of MMCs [36, 121]. A study by McGinty and Preuss [36] consisting of drilling Aluminium plates reinforced with 55% Alumina fibers compared flood coolant to air cooling. While flood cooling was applied, an abrasive slurry was formed which accelerated the wear to the tool. When air cooling was substituted, the accelerated wear stopped. A study performed by Shetty *et al*. [121] found compressed air to be a better form of coolant than oil water emulsion, yielding clear improvements in cutting force.

A study by Stjemstoft investigated the effects of pressurized water and CO_2 as coolants for the machining of MMCs. The results found a maximum of 5% increase in tool life when cooling with CO_2. In some of the tests conducted using water as a coolant, no significant change to tool life was observed, however it was noted that some damage was caused to the tool by the high pressure jet used to deliver the water [132].

Shetty *et al.* conducted a study on the feasibility of using steam as a coolant and lubricant. The study also tested oil water emulsions, compressed air and dry cutting as baseline comparison points [121]. The tests performed measured cutting force, thrust force, workpiece coefficient of friction, cutting temperature and surface roughness of the workpiece.

In all tests, steam was found to improve the cutting conditions. Conditions measured for compressed air typically showed cutting forces 5-10% higher than steam; with results for oil water emulsion and dry cutting varying determined to be 15-35% worse than steam. The results of the research support the viability of steam as a coolant and lubricant, however the results also identify compressed air as being a medium more promising than traditional cutting fluids or dry machining.

5.0 Conclusions

This review has confirmed many of the difficulties experienced when machining MMCs using commercial machining techniques. It has also identified areas of particular concern that contribute to the difficulty of the machining process. The careful selection of the machining parameters, tool type and method of cooling is the key to achieving an economical and accurate cutting process. The selection of a tool material will be the primary concern when seeking to economise the costs of machining. Generally PCD tools proved to be the most appropriate tool having the best lifespans when machined under optimum conditions. Cemented carbide tools may also be commercially viable for use in short run machining or for operations with low cutting speeds and high feed rates.

The parameters of the machining operation will affect the quality of the machine finish and the rate of wear to the machine tool. The selection of an ideal cutting speed will depend upon the priorities of the operation. Lower cutting speeds will assist in the formation of a built-up edge, which is critical to improving the performance of a cemented carbide tool. The formation of a stable built-up edge is also desirable for the economic performance of other tool types. Higher cutting speeds will result in improved machine surface finishes over the finish produced with a slower cutting speed and a built-up edge. The selection of feed rate is most relevant to the surface finish of the workpiece. Most studies concur that surface finish is improved at lower feed rates, however if surface finish is not of primary concern then the tool life has found to improve under high feed rates. The depth of cut has the least impact upon surface finish and tool wear. Generally speaking, the depth of cut should be maximised in order to remove as much material as possible and improve the economy of the process, however if the quality of the surface finish is of primary importance then the depth of cut can be reduced to improve the surface roughness.

The appropriate application of a coolant can extend the tool lifespan and improve the overall machinability of an MMC workpiece. The available literature suggests that dry machining will often result in damage to the surface finish of the workpiece due to increased machining temperatures and the presence of built up edge. Flood coolant has been found to decrease the tool life due to the difficulty in maintaining a protective BUE. Flood coolant may also form an abrasive slurry with machine chips in some circumstances, which may damage the surface finish of the workpiece. MQL has been shown to produce an effective compromise between extending tool life and protecting the surface finish. The application of any coolant will not yield results as effective as conventional application due to the harsh abrasive nature of the reinforcement particles present in MMCs.

The trend of recent research has shifted to focus more on non-conventional machining techniques than that of conventional machining. These processes include electro-discharge machining (EDM), laser cutting, electro-chemical, electro-chemical discharge and abrasive water jet cutting [133, 134]. The primary issue observed with the various non-conventional machining methods were issues of surface finish quality or dimensional inaccuracy [135]. Researchers are also examining the economic aspects of non-traditional machining of MMCs which naturally involves the speed of the abrasive electrical discharge and the machining energy of EDM [136]. This is also important for electro-chemical machining with researchers investigating better stability and high economic process improving the material removal rate [137]. For abrasive waterjet process to improve economically researchers are interested in how the reinforce particles in the MMCs effect the cutting parameters like the depth of cut [138]. Eliminating the use of traditional coolant and improving the tool life used [139], in conventional machining would provide substantial economic benefits. Research into both conventional and non-conventional methods of machining MMCs continues to develop an overall understanding of the optimal and economical methods of machining MMCs. However, at the current level of development it appears that the use of conventional methods will continue to be used in situations requiring accurate part geometries or good surface finishes.

MMCs continue to develop as a commercial material, especially for ultra-light high strength applications, however there is still much research to be performed in order to optimise the machining of these materials. Analysis of the cutting process of MMCs are increasingly using analytical and computer models to provide optimum solutions [141, 142, and 143]. As yet none of the available tool materials are capable of performing on levels approaching conventional commercial machining operations due to the harsh conditions they are subjected to while machining MMCs. Many of the more common methods of cooling have been shown to have negative effects upon MMC machining operations, meaning there is also a demand for a more ideal method of cooling these operations. Many recent studies have focused upon optimising the machining parameters for MMCs, and have generally concurred upon the general requirements for their ideal machining. Although the research presented in this review demonstrates a significant improvement in the understanding of the machining of MMCs since their inception, a substantial amount of work remains until the MMC machining process is fully understood.

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