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Review Article

A Review on Drilling of Metal Matrix Composites

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Abstract

Metal matrix composites have superior mechanical properties contrary to metals over a wide range of working conditions. This makes them a prominent option in replacing metals for different engineering applications. These materials are developed for engine blocks, bearing for propeller vanes, steering system, drive shafts in aircraft. Particle reinforced aluminium MMCs have received considerable attention due to their excellent engineering properties like high strength to weight ratio, high toughness, high impact strength etc. But these materials are usually regarded as extremely hard to machine, because of the abrasive characteristics of the reinforced particulates. It is also acknowledged that their machining behaviour is not fully understood. Amongst all machining processes, drilling is the most frequently useful for secondary machining of composite materials due to the need for joining the structure. The literature reviewed here is the effect of drilling parameters like feed rate, drilling tool and its geometry, cutting speed and other parameters like influence of coolants, heat treatment etc. on the quality of hole. The drilling characteristics were reviewed in terms of drilling forces, tool wear, and the surface quality of drilled-hole and their improvements.

Keywords: *Metal matrix composites, MMC, surface roughness, conventional machining, wear mechanism, tool life.*

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1. Introduction

Metal–matrix composites (MMCs) are a relatively new group of materials characterised by lighter weight and greater wear resistance than those of conventional materials. These materials have been considered for use in automobile brake rotors and a range of components in internal combustion engines. The machining of MMCs is very complex due to the highly abrasive nature of the ceramic particulate reinforcement. The distinctive reinforcing ceramic materials are Al_2O_3, SiC, B_4C can be used as long fibres, short whiskers or particles in either an irregular or spherical shape.

J. Paulo Davim (2001) stated that the cutting tool materials must be carefully selected to minimize wear due to the hard abrasive elements of the reinforcing phase in the work material. Machining of a composite material depends on the properties and relative content of the reinforcement and the matrix materials also on their response to the machining process.

Classification of MMCs into the following categories depending on the types of reinforcements:

1. Particle reinforced MMCs;
2. Whiskers or short-fiber reinforced MMCs;
3. Long-fiber or continuous fiber reinforced MMCs

Table 1 shows typical varieties of reinforcement used in each category of MMC. Usually, Manufacturing of these composites is done by following three techniques namely solid state, liquid state and powder metallurgy. Amongst them liquid state is the most extensively used due to its low cost and natural production process. Some new methods like melt-stir casting, continuous casting, direct-chill casting etc., have been stated by several researchers for production of MMC materials.

Table 1 Different reinforcement used in different MMCs

Types of MMCs	Particle reinforced	Continuous fibre reinforcement	Whiskers or
Reinforcements	Al_2O_3,	Al_2O_3, SiC, B,	Al_2O_3, B, C,
	SiC, WC,	C, Al_2O_3 +	Al_2O_3 +
	TiC, B_4C	SiO_2, Nb-Ti,	SiO_2,SiC, TiB_2
		Nb_2Sn, Si_2N_4	

G. Lane (1992) described that the most promising problem with particulate MMCs is that they are difficult to machine, because of the hardness and abrasive

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nature of the SiC or other reinforcing elements. The particles reinforced in MMCs are harder than tungsten carbide (WC). Polycrystalline diamond (PCD) is an exception, as its hardness is almost three to four times than that of the silicon carbide (SiC), hence PCD is recommended by many researchers.

Paulo Davim (2003) has performed the drilling experiments on the A356/20/SiCp- T6 with Polycrystalline diamond drill bits and studied the effect of cutting velocity, feed rate and cutting time on tool wear and surface roughness. From the study he has assessed the cutting time and feed rate as the governing factors in tool wear.

2. Drilling of MMC

Drilling is the process of cutting using a drill bit to cut or enlarge the holes in work material, such as wood or metal. Diverse tools and methods are used for drilling depending on the type of material, size of the hole, and number of holes to be drilled and the time to complete the operation. It is most commonly performed in material removal and is used as a preliminary step for many operations like reaming, tapping and boring. The cutting process in which a hole is created or enlarged by means of a multipoint, fluted, end cutting tool. As the drill is rotated and advanced into the work piece, material is removed in the form of chips that travel along the fluted shank of the drill. The main parts of the twist drill are shown in Fig.1a.

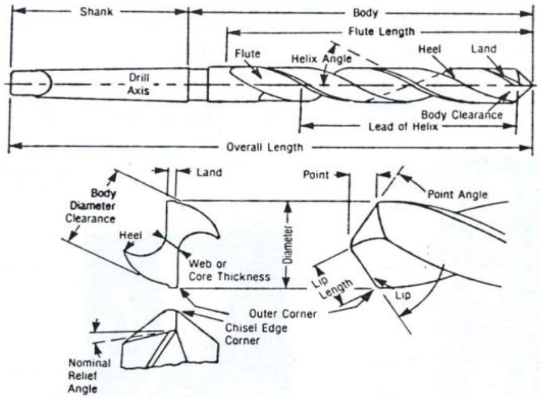

Fig.1a The main parts of the twist drill body (Lindberg, 1990)

Typical drill bit geometry is as shown in Fig.1b. The geometry of a drill bit very much affects the behaviour of drilling process. Land is the area remaining after fluting. In order to reduce the amount of land that creates friction with the hole wall which generates excessive heat, drill bits are margin relieved. The amount of land remaining in contact with the hole wall in drilling process is stated to as the margin. M. Nouari (2005), the wider the margin, the greater is the friction area and the higher the drilling temperature.

Increasing the land mass and the web results in a smaller flute area, less flute space indicates less area to remove chips, which again increases the drilling temperature.

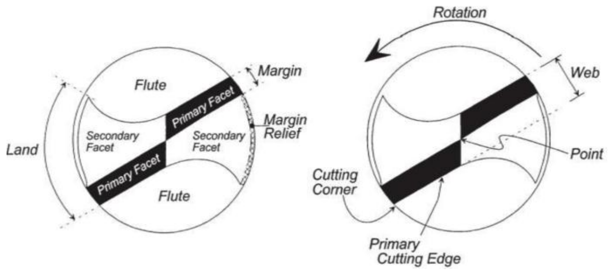

Fig.1b Drill bit geometry

Extensive research in the field of drilling MMC had been done to improve tool life, and for optimize the cutting conditions for different drills. Normally used drills in these studies include PCD tipped drills, high-speed steel (HSS), diamond-coated HSS, Coated carbide (tungsten carbide (WC) and TiN), and TiAlN coated drills. Cronjager and Meister (1992) calculated the effect of cutting speed on the tool wear of two different drills. It was observed that the tool wear of WC drills increases with the increase in the drilling speed. However, the drilling speed has no noticeable effect on the wear of PCD drills in the range of low to medium cutting speeds of 15–300 m/min. The tests were carried out on Aluminium alloy 2628 with 15% SiC reinforcement. The results indicated that PCD tipped drill bits perform the best under different cutting conditions amongst all the drill bit materials. They also reported that the cutting speed was not a significant factor affecting tool life which endorses the earlier findings reported by Lane.

3. Wear Mechanisms and Tool Life

Tool wear can be defined as the unwanted removal of tool material from the cutting edge leading to unwanted changes in the cutting edge geometry of the tool. Thrust and torque depend upon drill bit wear, which in turn depends on drill bit size, feed rate and spindle speed. J. Paulo Davim (2003) shows that tool breakage, tool wear and workpiece deflection are intensely related to cutting force. Once the initial cutting geometry is distorted, the cutting tool becomes less effective in material removal and quality machined surface. The tool wear mechanism can be classified into two major groups as physico-chemical wear and mechanical wear (Venkatesh, 1966). The chemical wear is diffusion wear and dissolution wear, while for mechanical wear are adhesion wear, abrasive wear and delamination wear. It is important to note that different tool materials have different responses to different wear mechanisms.

Abrasion wear theory is based on the idea of hard inclusions in the work material indenting the tool surface by the action of sliding chip or rolling in the shear zone, friction occurring between the tool flank and work material (Dixon and Wright, 1985; Bhattacharyya and Ghosh, 1964). Distinctive damage from abrasion consists of long straight grooves, as when a surface is lapped and polished with a hard abrasive. Damage of this type is rarely seen on worn carbide surfaces. Adhesion wear can also be known as attrition wear, occurred when the metallic surfaces are brought into close contact under moderate loads, thus, a metallic bond between adjoining materials take place. The strength of the bonding at the points of adhesion is often high such that while attempting to free the surface, the separation takes place not along the interface but in one of the materials itself shifting and removing materials often with the sliding member of the pair (Bhattacharyya and Ghosh, 1964).

Diffusion wear observed to occur if the mechanical process involved in adhesion is capable of increasing the localized temperature of the cutting area. Solid state diffusion is the mechanism by which atoms in a metallic crystal shift from one lattice point to another causing a relocation of the element in the direction of the concentration gradient (Bhattacharyya and Ghosh, 1964). Diffusion wear is associated with the chemical affinity between the tool and workpiece materials under the high pressure and temperature occurring during the machining process. It is dependent on the diffusivity of tool material into the work materials in the chip rolling over the tool surface. Diffusivity increases with increase in temperature during chip formation (Trent, 1991). Naerheim and Trent (1977) observed that the crater wear on the rake face when cutting steel using carbide tools is a result of atomic diffusion into the work material sliding over the surface.

Eyup Bagci *et. al,* (2008) showed that the Tool wear leads to adverse consequences such as reduction in cutting edge strength and surface finish, increased tool forces and power consumption, increased cutting temperatures, loss of dimensional accuracy, and finally loss of productivity. The tool wear rate will be contingent on the mechanical properties of composites volume fraction, the reinforcement morphology, distribution and volume fractions, as well as the matrix properties are all factors that affect the whole cutting process. Several researchers have also indicated that polycrystalline diamond (PCD) tools are the only tool material that is proficient of providing a useful tool life during the machining of particulate MMCs. PCD is adequately harder than most of the ceramic reinforcements and has no chemical affinity to react with the workpiece material. A PCD tool has larger grain structures that withstand more abrasion wear by micro cutting compared to tools with a smaller grain size.

Tomac and Tonnessen (1992) investigated the machinability of Al-SiC MMCs using PCD, chemical vapor deposition (CVD), and coated tungsten carbide tools. The investigation discovered that abrasive wear is the main mode of tool failure. The PCD tools had over 30 times higher tool life than carbides for similar cutting conditions. More recently Kishawy *et al.* (2005) presented an analytical model for calculating tool flank wear evolution during turning of particulate reinforced MMCs. The equation was developed to determine the flank wear:

$$\frac{dV_w}{dt} = K\sqrt{\left(\frac{Nv_c}{H_t}\right)^2 + \left[\frac{Nv_c}{xH_t}\left(\frac{H_a}{H_t}\right)^k\left(\frac{D}{d}\right)\left(\frac{f_v}{z(1-f_v)}\right)\right]^2} \qquad (1)$$

In fact, it has been predicted that an precise and reliable tool can increase cutting speeds from 10-50%, compared to worn out tools and a suitable hardened tool reduces the machine downtime by allowing to be slated in advance and an overall increase in savings between 10-40% (Adam, Dr. Jin Jiang and Dr. Peter, 2004).

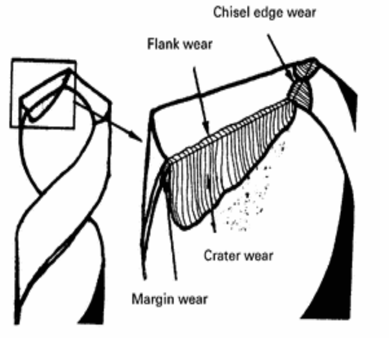

Fig. 2 Characteristics of worn Twist Drill

C C Tsao, (2004) stated that Many of the researchers have selected outer corner w ear as the predominant type of wear in drilling. However in practice, the most important types of wear in drilling of metals are flank and crater wear. Chowdhury S.K (2000) did numerous surveys of machining on metals; the tool wear is mainly due to abrasion at lower speed conditions. When the cutting speed is increased, temperature increases under dry machining conditions. Thus, diffusion is considered as the governing wear mechanism for tools at higher cutting speeds. The atoms that are diffused from the tool to the chip are carried away by the flow of work material along the contact surface. This will consequently lead to substantial reduction in tool life.

4. Chip Formation

The material in front of cutting tool edge is subjected to severe plastic deformation and successive shearing results in chip formation. Chip formation during turning of metal matrix composites differs somewhat in some aspects. The reinforcement particles or fibers are dispersed randomly at and about the tool edge. The manifestation of hard reinforcements alters the plastic deformation characteristics of the soft matrix material compared with conventional alloy. Thus, the change in mechanical properties coupled with reinforcement, pattern and distribution in the matrix determines the mechanism of chip formation (shearing, plowing, particle interface debonding, pull out and cracking) and therefore the machinability of MMCs.

A. Pramanik (2006), described the chip development forces during turning depend on the strength of the material, cutting conditions and tool geometry. Speed and feed influences the strength of the workpiece material in the deformation zones through temperature, strain and strain rate. In drilling, chip formation is controlled by the rake angle of the tool (Fig. 3a). When a positive rake angle takes place, it is able to shear off the work material hence requires little amount of force. However, when the rake angle is negative shearing does not take place. Thus, the tool thrusts the material ahead of it.

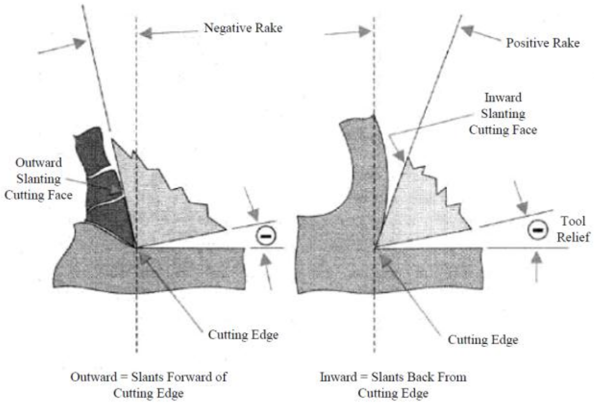

Fig. 3 a The effect of rake angle in chip formation (Schnieder, 2001)

In drilling operation as illustrated in Fig. 3b, the chips must depart through the flutes. The coiling shape of the chips should be avoided particularly when drilling a deep hole. As the chips blocked up in the flute, it will prevent the chips flow out of the hole. This will result in intense heat and blurring on the workpiece and the drill (Schnieder, 2001). The common method to solve this problem is by reducing the rake angle of the cutting lips which allows the chips to bend sharply. The thickness of the chips will also affect the tendency to coil up. Thinner chips are easy to roll up and form a coil instead of breaking. This phenomenon will cause clogging of chips in the flutes.

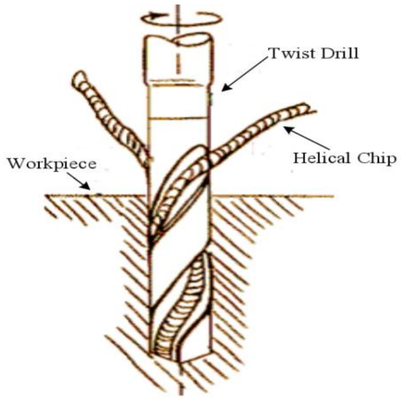

Fig. 3 b Curly chip ejected from the hole (Schnieder, 2001)

J.P. Davim (2007) found that, the measured F_{cc} and F_{ct} (chip formation forces in cutting and thrust directions, respectively), and Φ (shear angle) depend on the cutting conditions. Hence, the experimental shear strength values, τ_S, for both the aluminium alloy and MMC at different machining conditions were determined using the equation.

$$\tau_s = \frac{[(F_{cc}\cos\phi) - (F_{ct}\sin\phi)]\sin\phi}{A_c} \qquad (2)$$

A. Pramanik (2008) studied that at low feed (cut-thickness), the area of cut is small and the entire cut area may have been workhardened by preceding tool pass. This will result in a higher τ_S value at lower feed than that at greater feed. For the MMC, a chip shape varies over the substantial range for different speed and feed.

5. Surface finish

Mostly the machine tool rigidity, work material, cutting tool geometry, coolant, feed, speed and depth of cut are the key factors influencing surface finish. The reliability of the process in achieving the required surface finish is important as otherwise it adds to the cost of manufacture with rejection and rework.

Tomac N (1992) studied that almost 75% of all metal cutting process involves drilling operation. In automotive engine production the costing of drilling hole is of the highest value. Also, surface integrity is an important parameter in manufacturing engineering. It is because, surface integrity can influence the performance of final parts and it's quality.

Many of researchers have explored the relation between surface roughness and the cutting speed. Some of the obtained results were complementary while some showed a contradiction to the remaining. Outstanding surface finish can be produced when machining with a PCD tool.

An excellent surface finish is difficult to achieve because of fracture and pull-out of particles during machining of an MMC. Hence, the effect of machining parameters on machined MMC surface may be different to that on a non-reinforced material. The theoretical roughness of a turned surface can be calculated by using the following equations,

$$R_a \approx \frac{0.032 f^2}{r_\varepsilon} \qquad (3)$$

$$R_{\max} \approx \frac{f^2}{8 r_\varepsilon} \qquad (4)$$

Where Ra is the arithmetic mean value of surface roughness which does not indicate actual profile of surface but gives an idea of average surface geometry, R_{max} is the maximum peak to valley height within the sampling length, f the feed and r_ε the tool nose radius.

6. Various Parameters affecting the performance

6.1 Feed rate

Gul Tosun & Mehtap Muratoglu (2004) had stated that as the feed rate increased, the cutting temperature also increased and this may cause weakening of the binding between the matrix and the SiCp, Paulo Davim & Conceicao Antonio (2001), had suggested that at a constant cutting speed, the surface finish of the holes of the drilled samples deteriorates with increasing feed rate. Tamer ozben *et al.* (2008) reported that the cutting speed is the most important machining parameter on cutting tool wear and the tool wear increases with cutting speed as shown in Fig. 4.

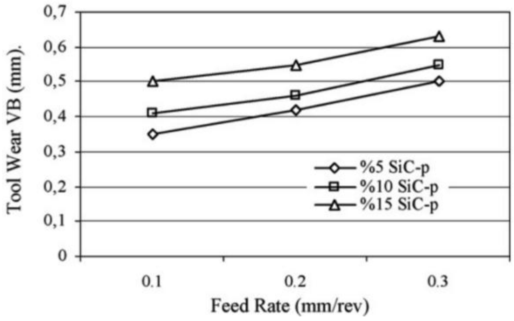

Fig. 4 Effect of feed rate on tool wear at V=50 by Tamer ozben (2008).

Coelho *et al.* (1995) had examined the various cutting parameters and selection of cutting tools for drilling of Al based MMCs and described that the low feed rates produced rapid flank wear on the tool.

6.2 Drilling tool and its geometry

Gul Tosun (2004) reported that as the point angles of HSS and TiN coated HSS drills increase, the destruction zone increased. However, with increasing point angles of solid carbide drills, the damage zone decreased. From their report, by increasing the point angles of all the drills, the surface irregularity decreased. Hard carbide tools produce a improved surface finish compared to that achieved when using the HSS and the TiN coated HSS drills.

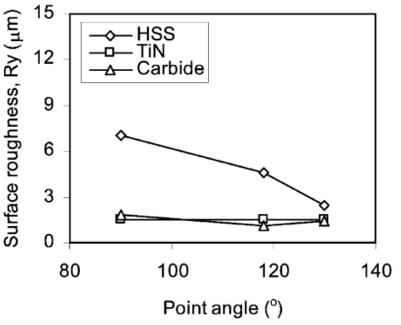

Fig. 5 Effect of the point angles on the surface roughness with the drills for as-receive

Ramulu *et al.* (2002) recommended that drilling forces were ominously influenced by tool materials. HSS drills are unsuitable for drilling MMCs because of very high tool wear, poor drilled hole quality, and higher drilling forces induced. Basavarajappa *et al.* (2008) reported that burr formation is less when multifaceted carbide drill is used when associated to conventional coated carbide drills. Conventional coated carbide drilling is preferred in applications that require a good surface finish. HSS is not a suitable tool material. PCD tipped drilling tools were effective over a wide range of operating conditions.

6.3 Cutting speed

Edith Morin *et al.* (1995) calculated the thrust forces; torque and flank wear for several feed rates and cutting speeds and described that cutting speed has no noteworthy effects on drilling force and wear over a range of speed. Ramulu *et al.* (2002) had assessed the drilling characteristics in terms of drilling forces, tool wear, surface finish etc. and reported that the lowest surface roughness parameters occurred at the lowest feed rate with highest cutting speed. Basavarajappa *et al.* (2008) had analyzed the drilling characteristics and suggested that the surfaced finish increases with increase in speed, or the surface roughness decreases with increase in spindle speed. Tamer ozben *et al.* (2008), reported that the cutting speed is the most significant machining parameter on cutting tool wear and the tool wear increases with cutting speed as shown Fig. 5.

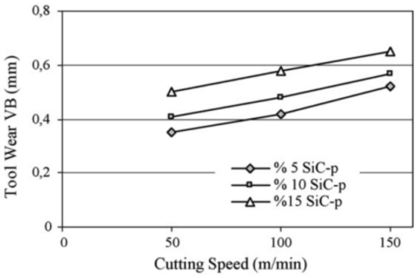

Fig. 6 Effect of feed rate on tool wear at V=50 by Tamer ozben *et al.*

Basavarajappa *et al.* (2008) also investigated the influence of various cutting parameters on the drilling performance of Al based metal matrix composites and suggested that the surface roughness value decreases with increase in cutting speed. Coelho *et al.* (1995) had investigated the various cutting parameters for drilling of Al based metal matrix composites and proved that the cutting speed was not a important factor affecting tool life. Edith morin *et al.* (1995), there is linear relation between torque and wear of the drill which indicates a linear variation of specific cutting energy with flank wear. Drilling forces are controlled by the matrix material and not by the particles. S. Basavarajappa *et al.* (2008) Feed rate is the main factor, which is influencing the thrust force in both the composites. The cutting speed and its interactions with feed rate are minimum and can be neglected. The incorporation of 3% graphite in Al/SiCp composite will reduce up to 25% of the thrust force for the range of parameters studied.

Conclusions

A widespread review on the effect of various parameters on drilling of MMC was presented in this paper. The review of the literature indicates that the research progress with the drilling of Al based MMC was scarce. The effect of feed rate, cutting speed, cutting tools, heat treatment and application of the coolant were reviewed and the results shows that the trend can be confirmed with more number of experimental and theoretical modelling. Hence it can be concluded that more research is required particularly on drilling of MMC. Furthermore the focus on development of predictive models will be useful in predicting the drilling performance of MMC. Hence it is believed that this review will provide the necessary guidelines for future research on drilling of Aluminium based metal matrix composites.

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